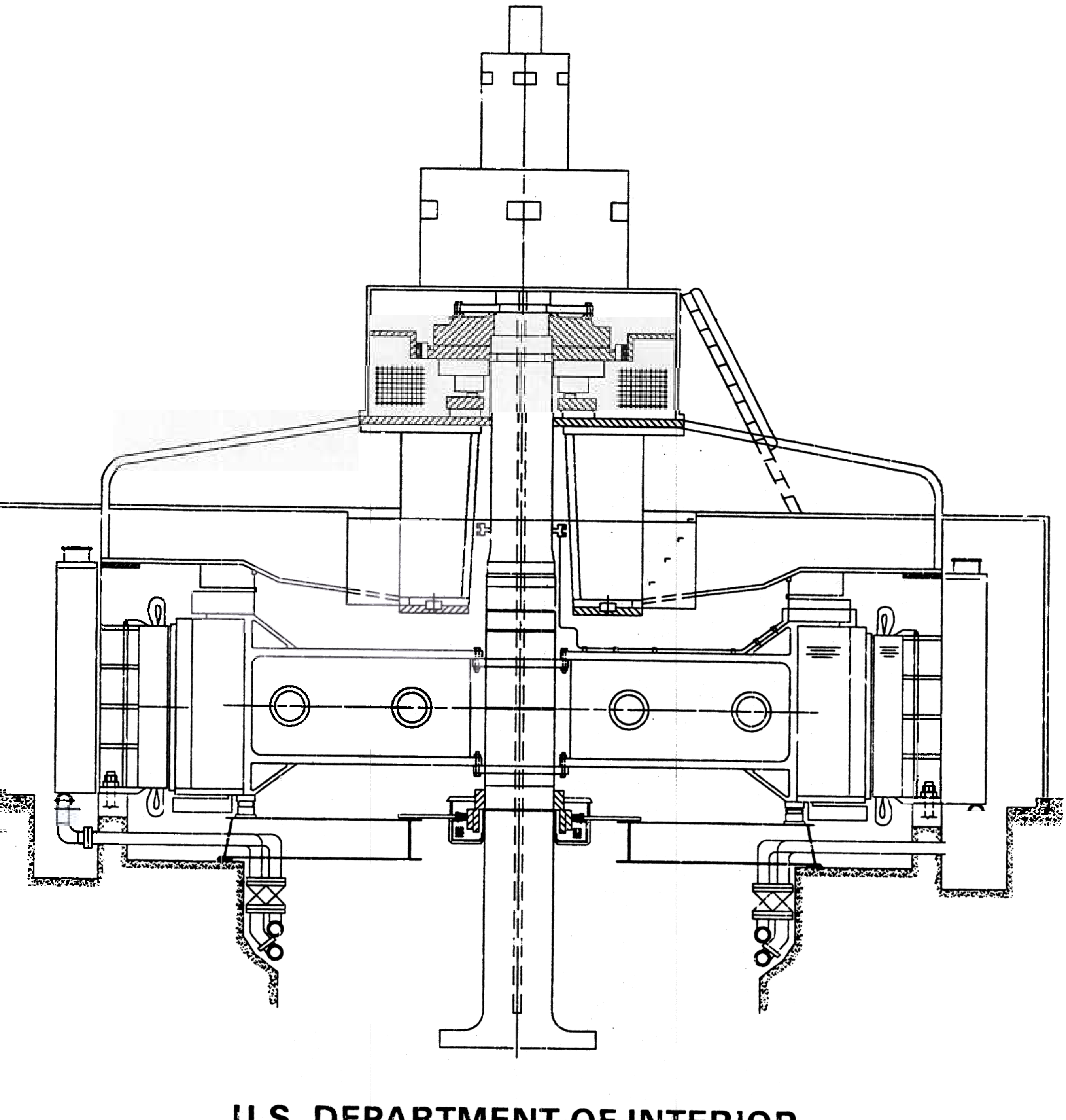
HYDROGENERATOR

DESIGN MANUAL



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16. ABSTRACT

The *Hydrogenerator Design Manual* provides information useful in preparing plans, estimates, specifications, review of manufacturer's design, installation, renovation, and repair of hydrogenerators. The manual does not provide basic electrical theory of design.

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HYDROGENERATOR

DESIGN MANUAL

Plant Equipment Section
Electrical Branch
Electrical and Mechanical Engineering Division
Bureau of Reclamation
Denver Office
Denver, Colorado

U.S. DEPARTMENT OF INTERIOR

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BUREAU OF RECLAMATION

Mission: As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally-owned public lands and natural and cultural resources. This includes fostering wise use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also promotes the goals of the Take Pride in America campaign by encouraging stewardship and citizen responsibility for the public lands and promoting citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. Administration.

Mission

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

SI METRIC

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PREFACE

The *Hydrogenerator Design Manual* has been prepared to provide information needed by design engineers to properly select and specify hydrogenerator requirements. Information is provided to assist in preparing powerplant layouts, developing requirements for generator renovation (rewind) and uprating, recognizing failure possibilities, and instituting machine maintenance. The manual is intended to be used primarily by Bureau of Reclamation engineers responsible for application design, specifications preparation, and technical review for hydrogenerators. However, other personnel engaged in planning, operation and maintenance, inspection, construction, electrical control, power system design, design of mechanical equipment associated with hydrogenerators, structural design and layout, and hydraulic systems will find the manual useful.

Many Bureau of Reclamation documents detail what was done, and how goals were accomplished for most Reclamation installations. However, little documentation exists as to why different options were selected in preference to other options for hydrogenerators. Also drawn upon here are the demonstrable facts gained by operation and maintenance through decades of experience.

The sundry options available, and the differing options selected for the various plants constructed by the Bureau of Reclamation, tends to convey a false impression that arbitrary choice, personal preference, or chance had governed some selections. The manual's objective is to reveal the basis for the existence of different options and thus to assist in selecting the best option for present day application. Improvements in materials, refinements in construction, and current design practices have been identified. Experience resulting from some of the various options has been noted.

Present plans contemplate revision of the manual at the appropriate time. Suggestions for revising and improving this manual are welcome; they should be submitted in edited format to: Bureau of Reclamation, Attn: Code D-3411, PO Box 25007, Denver CO 80225-0007.

The *Hydrogenerator Design Manual* was written by John B. Kirkpatrick, under a contract with the Bureau of Reclamation's Electrical Branch. Mr. Kirkpatrick was Head—Plant Equipment Section of the Electrical Branch at the time of his retirement in January 1985.

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This manual was prepared under the general direction of Daniel A. Green, Head—Plant Equipment Section of the Electrical Branch in the Electrical and Mechanical Engineering Division at the Bureau of Reclamation's Denver Office

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Symbols and Quantities

Quantity	Symbol	Quantity
Ampere, amp	m	Meter
Alternating current	mm	Millimeter
American wire gauge	MV•A	Megavolt ampere
Celsius, temperature	MW	Megawatt
Carbon dioxide	n	Rotational speed, r/min
Circular mil	O	Oxygen
Centimeter	O_3	Ozone
Current transformer	PF	Power factor
Direct current	PMG	Permanent magnet generator
Diameter	p/m	Parts per million
Efficiency	lbf/in^2	Pound-force per square inch
Extra high voltage	PT	Potential transformer
Fahrenheit, temperature	R	Resistance
Frequency, hertz	rms	Root mean square
Foot	r/min	Revolution per minute
Torque, foot-pound force	RTD	Resistance temperature detector
Ground-fault circuit interrupter	SCR	Short-circuit ratio
Gallons per minute	SCR	Silicon controlled rectifier
Rotational stored energy constant	Std	Standard
High potential dielectric test	t	Time
Horsepower	TIF	Telephone influence factor
Hour	UMP	Unbalanced magnetic pull
Heating, ventilating, air-conditioning	UPS	Uninterruptible power supply
Hertz	V	Volt
Electrical current	VPI	Vacuum-pressure impregnated
Negative sequence current	WR^2	Inertia, pound-foot squared
Inch	X	Reactance
Current squared multiplied by	X_d	Direct axis reactance
resistance, usually conduction	X_q	Quadrature axis reactance
or copper loss in watts	X'	Transient reactance (subscripts of
Integrated product		d and q for direct and quadrature)
Kilogram	X''	Subtransient reactance (subscripts of
Kilovolt ampere		d and q for direct and quadrature)
Kilovolt ampere, reactive	Z	Impedance
Kilowatt	ϕ	Phi, symbol used for phase
Pound	ϕ	Phi, symbol used for magnetic flux

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CHAPTER 1

BASIC DESIGN

1.1 INTRODUCTION AND GENERAL CONSIDERATIONS

The Bureau of Reclamation (Bureau) had designed, constructed, and is operating 51 powerplants in the Western United States (as of Sept. 1986). These plants contain 187 hydroelectric generators. Data for each generator is shown in the PLS Listing [1][1] for which operations are by the Bureau of Reclamation (Department of the Interior) and Western Area Power Administration (Department of Energy). This publication is updated at intervals; the above numbers of plants and generators are those shown as of September 1986. In addition to the plants, the Bureau has participated in design and construction of several powerplants for other agencies and countries.

Many generators shown are of enormous capacity, and of the latest technology when they were installed. Some generators are still among the largest ever constructed.

Many Bureau of Reclamation multipurpose water projects generate electrical power incidental to release of water for other purposes. Some plants, such as Glen Canyon Dam and Powerplant in Arizona, release water primarily for production of electric power. Pumped-storage plants, such as Mt. Elbert Pumped-Storage Powerplant and Forebay Dam in Colorado, are also constructed primarily for production of electric power; however, design and construction of the generators are considerably different than those used for only power generation.

Irrigation water is impounded and released primarily for the benefit of irrigators. The need for irrigation water may not coincide with demand for electric power. However, interconnection of electric power transmission systems has greatly diminished the need to match powerplant capacity with local loads, since modern water and power dispatch systems have been developed to make most efficient use of irrigation releases. Occasionally, water systems require energy dissipators, and hydroturbines may be selected to perform this service.

The Public Utility Regulatory Policies Act of 1978 (PURPA) created incentives for developing of additional energy sources, such as those that exist at many irrigation storage reservoirs, that were not originally constructed with hydrogenerating plants. This benefit factor, combined with an ever-increasing need for energy, makes development of hydroelectric generation an attractive option at dams and reservoirs where such development had not been originally planned. Increasing the electrical power generating capacity of older generators—described as "uprating"—has become a most beneficial procedure. Usually, uprating does not require modification to civil works at a hydropowerplant or dam.

To demonstrate economic feasibility, cost-benefit analyses must be performed together with studies of environmental impact and social acceptability to prove the value of a project before considering design of the hydrogenerators. The prime purpose of the plant, together with many other factors must be considered when selecting hydrogenerators. This manual's purpose is to assist in those considerations.

To prepare basic designs for a hydrogenerator, data must be acquired from field or project forces, from designers of other powerplant features, and perhaps from experts in the industry. Various levels of planning or design will dictate the extent to which designs are developed and the accuracy of the data required. Early planning studies may require only

[1] Numbers in brackets refer to entries in Bibliography.

a broad estimate of size and cost of a machine. A generator designer will probably use only experience and historical records (in-house data) consisting of estimating curves and weight and dimensional data obtained from existing similarly sized machines. As plans evolve into final design, increasing levels of accuracy are required in order to ensure a proper design. Detailed studies may be supported by estimates solicited from potential manufacturers when the level of design requires accuracy greater than can be obtained using in-house information. One must recognize that technology changes, materials availability, and other factors can effect obsolescence in equipment designs or features, and errors resulting from using inaccurate data or estimates will impose undue costs upon the constructed installation.

All the data listed in the following text are not required for every level of study. Some of the data may not be required on particular jobs—even at the final design level. The data requirements are primarily for vertical-shaft generators. Horizontal shaft generators are assumed to be smaller, and not all data requirements for vertical-shaft machines would be applicable to the smaller horizontal-shaft machines.

1.1.1 Service Conditions

Usual and unusual service conditions for hydrogenerators are described in ANSI C50.10 [2]. Both ambient and operational conditions are included in the literature. For most of the conditions, the rationale noted is fairly evident.

Machine designers must recognize the presence of foreign material in air and water to ensure proper operation and long life. The same concerns exist as a result of temperature, voltage, mechanical loading, electrical loading, and other operating condition excursions beyond normal expectations. Included in the literature is operation at altitudes above 3300 feet (1000 meters). Air density above 3,300 feet is reduced sufficiently to inhibit heat transfer. Machine designers must reduce generator winding insulation thickness to improve heat dissipation from electrical conductors through the conductor's insulation to the cooling air. Because of reduced insulation thickness, voltage ratings are also reduced. Thus, derating factors for voltage are applied to machines installed at altitudes over 3,300 feet.

1.2 FIELD DATA

Generator field design data requirements for generators are listed in *Reclamation Instructions, Part 133* [3], for various levels of study (appraisal, feasibility, and design). The data requirements are fundamentally general, while additional data for a particular job are usually required as designs develop. Data requirements for generator uprating and rewinding jobs are included in *Reclamation Instructions*. These data include changes from the original installation.

Field data may include the availability of hipot (high-potential dielectric test) equipment. Water and ambient air temperature extremes should be included with the data. Windborn dust, debris, and contaminants should also be noted.

1.3 STRUCTURAL AND GENERATOR DATA

Data regarding the structure is required by hydrogenerator designers; structural designers require data regarding the generator to complete their designs. These data are not developed and exchanged spontaneously. Rather, by interactive process, data are exchanged until a satisfactory final design is obtained. Structural data required *by hydrogenerator designers* include, but are not limited to:

1. Type of structure (indoor, outdoor, semi-indoor, or underground).

2. Space availability and limitations.

3. Foundation loading restrictions.

4. Equipment arrangement in plant.

5. Access-egress features (both personnel and equipment).

6. Time scheduling for completion of various structural features.

7. Shipping and handling limitations.

8. Data regarding any structural features which may inhibit ventilating air flow.

9. Availability of covered or protected storage areas during construction and for postconstruction storage of spare parts.

Generator data required *by structural designers*:

1. Weights and dimensions of assembled generators and auxiliaries.

2. Foundation openings or blockouts required, including purpose and size.

3. Foundation loading points and magnitude of loads, including torques, weights, and other forces supported by the foundation.

4. Location of various generator features such as access doors, bus connections, ladders, stairways, exciters, and auxiliaries.

5. Weights and dimensions of various components as prepared for shipment.

6. Weight, clearance, and space requirements for machine components during assembly or disassembly operations.

7. Setdown space requirements for components during generator assembly or disassembly.

8. Storage space requirements for tools and spare parts.

9. Need for special enclosures or sunscreens.

10. Time and other constraints imposed by generator on construction scheduling.

Although not necessarily structural, architectural and aesthetic appearance requirements must be agreed upon by machine designers and those responsible for appearance.

1.4 MECHANICAL AND GENERATOR DATA

Similar to structural data considerations, data must be exchanged between mechanical equipment and generator equipment designers. The final generator and turbine designs are developed by interactive process. The following lists are not necessarily complete as special requirements likely will arise for individual plants.

Mechanical data required *by hydrogenerator designers*:

1. Planned operation (including peaking, base load, pumped storage, and plant factors).

2. Type of turbine, and direction of shaft rotation.

3. Turbine rated speed, load rejection speed, and runaway speed.

4. Turbine rated horsepower and maximum horsepower.

5. Turbine horsepower at best efficiency.

6. Turbine shaft and shaft coupling diameters.

7. Turbine shaft coupling elevation, with tolerances, and if a bending moment is present at the coupling.

8. Size of turbine parts to pass through generator stator during assembly and disassembly operations.

9. Turbine weight and maximum unbalanced hydraulic thrust.

10. Requirement for combined turbine and generator WR^2, and turbine contribution to combined WR^2.

11. Requirements for intermediate shaft bearings between turbine and generator.

12. Determination of responsibility (turbine or generator manufacturer) for shaft coupling bolts and bolt covers (nut guards).

13. Determination of responsibility (turbine or generator manufacturer) for combined generator and turbine shaft alignment.

14. Coordinated scheduling of events for turbine procurement.

15. Turbine wicket gate leakage, or potential for unintentional shaft rotation, and maximum potential turbine torque and speed expected.

16. Cooling water details including quantity available, temperature and temperature variation, pressure and pressure loss limits, and whether water is derived from penstock or pumped from tailwater.

17. Location and size of piping and pipe terminations within generator housing for water, oil, and CO_2.

18. Details regarding temperature and quantity of cooling air available from HVAC (heating-ventilating-air conditioning) system.

19. Any shipping and handling size or weight restrictions for generator parts.

20. Plant crane capacity.

21. Crane hook (or hooks) details, travel, and lift limits (elevation).

22. Any special requirements or features required on generator for external (to generator) mechanical equipment. An example: attachments to and support from generator for winches, cranes, or hoists in the turbine pit.

Generator data required *by mechanical designers*:

1. Limitations on size of turbine parts required to pass through generator stator during assembly or disassembly operations.

2. Generator data required for performance of critical shaft speed analyses, including bearing spring constants for all generator bearings.

3. Coordinated scheduling of events for generator procurement.

4. Cooling water requirements.

5. Compressed air requirements.

6. Capacity of lubricating oil reservoirs.

7. Volume within air housing for CO_2 protection.

8. Performance requirements for fire protection system.

9. Piping requirements for water, lubricating oil, CO_2, and compressed air.

10. Loading imposed by generator and generator auxiliaries on HVAC equipment.

11. Generator component weights and dimensions for handling equipment (cranes).

1.5 POWER SYSTEM AND PLANT ELECTRICAL DATA

Data must be exchanged between designers of associated electrical features and the hydrogenerator designer. The following is an attempt to list sufficient data for final design; not all data are required for various stages of planning and design leading up to final design:

1. Generator armature resistance and negative sequence resistance.

2. Armature capacitance to ground.

3. Direct and quadrature axis reactances.

4. Direct axis rated voltage and rated current transient reactance.

5. Direct and quadrature axis subtransient reactances.

6. Negative and zero sequence reactance.

7. Potier (leakage) reactance.

8. Short circuit ratio.

9. Saliency ratio X_q''/X_d''.

10. Power system requirements for WR^2.

11. Direct and quadrature axis transient and subtransient time constant.

12. Short circuit time constant.

13. Initial and sustained RMS (root-mean-square) three phase, single phase, and phase-to-neutral short circuit currents.

14. Regulation.

15. Requirements for line charging and operation as a synchronous condenser.

16. Machine characteristic curves.

17. Value of efficiency and capacity.

18. Power factor requirements.

19. Excitation system requirements, including response time and field forcing capability.

20. Requirements for generator auxiliary alternating and direct current power, including voltage, number of phases, and kV•A capacity.

21. Data for neutral grounding equipment calculations including capacitance of winding (2. above) and of any surge sloping capacitors attached to armature winding.

22. Rate and frequency of occurrence—of generator load changes (peaking or base load operation).

23. Load at which maximum efficiency is desired.

24. Requirement for terminal boxes and their locations.

25. Current and potential transformer requirements, including number and purpose, burdens, and accuracy classifications.

26. Detection, indication, and control requirements.

1.6 MANUFACTURERS' DATA

As stated under section 1.1, data requirements may be such that estimates derived from "in-house" records and expertise may not be adequate. Usually, such situations occur at the final design stage when some contracts already have been made and construction of related structural and mechanical features is underway before procurement of the generators has begun. In such event, data from as many potential generator suppliers as possible are solicited. This permits the generator designer to make a composite estimate based on the latest technology in the industry.

Hydrogenerators are custom built by manufacturers to meet local power system requirements, local geographical conditions, plant arrangements, and hydraulic characteristics peculiar to each powerplant. The term "standard equipment" is applicable only to various features and auxiliaries available; equipment varies from one manufacturer to another. Only the smallest machines would be expected to be manufactured to an industry standard for repetitive manufacture of a complete generator. Standard equipment for larger generators will only occasionally fulfill all requirements for a new generator.

Sometimes, information from one supplier will be sufficiently different from other suppliers, and from "in-house" estimates, to cause a concern. In that case, related features may be adjusted sufficiently to accommodate the unexpected generator designs. It may be possible to specify limits that will permit the generator supplier—proposing the unusual design—to still bid the job, although not necessarily with the same design—features that had been submitted earlier. Limits or restrictions may eliminate some suppliers from competition. Therefore, restrictions should be avoided unless absolutely necessary.

The estimating data that may be solicited from the potential generator suppliers would include:

1. Weights and dimensions of assembled generator.

2. Weights and dimensions of generator parts as prepared for shipment.

3. Weights and dimensions of various components during field erection.

4. Shipping and assembly time requirements.

5. Maximum diameter of turbine parts that can be moved through the generator stator, and the maximum size of the circular opening in the concrete foundation below the generator.

6. Cooling water requirements (approximate).

7. Quantity of lubricating oil required (approximate).

8. Approximate electrical loads imposed by generator auxiliaries on station service system.

9. Approximate contract price may be requested, but the accuracy of any response received should be regarded as questionable.

10. Efficiency at generator rated capacity and maximum efficiency (if different from rated capacity).

11. Any features that potential suppliers might offer, which in their opinion could prove attractive to the Government. Any response to such a question might reveal available technology of which the Government generator designer was unaware.

12. Preferred, or most economical machine terminal voltage.

1.7 COORDINATION AND SCHEDULING DATA

As indicated in various preceding sections, proper design of a hydrogenerator, associated equipment, structure supporting the generator, and connected power system occurs as a result of coordinated iterative processes.

1.7.1 Initial Scheduling

Before final design begins, a schedule defining installation events with dates or time, sequence, and dependencies is developed. The amount of detail required for this schedule increases with the size and complexity of the job. For example, a small generator, which is shipped as an assembled unit, or with only minor disassembly for its shipment, would require a simple schedule. A large machine requiring systematic field assembly would require a complex schedule.

Assuming that field assembly is required, the following events might be identified for each generator:

1. Bureau design preparation start and complete dates.

2. Bureau specification preparation start and complete dates.

3. Bureau procurement solicitation issued and contract awarded.

4. Contractor drawing and data submittals.

   Note.–Submittal dates are staggered over a time period, as designs develop. The Bureau's needs for information, with time restraints for submittal, are identified in the solicitation for bids.

5. Turbine or generator shaft shipment for factory alignment.

6. Storage (inside and outside) available at powerplant for generator component parts.

7. Generator foundation bolt and sleeve shipping time.

8. Powerplant crane availability for generator assembly.

9. Rotor erection pedestal availability and generator shaft and lifting device received at powerplant.

10. Generator foundation availability for exclusive use by generator contractor in generator erection activities.

11. Generator erection complete.

12. Turbine and other plant equipment, penstock water, and power system available to start commissioning testing.

13. Commissioning tests complete and power "on-line."

Sometimes, generator bidders have proposed delivery and completion times either shorter or longer than that stated in the procurement solicitation. Bids stating time periods longer than that stated are usually considered nonresponsive. Shipment in less time than required by the Bureau may cause problems because of lack of proper space storage and erection facilities. Therefore, shorter shipping times may be considered not acceptable.

1.7.2 Design Coordination

Before generator design can begin, hydraulic system characteristics, number of generating units, and basic turbine design must be determined. A preliminary switching diagram showing the basic design of the power system and powerplant must be developed. Early studies will result in a choice between indoor, outdoor, semi-outdoor, or underground type of plant.

Data, previously listed in all preceding sections, are exchanged between the different designers and field forces until a final design evolves. Compromise is frequently necessary; as adjustment, modification, or improvement of designs becomes necessary to accommodate features essential to each component of powerplant equipment.

Following contract award, coordination between the generator contractor's design with Bureau designs, and with contractors' designs for other equipment is essential. Every possible action is undertaken to reveal details known of associated equipment design in each procurement solicitation.

However, it is impossible to cover all necessary details at the time of writing the solicitations. Therefore, statements are included in each solicitation that require each contractor to cooperate with other contractors and to exchange necessary information. Usually, the Bureau requires copies of design cooperation and coordination correspondence between contractors to ensure compliance with requirements.

1.7.3 Construction Coordination

Generator procurement solicitations are written to include critical coordination requirements and dates for construction. The dates are in addition to those required for design coordination. Many dates will be shown as events on the schedule discussed under section 1.7.1.

The generator contractor may be selected to perform alignment of the coupled generator and turbine shafts. The rationale for this may be that turbine procurement usually precedes generator procurement, and the turbine shaft may be fabricated and shipped to the generator manufacturer before generator shaft manufacture is complete—thus minimizing time requirements. However, overseas location of generator manufacture combined with domestic turbine manufacture may justify the opposite. Purchasing a combined generator/turbine unit may reduce or eliminate the Bureau's concern for which manufacturer performs shaft alignment.

The generator foundation bolts and sleeves must be shipped and embedded in the foundation concrete; proper concrete curing time must elapse before generator erection can begin. Shipping all the embedded generator components early, and coordinating the shipments with structural construction is required.

If steel templates are to be used for setting the generator foundation bolts, the templates must be made available at the proper time. Templates may be furnished by the generator contractor, but frequently, they are fabricated by others and comply with dimensions furnished by the generator manufacturer.

The generator contractor may be required to furnish a shaft (or rotor, less shaft) lifting device. The device is constructed so that the powerplant's crane hook (or hooks) attaches to the shaft or rotor. Generally, the device is furnished with retaining rings—but without pivots. Slings may be used to attach the rotor, less the shaft, instead of a lifting device. A shaft lifting device must be shipped in time so it can handle the shaft when it is delivered.

Plans may require the generator contractor to furnish a rotor erection pedestal, but frequently the Bureau will arrange to have a pedestal fabricated to accommodate the generator manufacturer's shaft design. Regardless of who furnishes the pedestal, it must be completed before the shaft can be placed on it to begin rotor erection. Good practice is to schedule the pedestal's availability to accommodate immediate placement of the first shaft onto the pedestal when it is delivered to the powerplant.

1.8 BIBLIOGRAPHY

[1] *PLS Listing*, "Power Facilities," Operated by the Bureau of Reclamation and Western Area Power Administration, U.S. Department of the Interior—Bureau of Reclamation, U.S. Department of Energy—Western Area Power Administration, includes: hydroelectric plants, large pumping plants, transmission lines and cables, switchyards and substations, reactive and voltage control facilities, grounding transformers, Bureau of Reclamation library cat. No. 139643 88A, 199 pp., October 1982 through 1986, Denver CO.

[2] *American National Standards Institute*, ANSI C50.10-90, Rotating Electrical Machinery—Synchronous Machines, New York NY.

[3] *Reclamation Instructions*, Part 133, "Design Data Requirements," Bureau of Reclamation, Washington DC 20240, 1985.

CHAPTER 2

DESIGN DEVELOPMENT

2.1 RATINGS

Characteristics required by standards, assigned by the manufacturer, or required by purchaser's specifications are on the nameplate. Such characteristics might include name of manufacturer, rating, synchronous or induction machine, shaft orientation (vertical, horizontal, or inclined), type of prime mover, excitation voltage, and armature connection (wye or delta). These other characteristics are discussed in section 2.2. The machine's nameplate data are required to conform to ANSI C50.12 [1][1]; and the nameplate rating includes six principle ratings:

1. kV•A or kW capacity
2. Power factor
3. Frequency
4. Number of phases
5. Voltage between phases
6. Speed

2.1.1 Number of Units and Capacity

The number of generating units in a powerplant, kilowatt capacity of each unit, and speed of each unit are determined primarily from hydraulic considerations, turbine design, and power system considerations.

Engineering Monograph No. 20 [2] presents an outline of criteria for determining turbine horsepower (kilowatt), capacity, and speed. Monograph No. 20 presents criteria for other turbine considerations that impact generator design such as impeller type (impulse, reaction, or propeller), weight, runner size, load rejection overspeed, runaway speed, performance curves (efficiency), and overload capability.

[1] Numbers in brackets refer ato entries in the Bibliography.

Power system considerations for generator design include:

- Load and load duration
- Daily and annual load factors
- Reliability/availability requirements
- Controllability (load following capability)
- Connected electrical load/anticipated load growth
- System VAR (volt-ampere-reactive) requirements
- System voltage
- Required generator characteristics

If the plant is a pumping/generating plant, the capability of the power system to start the machine(s) as a motor is a major generator/motor design consideration.

The initial or capital cost per kilowatt of generator capacity decreases as the requirement for generator capacity increases. Thus, capital costs for generators *only*—in any plant—will be minimized if the total plant capacity is developed for the fewest practical number of generators. The tendency to decrease capital costs for fewer machines also is true for turbines, powerplant structure, and control equipment.

Plant service equipment: cranes, compressors, lubricating oil, handling facilities, switchgear, transformers, and bus structures are usually more expensive for large capacity generators than comparable equipment for small capacity generators.

Usually, generator efficiency increases as machine kilowatt capacity increases. Operation and maintenance costs tend to decrease with fewer units.

Some damsites are located in relatively narrow canyons, which limit the space a powerplant may occupy—across the base of the dam. The situation may accommodate plant orientation with the plant's longitudinal centerline essentially parallel to the stream like Hoover Powerplant in Arizona and Nevada, or likewise an underground plant at Morrow Point in Colorado. Usually, long penstocks are associated with such configurations, capital costs are considerably higher, and plant efficiency may be lower than for a plant located at the base of the dam. Reducing the number of generating units to a minimum for such plants is necessary to limit capital costs.

For a reliable source of power, power system requirements will be improved by installing a larger number of smaller capacity units to achieve a plant's total capacity. Maintenance, for machine outages, can be scheduled more efficiently if distributed over a number of machines. Experience has demonstrated that machines of unusual design, including extra large capacity ratings, have a higher rate of unscheduled outage (failure rate) than that of conventional machines. The value (i.e., contract revenue, reliability, power system integrity, etc.) of capacity and energy may require increasing the number of units in a plant to ensure that system requirements are achieved for a reliable source of power.

In considering these factors, a compromise has led to selecting at least two generating units for most Bureau powerplants. Seldom has the Bureau developed the entire powerplant capacity into a single hydroelectric unit. Where a single unit plant had been constructed the capacity was small or waterway considerations prevented installing multiple units.

Manufacturing limitations had prevented installing generating units larger than about 350 MW until the mid 1960s. The largest capacity generators installed by the Bureau up to the 1960s was 125 MW. At that time, technology advances increased maximum unit capacities up to 600 to 700 MW; currently, unit capacities of 1000 MW are commercially available. The earlier maximum unit capacity limitations required installing a greater number of generating units at plants where the selection of fewer units could now be considered a cost effective solution.

Small capacity generators may be produced by repetitive manufacture of essentially identical units, to accomplish significant capital cost reductions. Also, foundation, structure, and service equipment requirements for such small generators tend to be less complex and relatively less expensive than for large-capacity generators. These factors, combined with minimal impact on most interconnected power systems may lead to development of all of a small powerplant's capacity into a single unit.

In some instances, power system requirements—at the time of original plant construction—were such that development of full water system capacity into electrical power capability was not practical. This led to initial installation of only part of a plants' ultimate capacity. Some powerplant unit bays were left vacant pending power system need. If the entire water system capacity had been developed initially, a smaller number of large-capacity units might have been selected. Another solution was to install units to the ultimate plant capacity; then, operate the units at part-load until system needs evolved. Part-load efficiency is usually lower than at rated-load efficiency; in addition, considerations for other (nongenerator) components tend to discourage the choice of excess capacity generators. Also, the capital cost of a generator is nearly proportional to its rated capacity. Thus, repayment considerations discourage installation of excess capacity generators.

Yet, another approach was to take advantage of some generators designed capability to operate at loads above rated capacity. Power system loads in excess of nameplate rating could be served—within limits—at the expense of somewhat shorter generator service life by operating the generator at overload. Bureau specifications, circa 1960–80, required that generators be capable of continuous output at 115 percent of rated kV•A at rated voltage, rated power factor, and rated frequency. When operated at loads in excess of rated, the temperature rise of various generator parts were permitted to exceed the limits imposed for operation at rated capacity—provided the additional temperature rise did not produce injurious heating. This specified overload capacity was permitted by industry standards. Turbine operation at full wicket gate and critical head [2] was capable of developing the generator overload capacity.

Industry standards were changed during the early 1980s which eliminated overcapacity requirements; after the change, Bureau specifications no longer included such requirements.

Many of the generators having 115-percent overcapacity capability had armature windings with asphaltic binder insulation. This type of insulation system required a greater proportion of the armature slot cross-sectional area to be used for insulation, as compared to copper conductor, than the newer polyester or epoxy binder insulation systems. Because the machines were required to have mechanical strength to provide continuous operation at 115 percent of their original rating, some machines could be rewound with armature windings having the newer insulation systems, and then operate continuously at loads up to 115-percent original nameplate rating without exceeding original temperature rise limitations. However, rewinding with new armature insulation systems to achieve greater capacity was not always possible. Some generators had load limit restrictions imposed by temperature rise of components other than the armature. Excessive field temperature rise was one of the restrictions encountered.

NOTE.-The Bureau differentiates between the terms "rewind" and "uprate."

The term *rewind* is used if only the armature winding is to be replaced. If a generator was originally equipped with an asphaltic binder insulated armature and had 115-percent mechanical overcapacity, it could be rewound to produce up to 115-percent original nameplate rating.

If a generator:
- did not have any overcapacity rating,
- was originally equipped with a polyester or epoxy binder insulation,
- had loading limits restricted by components other than the armature winding,
- or if ratings in excess of stated overcapacity rating were required,

the generator required *uprating* to achieve capacities in excess of original nameplate rating. Uprating almost always requires modifications or replacement of generator components in addition to the armature winding.

For each plant, studies must be made to compare various combinations of number of units and individual unit ratings necessary to develop a powerplant's rated capacity. All of each plant's factors must be carefully weighed and quantified to achieve the optimum design. Conforming to hardened rules is not the norm.

2.1.2 Power Factor

A generator's power factor, PF, rating is determined by delineating the requirements of the power system that the generator is connected to.

Synchronous generators are capable for supplying reactive power, VARs, to a power system by overexciting the generator field. The synchronous hydrogenerator may be operated underexcited to absorb VARs from the system. The reactive power generated or absorbed is vectorially additive to the real power, kW, that the machine supplies. A synchronous generator's components: exciter, field, and armature all impose limits on the magnitude of reactive power that can be supplied (or absorbed) by the generator. In addition to the above components, the generator's excitation control system places limits on the rate-of-change in VARs supplied or absorbed. The magnitude limits imposed by various machine components is controlled by the generator's rating. Synchronous generators are always rated in terms of kV•A at a certain power factor, and may be operated at any power factor—leading or lagging—within the machines rating. Operation at lagging power factors lower than rated is possible. Although, not always stated in the nameplate rating, the *rated* power factor of a synchronous generator is always unity or leading (overexcited).

Induction generators receive their excitation from the power system that they are connected to, and therefore, always absorb VARs from the system. In other words, induction machines always operate at a lagging power factor. The magnitude of the VARs required can be controlled to some degree by machine design. Induction generators are rated in terms of kW at a stated power factor. Although, not always stated in the nameplate rating, induction generator power factor rating is always lagging.

An induction generator is normally rated at 0.8 PF. Power factor ratings higher than 0.8 may be purchased—with a premium assessed. Modifications can be made to the induction generator itself to improve power factor, or power factor correcting capacitors can be connected to the generator armature terminals. Air gap spacing for an induction generator is small, in comparison to a synchronous generator, and air gap space is one of the variables affecting power factor (decreasing air gap increases power factor). Winding design also impacts power factor. Manufacturers should be contacted to determine the amount of improvement possible by machine modifications and the premium that may be assessed.

Synchronous generators have a power factor rating in a normal range from 0.8 to 1.00—selected to serve connected system requirements. Special condition ratings as low as 0.60 may be specified, at a premium price. Preferred power factor ratings are 0.80, 0.85, 0.90, 0.95, and 1.00, but intermediate power factors between the preferred ratings may be specified to achieve decreased costs.

2.1.3 Frequency

Normal power system frequency throughout the United States is 60 hertz; all Bureau hydroelectric units are rated at 60 Hz. Originally, some generators at Hoover Dam and Powerplant were rated at 50 Hz; then, later they were converted to 60 Hz. Machines rated at frequencies other than 60 Hz may be purchased, but at premium prices. For a situation that favors machines having a rating other than 60 Hz, manufacturers should be contacted regarding availability. It is noted that frequencies different than 60 Hz will effect both "normal overspeed" and "normal WR^2" of hydroelectric unit.

2.1.4 Number of Phases

All Bureau hydroelectric generators are three-phase, wye connected. Generators can be manufactured as single- or two-phase machines. In single- or two-phase selection, special precautions such as spring mounted frames and special amortisseur windings must be observed.

2.1.5 Voltage Between Phases

A hydrogenerator's voltage rating is the voltage between phases of the generator armature at which the generator produces rated power.

Generator armature winding insulation is not tapered or graded. All coils are furnished with the same insulation. Coils having full line-to-line voltage developed between them may be placed in close proximity to one another in the machine.

Small capacity generators serving only local loads may be operated directly connected to a power system. In this case, generator voltage rating must be the same as system voltage. In most cases where system voltage is over 480 volts, a step-up transformer to increase generator voltage to system voltage is used. This allows selecting generator voltage ratings independently from system voltage.

Generator manufacturers usually publish a listing of preferred voltage ratings for machines they design, with price adjustments for machines having voltage ratings either above or below those preferred ratings. The preferred voltage ratings increase (by increments) as generator kV•A capacities increase. The Bureau's largest capacity generators are at Grand Coulee Third Powerplant, Washington—voltage rating of 15 kV. Most generators at Hoover Dam and Powerplant (Arizona-Nevada) are rated at 16.5 kV, which was considered extraordinary at the time they were designed. The Bureau's smallest capacity generator (438 kV•A, 0.8 PF), installed at Lewiston Powerplant, California, is rated at 480 volts.

Generator rating less than 3000 kV•A may be rated at 480, 600, or 2400 volts. Ratings of 4160, 4800, 6900, 11 500, or 13 000 volts may be specified for small capacity generators, but a premium may be assessed.

Generator rating greater than 3000 kV•A is normally rated at 13 800 volts. Generator rating lower than 13 800 volts is available for over 3000 kV•A; a lower voltage rating (if selected) may reduce the generator price. Voltage ratings higher than 13 800 volts may be preferred for extra-large generators (400 000 kV•A and above).

Generators installed at high altitudes [over 3300 feet (1000 m), e.g., Mt. Elbert Pumped-Storage Powerplant and Forebay Dam, Colorado] are equipped with thinner layers of armature insulation to improve heat transfer characteristics. Because the insulation is reduced, the voltage rating is also reduced.

Higher speed machines usually have a longer stator core length in proportion to the stator diameter. This physical proportioning will frequently be associated with higher voltage ratings.

Generators are designed to standards that define operation below 95-percent rated, or over 105-percent rated voltage as "abnormal." A generator's continuous operation at abnormal voltages may produce unsatisfactory results and will almost certainly void manufacturer's warranty.

2.1.6 Synchronous Speed

The synchronous generator must operate at a single, fixed synchronous speed. The synchronous speed is established by turbine rotational speed. The turbine rotational speed is selected as the synchronous speed closest to the turbine design specific speed. Turbine designers will determine the turbine rotational speed using the relationship:

$$n = \frac{120f}{P}$$

where:
n = rotational speed, revolutions per minute
f = system frequency, hertz
P = generator poles, number

Multiples of two poles are required while multiples of four poles are usually preferred.

At some plants, extreme fluctuations in hydraulic head will take place; consequently, turbine operation at a single fixed speed becomes impractical. Turbine operation capability at two different synchronous speeds has been accomplished at several powerplants. One solution to this situation has been to install a generator having dual stators and dual rotors on the same shaft. Essentially, this creates two generators with a common shaft—each generator having a different synchronous speed. Another solution has been electrical switching of generator rotor and stator poles to change the synchronous speed of the generator. Yet, another solution has been to install different turbine runners for operating in different head ranges—with all runners having the same rotational speed.

A synchronous generator's diameter varies directly with the kV•A capacity and inversely with the square of the synchronous speed as shown on figure 2-1. Significant reductions in machine physical size and cost can be achieved by selecting the highest synchronous speed possible.

Hydroelectric generator speed range is roughly from as low as 60 r/min (revolutions per minute) to as high as 900 r/min. Grand Coulee Third Powerplant generators (3 units at 72 r/min and 3 units at 85.7 r/min) are the lowest rated speed generators purchased by the Bureau. Early plans and designs for the third powerplant generators anticipated that the generators would operate at 60 r/min. As designs developed, the required synchronous speed for the first 3 units was determined as 72 r/min, and later 85.7 r/min was required for the second group of 3 units.

Several Bureau powerplants have generators operating at 600 r/min. The Bureau had does not have a generator with a rated synchronous speed greater than 600 r/min.

An induction generator operates at variable shaft speeds above its synchronous speed and—within limits—produces increasing power for increasing shaft speed above synchronous speed. This characteristic is attractive because it matches a turbine's characteristic for increasing shaft speed and power with increasing head.

2.2 CHARACTERISTICS

In addition to the six principal ratings of a generator (noted in sec. 2.1), many important electrical and mechanical characteristics may be used to describe a generator or limit its operation. First, the following electrical characteristics might include:

1. Synchronous or induction generator.

2. Type of exciter and excitation voltage.

NOTE.-Paragraph 13 (15) of ANSI C50.12 [1] does not define clearly the term "excitation voltage" as meaning exciter rated voltage. Another possible interpretation is the excitation voltage required to produce *rated* generator output. Industry and Bureau practice has been to require exciter *rated voltage* to appear on the generator nameplate. Exciter ratings—including voltage rating—are discussed in chapter 8.10.

3. Armature connection (wye or delta—all Bureau generators are connected wye).

4. Minimum acceptable efficiency, and the generator output loading where maximum efficiency is achieved (see comments below).

5. Line charging capacity.

6. Zero power factor overexcited capacity.

7. Quadrature-axis, rated voltage, subtransient reactance X''_q.

8. Direct-axis, rated voltage, subtransient reactance X''_d.

9. Saliency ratio (ratio of value calculated for X''_q/X''_d.

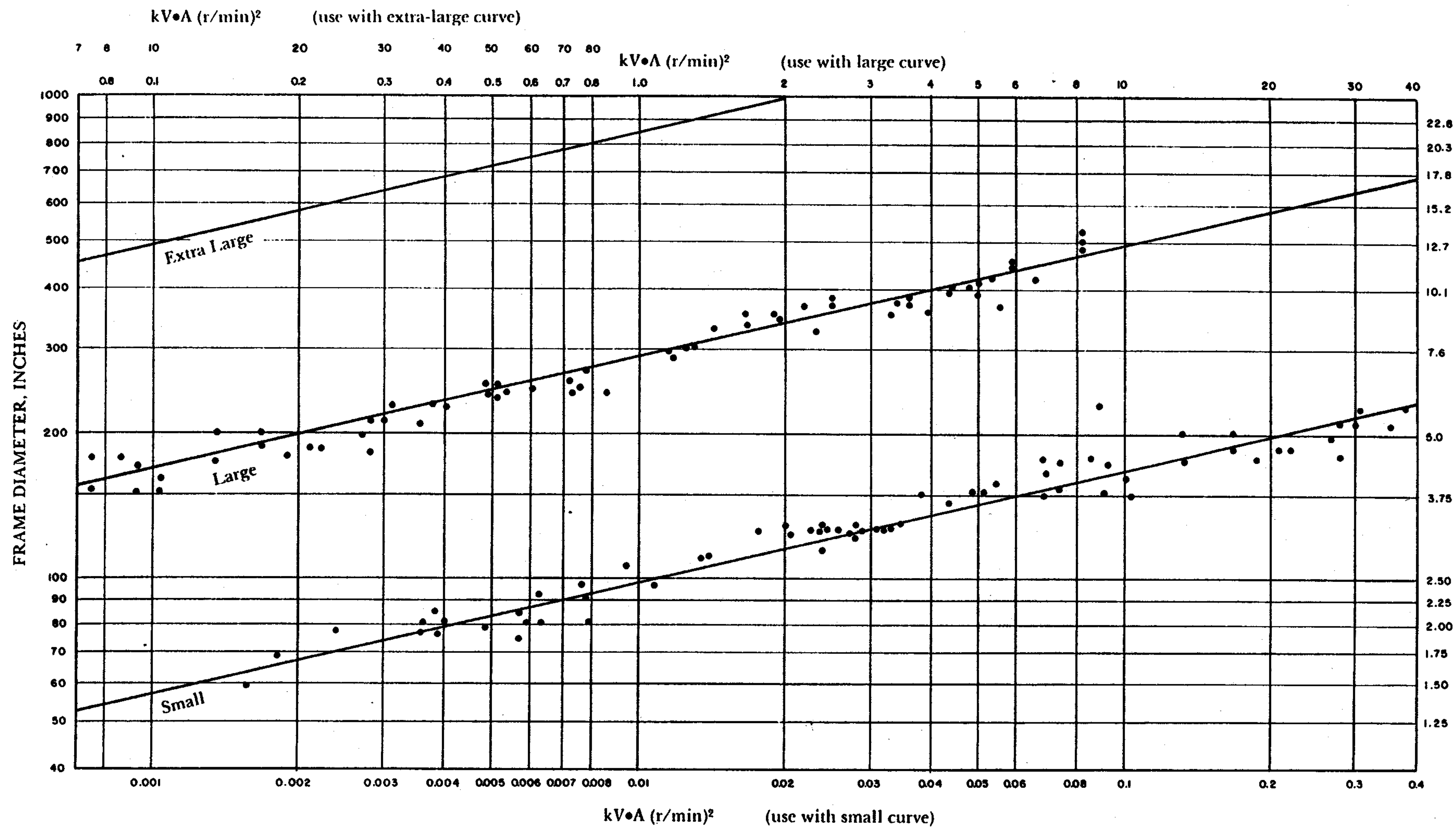

Figure 2-1. — Generator and motor frame diameters. The frame diameter is given without surface air coolers. Curves apply only to waterwheel generator and synchoronous motors.

10. Direct-axis rated voltage transient reactance X_d'.

11. Deviation factor of open circuit terminal voltage wave form.

12. No-load, balanced, TIF (telephone influence factor).

13. No-load, residual, TIF.

14. SCR (short circuit ratio).

15. I_2^2t integrated product.

As indicated in section 2.1.6, induction generators produce more power when turbine shaft speed rises above synchronous speed, within limits. Likely, induction generators could be manufactured for capacity ratings greater than 50 000 kW; although, they would be prohibitively expensive and would require significant investment in power factor correction equipment. Normally expected capacity ratings for induction generators would be less than 3000 kW.

Presently, the Bureau has not installed induction generators in any powerplants; although, studies of potential applications have been done. Generally, the studies' results indicated that for the capacities and speeds involved, the first cost (purchase contract price) of induction and synchronous generators were about the same. The induction generator offered advantages in reducing costs related to excitation and excitation control equipment, but usually required additional power factor correction equipment. The induction generator powerplant requires less complex controls and auxiliaries. An induction generator receives its excitation from the electrical power system it is connected to; therefore, it does not have an exciter. The generator can not operate independently from an electrical power system. This characteristic prevents "blacked-out" plant startup, and the generator can not supply power to station loads during power system outages.

Future applications for induction generators might include low-head powerplants or other small hydropower sites, where overall plant first costs must be minimized, and when inability to generate power during power system outages is a condition that can be tolerated. Some situations that make possible turbine variable speed operation attractive may make induction generators practical.

As noted earlier in this chapter, usually generator efficiency increases as machine kilowatt capacity increases. A small kilowatt capacity generator may exhibit 90-percent efficiency at rated capacity (nameplate), while extra-large kilowatt capacity generators may have an efficiency of 98.6 percent or greater at rated kilowatts. For any particular generator rating, the "normal" full-load efficiency is determined from information supplied by various generator manufacturers. "In house" information—derived from historical records—may be used to estimate approximate efficiency. Many factors affect efficiency; historical records should not be relied upon completely when determining minimum acceptable efficiencies to be guaranteed under contract. Manufacturers may be able to offer higher than "normal" efficiency for a generator at a premium.

ANSI C50.12 (pars. 4 and 7) [1] addresses generator excitation and ventilation power considerations for efficiency calculations. These standards indicate that if excitation or ventilation power is taken from the generator terminals, the generator output power is determined on the *line side*. That is, the excitation or ventilation power requirements are included with other generator losses. These standards indicate that excitation losses are *not* included in generator efficiency calculations if the exciter serves more than one generator.

All losses to be included in determining generator efficiency are described in ANSI C50.12 [1].

And secondly, the physical or mechanical characteristics of consideration are:

1. Temperature rise of armature and field windings.

2. Temperature rise of cores and mechanical parts in contact with, or adjacent to, armature or field insulation.

3. Temperature rise of collector rings.

4. Operating temperatures of bearing metal and coolant.

5. Temperature or temperature rise of other machine components, or of components at loadings other than rated capacity.

6. Cooling water/cooling air temperature limits.

NOTE.-Temperatures and temperature rise limitations may be listed separately from electrical and mechanical characteristics in specifications for generators.

7. Elevation above sea level where generator is installed.

8. Shaft orientation (vertical, horizontal, or inclined). See comments below.

9. Type of prime mover.

10. WR^2 (flywheel effect).

11. Thrust capability, including weight of generator rotating parts, turbine rotating parts, and unbalanced hydraulic thrust.

12. Thrust and guide bearing locations.

13. Direction of rotation.

14. Runaway speed.

15. Ability to endure stresses associated with temporary overspeeds.

16. Turbine shaft coupling elevation and coupling size.

17. Component weight limits imposed by crane limitations.

18. Component dimensional limits imposed by crane or powerplant limitations.

19. Foundation loading limits for all soleplates and anchors.

20. Projected area restrictions for the hydroelectric unit, or its components and auxiliaries.

21. Design limits for cooling water working pressure.

22. Hydrostatic pressure test limits for coolers.

23. Allowable pressure loss through coolers.

Hydroelectric generators may be of horizontal shaft, vertical shaft, or inclined shaft construction. The shaft orientation is controlled by the turbine prime mover shaft orientation. Shaft orientation has a major impact on the type, number, and location of machine bearings. (Reference [3]: ANSI C50.10, 3.2(11) defines operation in an inclined position as an "Unusual Service Condition.")

Thrust load, longitudinal to the shaft axis will exist in vertical and inclined shaft machines. Thrust load must be supported by a thrust bearing. Horizontal shaft machines may or may not develop shaft thrust loading—depending on turbine characteristics. Vertical and inclined shaft machine thrust loading include the generator rotating parts weight, turbine rotating parts weight, and hydraulic loading. Hydraulic loading may be in different directions under various conditions. In vertical and inclined machines, locating the thrust bearing may be controlled by both turbine and generator considerations (see sec. 8.2). The thrust bearing location is used to describe various types of generators in a vertical shaft hydrogenerator. These types include:

- Suspended or conventional where the thrust bearing is located above the rotor.

- Modified or umbrella where the thrust bearing is located immediately below the generator rotor.

- Another type of turbine-generator unit is described as a "close coupled" machine. This machine has the thrust bearing installed on the turbine head cover rather than a location in the generator. The Bureau has not installed machines of the close-coupled design.

2.3 TYPE OF CONSTRUCTION

Hydroelectric powerplants may be outdoor, semi-outdoor (or semi-indoor), indoor, or underground type. The type of plant structure impacts the housing requirements for the generator. Machines installed outdoors will require a weatherproof housing, and some form of sunscreen may be required. The same requirements exist for machines installed in semi-outdoor plants, although weatherproofing may not be required for the entire machine.

Generators connected to bulb turbines are a special case consideration because the generator is installed in a capsule, or bulb, completely immersed in the waterway.

For even the smallest machines weatherproof housings are expensive options, although they may be somewhat standardized for repetitive manufactured machines. As machine physical size increases, weatherproof housings become more complex and expensive; maintaining the housings to resist weather becomes more difficult. Machine temperature rise is a major consideration and special cooling provisions may be necessary. To protect a generator from direct rays of the sun during operation a sunscreen may prove beneficial in reducing machine temperature at outdoor and semi-outdoor plants.

Conditions may develop that permit heated air—discharged from the generator—to be unintentionally recirculated to generator cooling air intakes. Special baffles, ducting, or an enclosed machine cooling system may be necessary to correct the condition if recirculation is a possibility.

Lifting and handling facilities are required for generator installation, assembly, disassembly, and maintenance. At outdoor and semi-outdoor plants, these facilities may be permanently installed or for small size generators, either portable or mobile equipment may be used.

Scheduled maintenance periods for hydrogenerators usually occur during nonirrigation periods. Inclement weather often occurs during the periods so maintenance must be delayed or extended, or special weather protection must be installed on a temporary basis—if the generators are exposed to the weather. Inclement weather conditions may impede rapid return to service for an unprotected machine resulting from an unscheduled outage.

Larger generator sizes, which are equipped with an air-housing to provide an enclosed cooling air system, must enclose the collector rings (and exciter if machine is equipped with a rotating exciter) inside of the air housing if the machine is exposed to the weather. Usually, these component parts are not enclosed by the air housing in indoor and underground plants.

Generators installed outdoors at unattended plants may require special devices to prevent intrusion or tampering by unauthorized persons.

2.4 PHYSICAL ESTIMATES

As discussed under section 1.1, various levels of planning or design will require various levels of accuracy in estimates. Bureau standards have been developed to assist in making basic or preliminary estimates. Figure 2–1 [4] contains data developed from historical records and represents "in-house" knowledge. The frame diameter data does not reflect space requirements for surface air coolers nor for an air housing. If surface air coolers are required, the projected area under the generator must be increased. Typical cooler arrangements are shown on figures 5–1, 5–2, 5–3, and 5–4. If machine size is such that personnel access inside the machine is required, it may be necessary to provide for personnel passage between the coolers and the air housing. A cooler and its mounting support may add from 1 to 2 feet (300 to 600 mm) in radius, and passage clearance may require another 2-1/2 feet in radius. Thus, surface air coolers may require an additional 1 to 4-1/2 feet in radius or 2 to 9 feet in generator projected area diameter.

The Bureau has not used calculating means to estimate generator physical dimensions other than those developed from figure 2-1. Data tabulations, from filed material, have been developed over the years which reveal dimensional data for all generators installed by the Bureau and also for some other machines. These data cover a wide range of machines; fairly accurate estimates for planning and early design purposes can be derived from the tabulations.

Physical dimensions developed from the above source may reveal potential conflicts or restrictions within the powerplant. To resolve such problems, it is prudent to contact machine manufacturers to determine if their more refined and accurate estimating procedures will eliminate the concern, or to determine if it is practical to implement special machine designs. If neither of these actions reveal a satisfactory solution, it will probably be necessary to make modifications to the plant or to equipment other than the generator.

Past Bureau practice has been to check with machine manufacturers and potential suppliers to assure that physical estimates are reasonably accurate, before designs have become finalized.

2.5 COST ESTIMATES

For determining cost of hydrogenerators, requests are usually referred to Bureau specialists in cost estimation. For them to make reasonably accurate estimates, machine designers must develop:

- Relatively complete ratings
- Required standard and special equipment lists
- Special features
- Spare parts
- Required electrical and mechanical characteristics (including identification of any characteristics that are other than normal or standard)
- Testing requirements
- Delivery times
- Shipping restrictions
- Other known requirements that can impact price

Thereupon, delivery of these data is made to the cost estimator.

Discussions with the cost estimator for any particular job will usually lead to an understanding of the degree of detail required for that job. A simple or crude estimate might be based only on current dollars per kV•A for hydroelectric plants (current at the time of estimation) for early planning purposes, or a highly detailed estimate might be required for firm budgeting purposes.

Although the cost estimates are made by experts in that field, the generator designer must be aware that many modifications and options are available, and that these modifications or options can significantly increase the price of the machine. Technology advances and market conditions also affect price; these advances may easily change the impact that some modifications or options may have.

Base price of machines is calculated from machine kV•A rating, preferred voltage at that rating, speed or number of poles, normal WR^2, normally expected turbine weight, estimated hydraulic thrust, rated power factor, normal efficiency and normal short circuit ratio. The "normal" values of the various factors may be obtained from manufacturers or from sources of "in-house" data.

The following factors produce added costs to the base price of the machine. The amount will vary with machine size.

1. Difficult shipping and/or installation conditions.

2. Requirement for saliency ratio less than 1.35.

3. Excess excitation requirements.

4. Increased efficiency greater than normal.

5. Increased WR^2 greater than normal.

6. Requirements for an air housing and surface air coolers. High cooling water temperature can increase the size and cost of the coolers.

7. Requirement for spare armature coils.

8. Requirement for spare field coils and poles.

9. Requirement for spare thrust bearing runner and shoes.

10. Requirement for spare collector rings, brushes, and brush holders.

11. Requirement for exciter spare parts.

12. Excess line charging capacity (over 80% rated kV•A at 1.0 short circuit ratio).

13. Overspeed requirement higher than normal.

14. Short circuit ratio greater than 1.0.

15. Power factor less than 0.80 for synchronous generators, or greater than 0.80 for induction generators.

16. Single turn armature coils for machines with less than about 60 000-kV•A rated capacity.

17. Requirement to field stack armature cores for machines that could otherwise have factory stacked cores.

18. Requirement for excess thrust bearing load.

19. Requirement for a guaranteed value of transient reactance.

20. Installation above 3300 feet (1000 m) in altitude.

21. Voltage rating other than preferred for the kV•A rating and synchronous speed.

22. Unusually low wave form deviation and telephone influence factor requirements.

23. Requirements for, and type of, fire protection/detection system.

24. Requirement for multispeed ratings.

25. Unusual synchronous speed rating.

26. Special tests.

27. Unusual foundation design, such as excessively large opening under generator.

28. Decorative features and special painting.

29. Type of exciter required (e.g., rotating or static).

30. Special accessories.

31. Requirements for pumping/generating operation.

32. Requirement to start the generator as a motor.

33. Special tools, handling devices, and erection templates.

34. Requirement for unusually short completion time.

35. Requirement for unusual temperature rise limitations.

36. Requirement for extended warranty period.

Many other factors and conditions may affect generator price. Special features may offer some potential benefit, but at a premium. The value of the potential benefit must be weighed against the price added on.

2.6 OPERATIONAL CONSIDERATIONS

In addition to ratings, characteristics, type of construction, and accessories, the following operational considerations can impact the design of a generator.

1. Peaking or base-load operation.

2. Minimum, maximum, and normal continuous loadings.

3. Estimated time duration at various loadings and at shutdown.

4. Rate of load changing.

5. Potential for load pattern changes resulting from power system growth or modification.

6. Requirement for power system stabilization, including potential for changes in system requirements for stabilization.

7. Requirement for hydraulic system stabilization.

8. Requirement for synchronous condenser operation, with and without turbine connected.

9. Requirement for generator/motor operation (pumped storage).

10. Starting limitations as a motor, including power system limits and number of restarts permitted or required within a certain time period.

11. Requirement for production of station or local load power when generator is isolated from power transmission system.

12. Ease of maintenance for: collector rings, brakes and brake rings, bearings and bearing runners, surface air coolers, valves, pumps, and other components.

13. Ease of access to, inspection of, and adjustment of various auxiliaries, accessories, and components.

14. Necessary dismantling of generator to facilitate turbine maintenance.

15. Ambient conditions including altitude, air temperature, humidity, wind and wind-driven particulate matter, solar heating, cooling water temperature, and the need for heaters during shutdown periods.

16. Attended or unattended plant, and needs for local, automatic, or remote control.

17. Need to use generator temperature rise for plant heating.

18. Existence of centralized plant systems for cooling water, compressed air, lubricating oil, and fire control.

19. Value of capacity.

20. Value of efficiency.

21. Need for special provisions for visitors.

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CHAPTER 3

PROCUREMENT

3.1 PROCEDURES USED

A procurement official, usually the Contracting Officer, will make the decision as to which procedure will be used for each job. The official may ask the Bureau generator designer for information to assist resolving that decision.

A variety of procedures are available for procurement of hydrogenerators. Past procedures have included the first four of five on the following list:

1. Advertised procurement of generator only.
2. Advertised procurement of combined turbine and generator unit.
3. Negotiated procurement, for generator uprating.
4. Bureau supply—construction contractor install.
5. Construction contractor furnish and install.

NOTE.-Procedure (5.) is rarely used for generator procurement. The procedure has been frequently used for electrical motor procurement.

This manual will not discuss the Bureau's procurement policy and rules, nor their applicability.

Large size generators almost always require field assembly and erection on the machine foundation. Field assembly and erection is critical to successful performance of the generator. To avoid divided responsibility, the generator contractor may be required to furnish the generator and install it on its permanent foundation. For small machines, which can be shipped either fully assembled or with only minor disassembly, the concern for divided responsibility becomes moot; the machine may be furnished by a supplier (manufacturer) and installed by others.

The particular construction and complexity of each generator, and specialized techniques used by different manufacturers, will require the presence of a manufacturer's erection supervisor during field installation. This would probably be true even for small machines furnished and installed by a construction contractor.

As machine sizes increase, the need for factory trained field erection personnel who are familiar with the machine manufacturer's procedures and product becomes essential.

Large generators are categorized as meeting the criteria of the field erection being an extension of the manufacturing process. This rationale has been used to categorize generator procurement solicitations as "supply" contracts, even though the contract requires field installation work which might otherwise be called "construction."

3.1.1 Advertised Procurement of Generator

During the time when many of the Bureau's generators were purchased, only one domestic manufacturer and only a few foreign manufacturers were capable of manufacturing both turbine and generator. Therefore, procurement documents were written to require the generator to be furnished separately from the turbine so that all domestic manufacturers could bid the job, thus providing more competition. The separate procurement documents for turbine and generator were written to require cooperation and coordination between suppliers of turbine and generator.

Separate procurement of turbine and generator places a greater responsibility upon Bureau engineers for coordinating two procurements. A problem may arise if operational difficulties occur which can not be easily and decisively attributed to either the turbine or the generator. Each machine supplier may claim that the problem's source is within the other supplier's domain, and the Bureau may suffer as a result of the conflicting claims.

3.1.2 Advertised Procurement of Combined Unit

A trend has occurred in industry for various manufacturers to form associations which permit the association to offer both turbine and generator. This trend has proved advantageous to the Bureau—particularly when the work involves unusual machinery. A single contract for both turbine and generator virtually eliminates the concern for divided responsibility in the event of operational problems, and reduces the need for coordination by Bureau engineers. The combined procurement may allow the suppliers to exercise more design flexibility and may result in lower overall costs to the Bureau.

A concern remains if a manufacturing alliance is made for only one specific job, and if the alliance is dissolved upon completion of the contract for that job. Should operational problems arise after dissolution, more effort by the Bureau may be required to correct the difficulty.

3.1.3 Negotiated Procurement

For uprating existing generators, procurement procedures have included negotiation. The justification for using this procedure has included the Bureau's lack of ability to write specifications defining exactly what is required to increase the capacity of a particular generator. An analysis of each generator component from each offeror's viewpoint is required, and the successful offeror (contractor) is required to *warrant* the generator's uprated capacity. The decision to retain, modify, or discard and replace various components of the uprated generator is made by the offeror, as necessary to achieve the level of uprated capacity that is warranted. The offeror's proposals for changes necessary to achieve the uprated capacity become a part of the contract.

3.1.4 Bureau Supply—Construction Contractor Install

This procedure offers advantage for generators that can be assembled and tested in the factory, and which require only minor disassembly for shipment and field erection. Manufacturer's erection supervisors ensure satisfactory reassembly by the construction contractor, and manufacturer's warranties are given directly to the Bureau.

Competitive bidding for both supply and installation will produce lowest overall cost to the Bureau. Concerns about divided responsibility between supplier and installer are minimized through the manufacturer's erection supervisor.

Field testing, to demonstrate generator performance, freedom from shipping damage, and proper reassembly is required.

3.1.5 Construction Contractor Furnish and Install

Small generators that are essentially identical with other generators having nearly the same ratings, and manufactured on a production line basis for consumers can be described as "repetitive manufacture" machines. These generators contrast those that have been custom designed and manufactured for installation at a specific site.

Small repetitive manufacture generators, which can be completely assembled and tested in the factory and then shipped with little or no disassembly, could be included as an item for a construction contractor to furnish and install. This procedure reduces Bureau coordination and scheduling concerns by placing those responsibilities upon the construction contractor. The same machinery specifications could be written regardless of procurement procedure. If this procedure is used, care should be taken to ensure that generator manufacturer's warranties are passed through the construction contractor to the Bureau. This procedure has been used successfully for many pumping plant motors of repetitive manufacture. These pump motors have had relatively the same electrical size and complexity as small hydroelectric generators.

Since the Bureau has not yet installed generators of the "repetitive manufacture" type, using this procurement procedure has not been considered advantageous for generator procurement.

Some minor testing, to demonstrate generator performance and to prove that damage has not occurred during shipment or installation should be performed by contractor personnel and witnessed by Bureau staff.

3.2 AMENDMENTS AND CHANGES

Amendments and changes to procurement documents are almost always required, following the initial printing and distribution. However, attention to detail will minimize the need for such changes and amendments.

All amendments must be carefully reviewed by each offeror, and frequently by several entities within each offerors' organization. The required reviews will infringe on the time the offerors have available to prepare and submit their bids, and can impair the quality of their bids.

Each proposed amendment should be reviewed by all affected Bureau staff to ensure that the change is essential to the bidding, and to determine potential impact on other associated equipment.

It is important that designers of various associated equipment installations and construction also exchange information with generator designers regarding proposed amendments to their procurement documents for associated features. That is, a proposed amendment to a turbine procurement document should be coordinated with the associated generator designer.

Using standards and guide specifications paragraphs and drawings will help minimize required changes. Review of draft specifications by knowledgeable staff should be performed before releasing the drafts for printing.

3.3 WARRANTIES

Procurement documents require that the generator contractor warrant the machine to meet certain performance and quality requirements. Penalties for failure to meet warranties are stated in the procurement document. In support of these warranties, some generator procurement documents now include a requirement that the contractor must repair all defects—without cost to the Bureau—that may appear during a stated number of years after first operation of the generator.

The above descriptions are generalized and paraphrased to convey procurement concepts. The reader is encouraged to contact personnel responsible for procurement and contracting to develop a better understanding of these provisions.

Presently, the Bureau's generator procurement solicitations are written to require a warranty period of 5 years after acceptance of the generator.

During this period, the Bureau expects to perform only routine maintenance, including cleaning, and replacement of expendable parts. If a major component of the generator fails, or otherwise is found not to be in compliance with requirements of the procurement solicitations (during the 5-year period), the contractor is required to correct the failure or deficiency at their expense.

NOTE.–Care should be taken to ensure that the contractor replaces any and all Bureau owned spare parts that may be required to correct failures or deficiencies during this time period.

Contractor's use of Bureau-owned spares may significantly reduce outage time required for return of the generator to service.

It is the Contracting Officer's responsibility to make a final decision regarding failure to meet warranty requirements. The Contracting Officer may require information from the generator designer to help make a decision. The generator designer may be called upon to collect and coordinate information from construction and/or operating personnel during investigation and review by the Contracting Officer.

3.4 COORDINATION WITH CONTRACTOR

As indicated in section 3.1, the procedure for procuring a generator will have a considerable impact on the amount of coordination required between the generator contractor and Bureau generator designers.

The least amount of coordination required by Bureau generator designers probably would be the procedure selection: "Construction Contractor Furnish and Install." With this procedure, the contractor would be required to: design and furnish the supporting and handling features, auxiliary system, power connections, and furnish details of the generator and its installation to the Bureau. Following submittal of drawings and data, minimal coordination would be required to be performed by the Bureau designer. The contractor would be responsible for coordination between suppliers and subcontractors.

As generator size increases, the number of required separate supply and construction contracts tends to increase. As the number of separate contracts increase, the need for information obtained from each contractor and the amount of information which must be given to each contractor increases. The Bureau generator designer may be asked to take action necessary to make sure that all necessary information regarding the generator is exchanged between contractors.

The Bureau generator designer must assume more responsibility for installation design as generator capacity rating increases. It becomes necessary for the Bureau to obtain information from the generator manufacturer at an early time after award of contract. In addition to information required to determine compliance with the procurement solicitation, information necessary to design the supporting and handling facilities, service facilities, control systems, auxiliary systems, power transmission facilities, structural facilities, and architectural features must be obtained. These data must be obtained and finalized with sufficient time allowance to permit completion of necessary design and construction before beginning generator installation. Seemingly small changes in the generator design or construction can produce chain reactions and delays in other associated contracts. Therefore, careful attention to detail and coordination is required.

In general, little or no data are received with the offeror's bids under advertised procurement procedures. In fact, submittal of bid data is discouraged by the Bureau. A post-award conference with the successful offeror may be scheduled to review solicitation requirements with the contractor's engineers. A review may eliminate misinterpretation of requirements by the contractor, and may provide valuable early information to the Bureau.

Most procurement solicitations for generators define certain key drawing and data requirements that must be submitted by the contractor. These drawings and data reveal compliance with requirements and provide information required by the Bureau to complete design and construction of related features. A conference with the generator contractor's personnel is scheduled, and a face-to-face review of the key drawings and data is conducted. These key drawing conferences have proved to be successful in reducing the required resubmittal of material for approval. The key drawing and data review is held at the earliest practical time after submittal of the material.

Conferences, in addition to those above, are not usually required by the solicitation. However, additional meetings and conferences usually do occur on an "as required" basis.

Submittal of material by the contractor—with subsequent review and return by the Bureau—formalizes coordination between the two. The contractor indicates an understanding of, and submits proposed methods of compliance with the Bureau's solicitation requirements through the submittals. The Bureau indicates acceptance and approval (or lack thereof) by review and return of those submittals. If the contractor proceeds with design, manufacture, or shipment without having received approval, the contractor does so at one's own risk. Mindful of this, the contractor must have assurances that all submittals will receive prompt review and return. Otherwise, unreasonable delays or risk may materialize. If the contractor's submittals are disapproved and returned promptly, any resultant delay in manufacture may prove to be the contractor's problem. If the material submitted is approved, but is simply returned late, the contractor may be entitled to an extension in contract completion time. Therefore, the maximum time allowed for return of each of the contractor's submittals is clearly stated in the procurement solicitations so that the offeror may include the time in the offer. If Bureau review of several simultaneous contractor submittals exceeds the maximum time allowed in the solicitation, the contractor is only allowed one extension of time equal to not more than the longest time taken for review of one of the submittals. In other words, a contractor can not be delayed more than one day for any one calendar day of late Bureau return of drawings. In addition to the formal coordination realized through the drawing and data submittal procedure, a significant amount of coordination may be achieved through informal contacts between contractor and Bureau personnel. To materially improve coordination and reduce misconceptions, it is suggested that correspondence and telephone discussions take place between:

- Contractor factory personnel,
- Contractor field personnel,
- Bureau factory inspectors,
- Bureau field personnel, and
- Generator designer.

CHAPTER 4

INDUSTRY STANDARDS

4.1 GENERAL

Generator procurement solicitations are written to require that the machine comply with various industry standards. The standards are considered as guides or recommended practices to assist manufacturers and purchasers in their decisions and selections. Manufacturers and suppliers usually are not bound by law to comply with any particular standard, and compliance with a standard becomes mandatory only through contractual commitment.

Reference in the procurement solicitation to appropriate portions of the various standards, and requirement for compliance with those standards is necessary. Most standards cover several different options from which a purchaser may select; a simple reference to an overall standard in a solicitation usually will not suffice. Occasionally, it may become necessary to specify equipment, or some part of equipment that does not comply with or is not included in existing standards. In this case, good practice will require that the requirement be emphasized in the specifications as being noncompliant. The reasons for deviation from standard requirements should be retained in records for the job.

Most standards are revised and updated; procurement solicitations will refer to "the latest revision thereof," when identifying a standard. The revision in effect—at the time of contract award—becomes a basis for the job. Revisions made to standards, after the time of contract award, do not influence contractual impact, even though the contract is still active and even if the revision might otherwise be applicable to the contracted equipment.

Reference to standards in existence at the time of original manufacture is required for work involving repair, modification, or replacement of existing equipment. The repaired, modified, or new parts usually are required to meet latest industry standards rather than those in effect at the time the original component was manufactured.

Domestic (United States) standards may contain differences from foreign and international standards. If compliance with a standard other than a domestic one is required for some part of a generator, care must be taken to obtain sufficient information about the part and the standard to assemble a proper document file for future repair or replacement purposes.

4.2 SPECIFICATIONS USE OF STANDARDS

Procurement solicitation requirements for contractor compliance with industry standards enables the Bureau generator specifications in many ways, notably:

1. Select a required quality or performance level for a generator without writing an extensive specification. Most standards contain many detailed requirements that can not be reasonably stated in a procurement solicitation.

2. Reduce requirements for coordination between various suppliers. Standards usually reflect certain requirements for interconnections with other associated equipment that various suppliers must meet. This is important when considering components that must be replaced as a unit. For example, threaded connections are usually required to meet domestic standards. Nonstandard threads are permitted for connections made internally in small devices, if the device is integrally replaceable. Taps and dies for nonstandard threaded devices may be required by the solicitation.

3. Improve competition between various offerors because each offeror will know the quality level required by the solicitation. Machines of foreign origin can be constructed to domestic standards. A trend seems to be developing for Bureau use of international standards, which appears to offer advantages when domestic suppliers can meet those standards.

4. Define an information source for future needs. The changing nature of standards and specifications requirements demands production of records to identify standards in effect at the time of original manufacture.

5. Advise an offeror or contractor of the tests that the Bureau designer requires that the machine must pass.

6. Establish a glossary of terms to be used. Standard terms and abbreviations will reduce errors and improve understanding.

7. Depict requirements for expendable or renewable components. Components such as lubricating oil, lighting components, brushes, and so forth should be readily available locally. Serious operational delays could result if replacements for expendable components were required to be of special manufacture or were available only from foreign or limited sources.

8. Establish a firm basis for solicitation requirements, in event of challenges or legal action.

Likely, the above listing could include additional advantages in using standards. However, regardless of the reasons, the specifications writer will probably never have to justify reference to standards.

CHAPTER 5

DRAWINGS AND DATA

5.1 GENERAL

A considerable number of drawings and data must be developed for each generator solicitation. Some of the drawings and data are prepared by the Bureau in various offices, and some by contractors and/or their suppliers. Bid drawings prepared by each offeror under a solicitation were received by the Bureau during one period of time, but this practice is no longer observed. Shop drawings showing manufacturing dimensions, tolerances, finish, materials, and other details are prepared by each manufacturer for their own internal use, but these drawings are not required to be made available to the Bureau. Much of the information on the shop drawings may be considered proprietary by the manufacturer.

5.2 BUREAU PREPARED DRAWINGS

The first drawings prepared by the Bureau for a hydrogenerator are usually conceptual in nature and reveal estimated weights dimensions, outlines, and some characteristic data. Outline drawings with blank dimensions have been made (figs. 5-1, 5-2, 5-3, and 5-4) to expedite preparation of estimates. Other drawings may be prepared on an "as needed" basis from time-to-time. After one of the blank outline drawings has been prepared for any particular generator, it may be revised to show changes or refinements in data contained thereon.

Data from these estimating drawings are used to prepare powerplant general arrangement and other installation drawings, which will show location of plant equipment, clearances, handling details, access, interconnections, and many other plant details. Obviously, any major change in data shown on the generator estimating drawings can have major impact on the plant arrangement.

Preparation of one of these estimating drawings may fulfill all requirements for generator drawings when preparing planning estimates. However, as designs progress up to the stage when procurement solicitations are being prepared, more drawings showing more details will be required.

Procurement solicitations usually contain at least three categories of Bureau prepared drawings:

1. *Site-specific drawings* showing location of the plant with details of the plant itself and the equipment within the plant. These drawings might include, but are not limited to:

- location maps
- general arrangement drawings
- switching diagrams or main single line diagrams
- piping diagrams
- schematic and/or wiring diagrams required for various auxiliaries

Drawings showing location of:

- main lead terminals
- type of main lead bus or conductor
- terminal boxes
- height and projected floor space restrictions
- foundation loading restrictions
- location and space allocation limits for auxiliaries
- crane hook limits
- handling restrictions
- shaft coupling location and details
- foundation details
- turbine parts dimensions
- other information essential for the offerors to prepare a satisfactory bid must be included.

2. *Reference drawings* showing details typical for similar installations, but that have not been prepared particularly for the current job.

NOTE.-These drawing would reveal the type of information required from a supplier to permit later preparation by the Bureau of drawings particular for the current job. Typical drawings would be those that show interconnections with other equipment.

3. *Bureau standard drawings* are required which show details that the generator contractor must comply within the specifications.

5.3 BID DATA

Bid data—including bid drawings—are not required when generators are purchased under advertised procurement procedures. In fact, offerors are discouraged from submitting this type of material with their bids. Bids are accepted only on equipment conforming to the specifications, and any bid data indicating an offerors' intent to furnish supplies or services other than those required by the solicitation could be sufficient to cause the bid to be considered nonresponsive.

When negotiation procedures are used for procurement, as in uprating existing generators, material submitted by the successful offeror becomes a part of the contract requirements upon award. In concept, the specifications written for the uprate procurement document are considered incomplete. The successful offeror's proposal data completes the requirement, and award is based on the combination of Bureau specifications and offeror's proposal data.

It is emphasized that the preceding remarks are a layman's interpretation of procurement regulations. A procurement official should be consulted regarding procedures.

5.4 CONTRACTOR PREPARED DRAWINGS

5.4.1 General

Following award of contract, various drawings are prepared by the contractor (manufacturer) and submitted to the Bureau. Some of these drawings may be informational only and others may require Bureau approval. A listing of Bureau needs for drawings prepared by the contractor should be included as part of every procurement solicitation. The number of drawings required for each job tends to vary with the procedure used for procurement. If the procurement procedure is a "Construction Contractor Furnish and Install" (see sec. 3.1.5) comparatively few drawings would be required. Bureau approval of contractor prepared drawings would probably be minimal. Likely, the contractor would be required to prepare drawings showing the generator as installed in its final location. Drawings and data necessary for generator operation and maintenance would be required. Drawings and data verifying compliance with specifications requirements, and drawings showing overall weights, dimensions, ratings, characteristics, and test data also would be required.

Generator procurement procedures other than the "Construction Contractor Furnish and Install" type will require the generator contractor to furnish sufficient information to permit the Bureau to design the related facilities for the generator installation. Drawings and data that indicate compliance with specifications requirements will be required.

5.4.2 Key Drawings

Installation details are usually among the first required submittals from the contractor. As noted in section 3.4, these details are required so that the Bureau can design the foundation, handling features, power supply and transmission features, auxiliary systems, and related electrical mechanical, structural, and architectural features. The foregoing details, together with details that indicate compliance with major specifications requirements, may be classed as "Key Drawings."

Generator procurement solicitations require the contractor to prepare and submit a list of Key Drawings, which—in the contractor's opinion—will provide the required information. Submittal of the list to the Bureau is required shortly after award of contract. The list of drawings is reviewed by the Bureau and returned to the contractor with any comments for change or acceptance.

Following actual submittal of the Key Drawings and subsequent review by the Bureau, a meeting between contractor personnel and Bureau staff is held to discuss material presented (see sec. 3.4).

Some or all of the Key Drawings are also classed as "approval drawings." These key approval drawings must be reviewed, approved, approved with comments, or disapproved, and then returned to the contractor within a specified time period. Receipt by the Bureau of only part of the key drawings will inhibit a proper review. Therefore, specifications are written to state that the fixed time period for Bureau review will begin with receipt of the last material required to complete the previously accepted list of Key Drawings. Considerable care is taken to ensure a thorough review of the key drawings. This review will permit the Bureau to complete designs for the generator installation, and will permit the contractor to make a rapid and confident manufacturing start.

5.4.3 Approval Drawings

The purpose of the requirement for Bureau approval of contractor drawings are (1) to assure the Bureau that the contractor's work will meet Bureau specifications requirements and intent, and (2) to assure the contractor that their interpretation of the specifications is in accordance with Bureau intent.

The Bureau signifies approval by affixing a stamped marking on each contractor drawing, dating and signing the stamp, and by narrative approval in correspondence covering return of the drawings to the contractor. The specifications narrative includes a disclaimer, which indicates approval is of general design and controlling dimensions only, and that the approval does not relieve the contractor of responsibility for meeting specifications requirements. This manual will not address the contractual implications of this disclaimer, other than to say that affixing an "approved" stamp to a contractor's drawing that shows noncompliant features will cause a great deal of extra work for both the Bureau and the contractor.

Time permitted for Bureau review and return of contractor submittals of approval drawings is discussed under section 3.4. The important factor, regarding the amount of time taken for Bureau review and return, is that the contractor must proceed at one's own risk until approval is received from the Bureau. If the Bureau uses time in excess of the period stated in the procurement solicitation, the contractor must either delay manufacturing until approval is received or accept the possibility that any manufacturing accomplished may later be found unacceptable by the Bureau. By granting a day-for-day extension of contract time for time taken in excess of that stated in the specifications for return of approval drawings the Bureau is, in effect, saying that contract progress may be delayed until the drawings are returned. Costs or damages, such as idle time expenses, suffered by the contractor as a result of late return may not be corrected by the contract time extension. Therefore, prompt review and return—by the Bureau—of all contractor submittals will help the contractor meet schedules and minimize costs.

The Bureau can experience problems if a contractor fails to resubmit disapproved, or conditionally approved, drawings within a reasonable time period. Bureau designs for, and construction of, related features must either be delayed pending resubmittal or must proceed based on assumptions by the Bureau. For example, the Bureau might assume that the contractor will accept all of the Bureau's conditions, and that the contractor will proceed with manufacture in accordance with those conditions. Some risk may be associated with such assumptions. Therefore, some solicitations are now written to require the contractor to resubmit conditionally approved or disapproved drawings within a stated time period.

All drawings and data that cover field erection procedures must be submitted and accepted prior to commencement of generator erection.

The contractor's drawing sizes are now required to comply with American National Standards Institute, Drawing Sheet Size and Format, ANSI Y14.1-80.

In addition to furnishing information that will indicate the contractor's compliance with specifications requirements, the approval drawings will provide the Bureau with a significant amount of information that is needed to complete its design of related powerplant features. Some contractor submittals may be classed as "informational drawings," which do not require Bureau approval. These drawings would be exclusively devoted to furnishing information that the Bureau requires.

As indicated above, every procurement solicitation should contain lists of information and data that must be submitted by the contractor for approval. The listing may include any or all of the following requirements:

1. Major dimensions and design of all important generator components. These components might be identified as:
- overall assembled generator
- rotor subassemblies
- air housing
- stator
- rotor
- shaft
- bearings
- bearing brackets
- brakes
- exciter
- coolers
- soleplates
- anchor bolts

2. Plan and axial cross-section views of the assembled generator.

3. Weights of principal components, and of the assembled generator.

4. Operational clearances required (e.g., minimum spacings, accesses, etc.).

5. Weights and dimensions of parts to be handled by the crane, details of required lifting devices, and handling clearances required.

6. Foundation design, including details and locations of soleplates and anchor bolts.

7. Maximum vertical, radial, and tangential loading on each soleplate.

8. A step-by-step rotor erection procedure should be developed.

- The erection procedure should include:
- a narrative description
- sketches and drawings
- descriptive literature

- The procedure should cover:
- shaft handling
- shaft placement on rotor erection pedestal
- pedestal loading
- rotor erection area foundation loading
- rotor erection clearances required
- rotor spider connection to shaft
- rotor rim stacking methods
- rotor rim treatment
- pole attachment
- brake ring attachment
- fan and shroud attachments
- lists of tools
- equipment
- time required
- worker skills required
- materials required
- description of any testing performed before rotor installation in the generator stator

- Special attention should be directed to techniques for compacting, seasoning, expanding or shrinking, keying, wedging, and balancing the rim. Details should be included of:
- pole installation
- pole wedging and keying
- field lead installation
- field interpole connections
- amortisseur connections

- Methods should be covered for:
- determining tightness
- concentricity
- circularity
- uniformity
- clearances
- any other means to ensure proper assembly

- A description should be included of procedures for future field pole removal.

9. A step-by-step stator erection procedure should be developed.

- Each progressive step of stator erection should include:
- a narrative description
- sketches and drawings
- descriptive literature

- The procedure should cover:
- frame installation
- core stacking
- keying procedure (if core is field erected)
- armature winding installation or coil installation at stator split joints

- Procedures for armature coil installation should include:
- sequential placement of materials and components
- methods for determining proper installation and connection at the coil
- tests to be performed upon the coil

- list of tools
- equipment
- time required
- worker skills required
- materials required

10. A step-by-step procedure for final or complete generator erection including:
- soleplate settings
- rotor installation
- bearing bracket installation
- stator centering
- concentricity adjustments
- sequence of events
- precautions to be observed
- assembly tolerances
- methods determining proper fit and tightness
- list of tools
- equipment
- materials required
- tests and adjustments required
- time required
- worker skills required
- any other information which could assist Bureau personnel during:
  - field erection inspection
  - future maintenance assembly
  - disassembly operations

11. Thrust and guide bearings:
- loadings
- dimensions
- construction details
- insulation
- cooling
- lubrication
- installation
- adjustment
- removal procedures

12. Weights and dimensions of major parts as prepared for shipment.

13. Factory shipping point and United States port or ports for equipment of foreign origin.

14. Maximum dimensions of parts which can be moved through the generator stator and through the opening in the concrete foundation below the generator.

15. Cooling water requirements should be included:

• Quantity of cooling water required in addition to pressure drop (loss) across each colller for:
- entire generator
- each surface air cooler
- each bearing cooler

• Volume of cooling water at generator rated load:
- with all coolers in service
- with one cooler out of service.

16. Shaft coupling information including coupling details, dimensions, and elevation.

17. Required recesses in concrete foundation.

18. Main and neutral lead locations, sizes, dimensions, and connection details.

19. Piping layouts.

20. Lubricating oil piping connections and oil volume required to fill each bearing reservoir.

21. Compressed air requirements for the generator—including volume, pressure, and piping connections.

22. Details and description of thrust bearing high pressure lubrication system—including operating pressure.

23. Details and description of brake and jack system—including dimensions, loading, and operation.

24. Rating in volts, kilowatts, and amperes of the exciter. Exciter response ratio and exciter ceiling voltage.

25. Cooling air or water requirements of the exciter.

26. Auxiliary power requirements of the exciter.

27. Description of surface air cooler construction—including weight, dimensions, handling details, connection details, tube, tube sheet, and water box dimensions, materials, and cooler maintenance details.

28. Critical shaft speed analysis of the turbine and generator shafts when coupled, and for the generator when uncoupled from the turbine. The data required should include:

- combined WR^2
- generator WR^2 alone
- bearing support points
- rotor center of gravity
- bearing and bearing support spring constants
- maximum runaway speed
- other pertinent data for the analyses for both torque and vibration

NOTE.-The turbine contractor may be required to perform this analysis instead of the generator contractor. If the analysis is to be performed by the turbine contractor, generator data must be supplied for the analysis.

29. Schematic and wiring diagrams for the exciter.

30. Schematic and wiring diagrams for all electrical accessories and devices.

31. Front and rear views of various panels and terminal boxes.

32. Bills of material giving complete information on each accessory device.

33. Nameplate list.

34. An armature winding diagram—including slot numbers and location of RTDs (resistance temperature detectors).

35. A cross section of a typical stator slot showing armature coils and supporting materials—including dimensions.

36. Amount that the rotor must be raised to provide for inspection, adjusting, or dismantling of the thrust bearing.

37. Dielectric test voltages for all the generator components.

38. Transducer data including relationship between temperatures, pressures, and levels with corresponding transducer and transmitting device outputs.

39. Generator field data including:
- pole body construction
- coil construction
- coil insulation
- resistance and voltage drop for each coil
- field winding interconnection details
- collar details
- temperature rise under various loadings
- end cap and clamping details
- amortisseur winding and connection details
- any other required construction or operational information

40. Commutator data including:
- temperature rise
- maximum reduction in depth permissible for turning down
- number of brushes
- brush size
- brush type
- brush mounting locations
- commutator dimensions
- commutator material
- insulation
- installation details

41. Contractor's nondestructive factory testing procedure for principal generator parts.

The above lists may be expanded to cover additional items, and individual items may be expanded to require more details. Some of the items listed may not be required, especially for small capacity generators.

5.5 CALCULATED DATA

Data calculated by the manufacturer for a generator must be used by the Bureau to design associated power transmission system and other features. These data may be called "design data," and are required to be submitted by the contractor among the first data requirements. Some data may be required to reflect guaranteed or specified values, and therefore, may be reviewed for approval. Some data are informational in nature; therefore, approval of the values is not required. Some overlap or redundancy may appear between the approval data listed under section 5.4.3, and the lists of typical design data required as follows:

1. Generator efficiency and segregated loss data at various levels of generator loading.

2. Resistance of armature and field windings.

3. Capacitance to ground of armature and field windings.

4. Direct and quadrature axis values of synchronous reactance.

5. Direct axis values of rated voltage and rated current transient reactance.

6. Direct and quadrature axis values of rated voltage subtransient reactance.

7. Zero sequence reactance.

8. Negative sequence reactance and resistance.

9. Potier (leakage) reactance.

10. Short circuit ratio.

11. Direct axis transient open and short circuit time constants.

12. Quadrature axis transient open circuit time constant.

13. Direct axis subtransient open and short circuit time constants.

14. Short circuit time constant of armature winding.

15. Initial rms (root-mean-square) symmetrical single and 3-phase short circuit currents.

16. Initial rms symmetrical phase-to-neutral short circuit current.

17. Sustained rms 3-phase and single phase short circuit currents.

18. Sustained rms phase-to-neutral short circuit current.

19. Characteristic curves including:
- no-load saturation
- full-load saturation zero power factor leading
- full-load saturation unity power factor
- full-load saturation rated power factor lagging
- full-load saturation zero power factor lagging
- short circuit lagging

20. Maximum line charging capacity.

21. Overexcited synchronous condenser capacity.

22. Integrated product capacity, I_2^2t.

23. Moment of inertia, WR^2.

24. Quantity of oil required to fill each bearing reservoir.

25. Quantity of water required for each cooler or heat exchanger at rated generator load.

26. Volume within generator air housing for CO_2 protection.

27. Ratings and electrical requirements of all motor-driven accessories, heaters, lights, and other devices requiring station-service alternating current power or battery power.

28. Direct-current requirements from station battery for flashing generator field and duration of time necessary for flashing.

29. Weight of heaviest part for shipment, and for handling by plant crane.

30. Compressed air requirements for braking.

Special requirements for each job should be expected, and additional information may be required to permit Bureau designers to proceed with their work. Similarly, many of the typical items listed above may not be required for some jobs. Data requirements for small capacity generators would be significantly less than indicated above.

Some of the calculated values of data may later be confirmed by test measurements. The items may include those of required or guaranteed value.

5.6 TEST DATA

The generator contractor is required to submit various test procedures, to schedule times when tests are conducted, and to provide the Bureau with test results. Some of these items require Bureau approval, and some are for information only.

The actual tests are discussed in chapter 12. This section will discuss only the data requirements for the tests.

Test data submitted to the Bureau, for information only, might include:

1. Factory and supplier materials test reports.

2. Performance tests of various subassemblies.

3. Welding qualifications test reports.

4. Results of dielectric tests performed at the factory and at the jobsite during field erection on various subassemblies and components. These tests may be preliminary in nature, and performed on a daily or shift basis. The tests may be made to ensure quality of a component before assembly into the machine.

5. Results of acceptance tests.

Test data submitted by the contractor to the Bureau for approval might include:

1. Nondestructive testing procedures.

2. Armature strand insulation test procedure.

3. Commissioning test procedure and schedule for the tests.

4. Acceptance test procedure and schedule for the tests.

5.7 PHOTOGRAPHS

The contractor is required, by procurement solicitation specifications, to submit photographs showing progress during factory manufacture of the generator. Photographs of each major assembly or subassembly are required. Usually, the solicitation states an estimated number of photographs, but indicates that additional photographs may be required by the Contracting Officer. Bureau field personnel usually are available to take photographs of field erection progress; the generator contractor, therefore, is not required to furnish field erection photographs. Many details will appear on these photographs that cannot be depicted clearly on drawings; hence, the photographs have proved to be of value for both review and record purposes.

5.8 FINAL DRAWINGS AND DATA

Occasionally, after drawings have been approved, changes to the machine take place. The changes may have been necessitated by test results or by unforeseen events that may occur during fabrication or erection. Therefore, drawings representing the machine as it is finally constructed and accepted are required.

In general, all drawings submitted for approval and/or information are revised (if necessary), then submitted as final. Oftentimes, a request is made for a few final drawings and data that do not require submittal during the data collection and approval process.

It is common practice to have discussions with the contractor regarding Bureau final drawing and data requirements. Most procurement solicitations include a listing of required information that must be included in the final material such as:

1. Generator capability curves.

2. Jack adjustment and operation details.

3. Recommended settings for all temperature, pressure, and liquid level switches.

4. Recommended operating ranges for various accessories.

5. Instruction books for dismantling, reassembly, operation, maintenance, and repair.

6. Manufacturers pamphlets, leaflets, catalog cuts (extracts), and other identification material.

7. Recommended excitation and excitation control settings.

8. Recommended tests and test results for routine maintenance.

9. Sample and actual calculations and formulae used for determining various settings and curves.

10. "As-built" prints of reproduced tracings of electrical schematic and wiring diagrams (see 5.9).

11. "As-built" drawings showing all revisions, with revision dates, made to the drawings up to the time of equipment acceptance.

12. Photographs taken during manufacture.

13. Reports of tests performed in the factory, during erection, and during commissioning and acceptance testing of the machine.

14. Final bills of material.

15. A complete list of drawings.

16. Parts identification lists.

17. Data on the thrust bearing and all guide bearings—including information for:
- shoes
- runners
- assemblies
- installation and removal procedures
- adjustments
- bearing surface repair
- replacement
- clearances
- insulation
- lubrication details

18. Collector ring and brush details.

19. Brake ring and brake assembly details including wear and warp tolerances, adjustment, repair, and replacement.

The actual number of drawings and data submitted as final material varies with the job and between various contractors. Experience has shown that the quantity of material for large machines can be considerable. Therefore, Bureau practice has been to require the generator contractor to submit microfilm negatives, mounted in aperture cards, of all final drawings. These microfilms become final records for the generator. Final material other than drawings are not submitted in microfilm format by the contractor.

5.9 REPRODUCED TRACINGS

Solicitations for small generating units may not contain reproduced tracing requirements for any drawings. Most solicitations for large generators require generator contractors to furnish reproduced tracings of all electrical schematic and wiring diagrams.

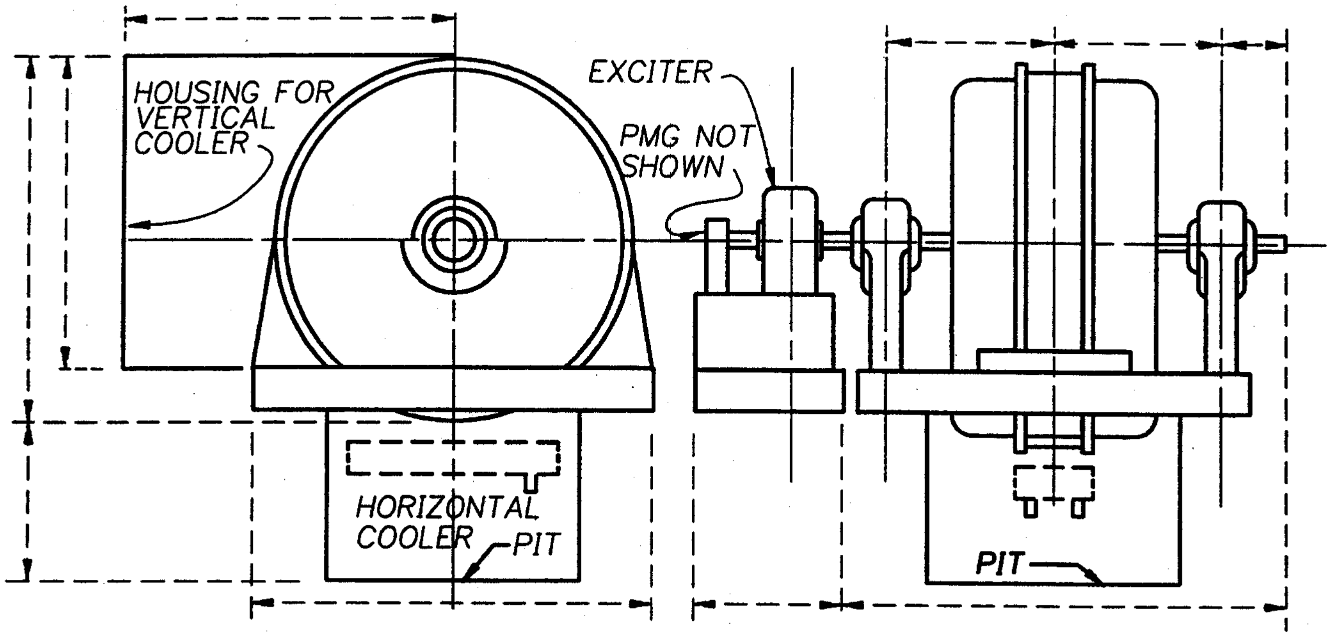
The drawings are prepared with a Bureau title block—within the margins of the drawing. The manufacturer's title block outside of the margin may later be trimmed off the drawing, leaving only the Bureau title block on the drawing.

Then, the reproduced tracings then become the Bureau's permanent record drawings. If revisions are made, after submittal of the tracings to the Bureau, "as built" prints of the drawings are furnished to the Bureau by the contractor and the Bureau makes the corrections to the reproduced tracings.

Contractor preparation of the electrical schematic and wiring diagrams—to a required Bureau format—relieves the Bureau of the need to prepare interconnection drawings of the generator to the Bureau furnished auxiliary and control equipment.

A requirement for reproduced tracings of drawings, other than schematic and wiring diagrams, has been included in some Bureau generator procurement actions. The basis for contractor-prepared reproduced tracing is the alleviation of problems related to available staff time restraints within the Bureau.

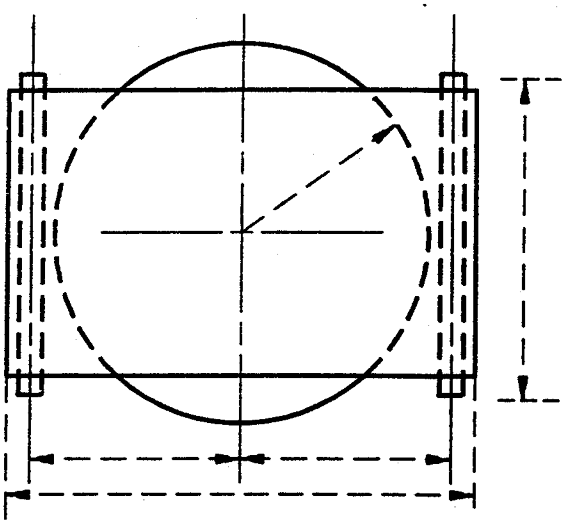
A recurrent problem of the contractor's failure to follow the required Bureau format has tended to frustrate the goal of the Bureau workload reduction program. A considerable amount of time has been expended, during several past jobs, just to correct the contractor's format to meet Bureau requirements.



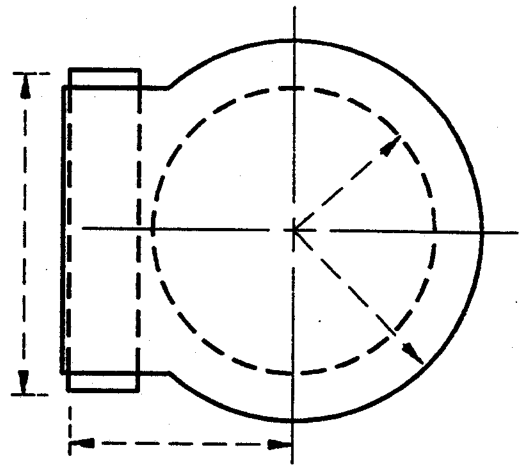
DATA

1. Source ______________________
   (in-house or manufacturer)
2. Plant name ______________________
3. kV•A ____________ r/min ________
4. Volts ____________ P.F. ________
5. Main exciter ________ kW ________
   Volts _____ amperes full-load field current
6. Volume of air in housing __________ ft³
7. Generator cooling water at ________ gal/min
8. Bearing cooling water at _________ gal/min
9. WR^2 ______________________
10. Total net weight ______________ lbm
11. Weight heaviest part ___________ lbm
12. Bid price, $ ______________________
13. kV•A/(r/min)² ______________________
14. Stator shift provided _______ Yes _______ No
15. Date ___________

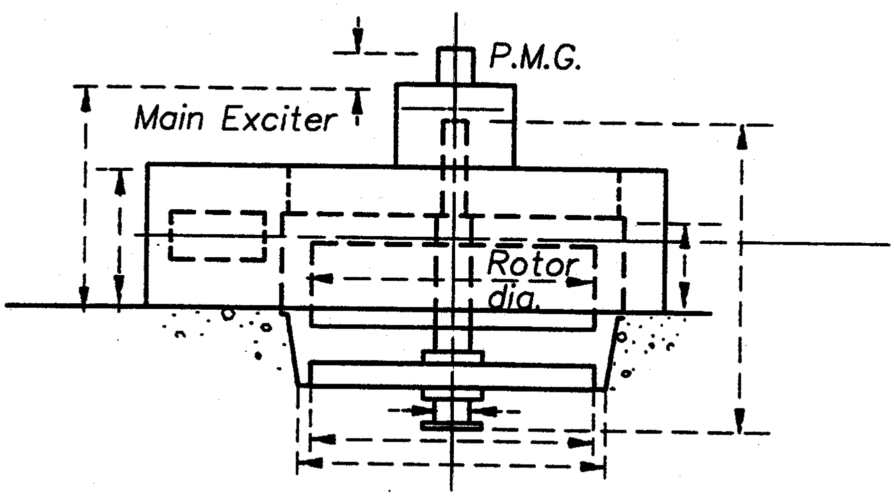
Figure 5-1. — Waterwheel driven generator outline — horizontal type unit.



COOLERS ON OPPOSITE SIDES



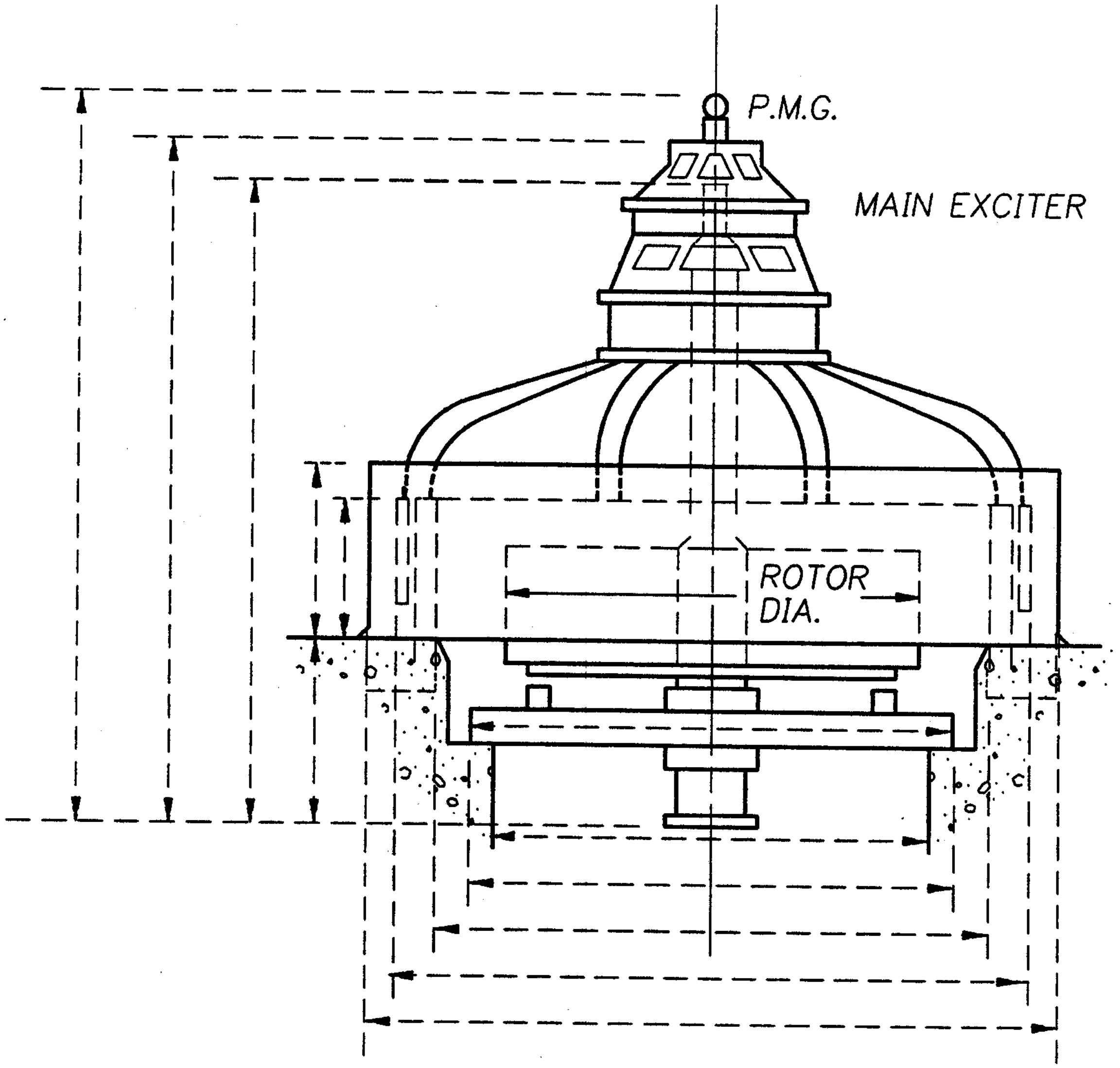
COOLERS ON ONE SIDE



DATA

1. Source ______________________________
(in-house or manufacturer)
2. Plant name ______________________________
3. kV•A ______________ r/min ____________
4. Volts ______________ P.F. ____________
5. Main exciter ___________ kW ____________
   Volts _______ amperes full-load field current
6. Volume of air in housing ______________ ft³
7. Generator cooling water at __________ gal/min
8. Bearing cooling water at __________ gal/min
9. WR^2 ______________________________
10. Total net weight ____________________ lbm
11. Weight heaviest part _________________ lbm
12. Bid price, $ ____________________________
13. kV•A/(r/min)² __________________________
14. Date ____________

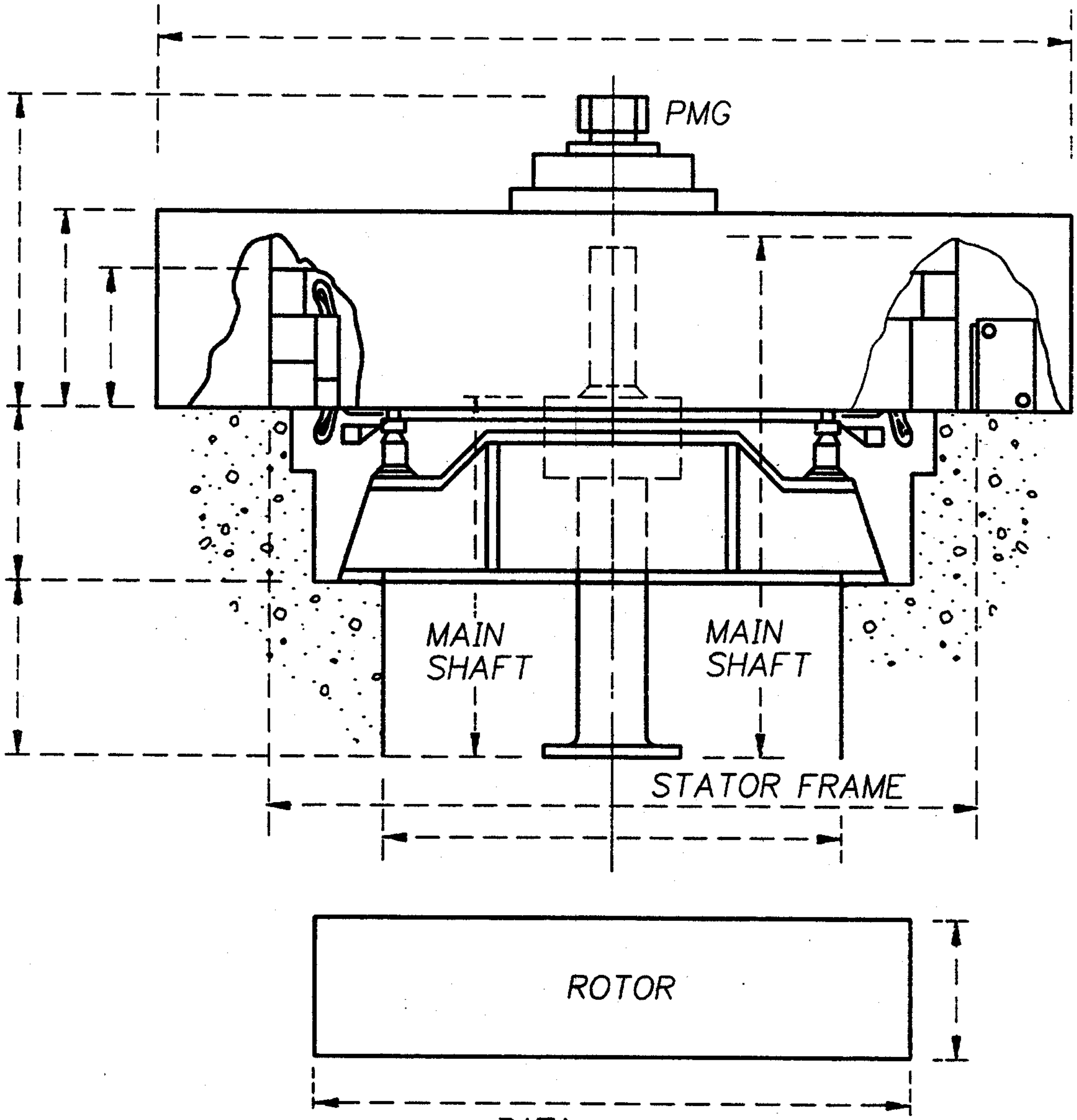
Figure 5-2. — Waterwheel driven generator outline — coolers on one or opposite side.



DATA

1. Source ______________________
(in-house or manufacturer)
2. Plant name ______________________
3. kV•A ____________ r/min ____________
4. Volts ____________ P.F. ____________
5. Main exciter ____________ kW ____________
Volts ________ amperes full-load field current
6. Volume of air in housing ____________ ft^3
7. Generator cooling water at ____________ gal/min
8. Bearing cooling water at ____________ gal/min
9. WR^2 ______________________
10. Total net weight ____________ lbm
11. Weight heaviest part ____________ lbm
12. Bid price, $ ______________________
13. kV•A/(r/min)² ______________________
14. Date ____________

Figure 5-3. — Waterwheel driven generator outline.



DATA

1. Source ______________________________
(in-house or manufacturer)
2. Plant name ______________________________
3. kV•A ______________ r/min ____________
4. Volts ______________ P.F. ____________
5. Main exciter __________ kW ____________
Volts ________ amperes full-load field current
6. Volume of air in housing ______________ ft³
7. Generator cooling water at __________ gal/min
8. Bearing cooling water at ___________ gal/min
9. WR^2 ______________________________
10. Total net weight __________________ lbm
11. Weight heaviest part ______________ lbm
12. Bid price, $ ______________________________
13. kV•A/(r/min)² ______________________________
14. Date ______________

Figure 5-4. — Waterwheel driven generator outline — umbrella-type unit.

CHAPTER 6

SHIPPING, STORAGE, AND HANDLING

6.1 GENERAL

The procedure selected for procuring of a generator (see ch. 3) has a major influence on the division of responsibility between a generator supply contractor, generator installation contractor (if other than the supplier), and the Bureau for shipping, storage, and handling.

Size and weight restrictions for rail and highway shipments to the powerplant site are frequently encountered. When restrictions exist—and are known by the Bureau—they must be made known to the bidders by the procurement solicitation. Most solicitations that require the generator contractor to be responsible for shipment also require the contractor to be responsible for determining all shipping restrictions, and to obtain necessary permits from the appropriate agencies.

Figure 6-1 shows estimated shipping weights for generators. The data for these estimated weights were derived from historical records; they may not be entirely accurate for modern machines and equipment.

Regardless of the procedure selected for procurement, all special tools, lifting beams, rigging arrangements, attachments, handling devices, or other equipment necessary for future maintenance must become the Bureau's property. Instructions for using all devices properly must be furnished by the contractor.

Spare parts must be packaged properly and prepared for extended storage. Waterproof containers are frequently used. Hazardous materials must be identified; instructions for their proper storage, handling, use, and disposal must be furnished. Materials having limited shelf life should be identified and marked.

Speed r/min	Generator and exciter weight in pounds†		
60	Generator kV•A rating	× 32.27	+ 165,000
72	"	× 27.31	+ 139,000
80	"	× 25.47	+ 122,500
90	"	× 24.03	+ 108,000
100	"	× 22.11	+ 98,500
112	"	× 21.09	+ 85,500
120	"	× 20.50	+ 77,000
128	"	× 19.66	+ 74,000
138	"	× 19.18	+ 64,000
150	"	× 18.09	+ 64,000
164	"	× 17.33	+ 55,500
180	"	× 16.75	+ 50,000
200	"	× 15.70	+ 48,000
225	"	× 14.90	+ 40,000
240	"	× 14.00	+ 40,000
257	"	× 13.31	+ 39,000
277	"	× 12.69	+ 37,500
300	"	× 12.10	+ 36,000
327	"	× 11.51	+ 34,000
360	"	× 10.85	+ 33,000
400	"	× 10.25	+ 31,000
450	"	× 9.41	+ 31,000
514	"	× 8.80	+ 28,000

† The weights are for normal WR^2 and do not include air housing or coolers.
For horizontal-type generators, use 80 percent of weights computed for vertical generators.
To convert to kilograms, multiply pounds by 0.45436.
This tabulation is based on manufacturer's data.

Figure 6-1. — Vertical waterwheel (3125 kV•A and larger) generators and direct-connected rotating exciters — combined shipping weight.

6.2 CONSTRUCTION CONTRACTOR FURNISH AND INSTALL

If this procurement procedure is selected, the construction contractor should be responsible for all required costs of: supply, transportation, storage, handling, tools, and materials. Any loss, damage, or delay would be problems that the contractor would have to resolve. Inspection by the Bureau would be at the Bureau's option—in the same manner as for other procurement procedures.

If the Bureau has existing facilities at the jobsite, these could be made available for the contractor's use. If facilities are offered, the solicitation would have to define clearly all conditions for their use.

6.3 BUREAU SUPPLY—CONSTRUCTION CONTRACTOR INSTALL

Procurement involving Bureau supply, or purchase of a machine from a generator manufacturer and the machine's installation by other than the manufacturer, may be chosen for small capacity generators. The size of these generators should be such that complete assembly and testing of the generator can be accomplished at the factory. Shipment can be made either a Bureau responsibility or a generator contractor responsibility.

If Bureau acceptance of the generator is made at the factory (free on board origin), shipment becomes a Bureau responsibility and the generator supply contractor is not held responsible for shipping loss, damage, or delays. Similarly, the construction contractor would not be responsible until delivery of the generator. Actual delivery may be to a railhead or delivery point other than the jobsite, or may be to the jobsite. Regardless of delivery point location, an inspection of parts—when delivered—must be made to establish "as received" condition.

If delivery is made at a location other than the jobsite, transportation between the delivery point and the jobsite may be made a part of the installation contract. A second inspection, involving both installation contractor and Bureau inspectors, may be scheduled to establish machine condition at the time of turnover to the contractor for installation.

If shipping costs are included in the generator contract price, the generator contractor is responsible for resolution of any shipping problems.

Bureau inspection at both the factory and at the jobsite are Bureau options that are usually exercised.

Storage may be necessary for generator parts while awaiting installation. Inside storage may not be available, and extended time lapse may occur between delivery and installation. Therefore, shipment in waterproof containers may be required for sensitive parts.

The generator or its component parts, as prepared for shipment, must be prepared for handling so as to protect the equipment from damage. This may involve crating or skids with special provisions for attaching slings or other lifting devices. Crates and skids should be marked and handling instructions should be furnished with each crate or skid. Some equipment may require eye bolts, lugs, or slings, which project through the crates or container. This will facilitate attaching the lifting device to the crane.

Requirements for storage and handling must be made known to the installation contractor, in advance of delivery, so that the installation contractor to make necessary arrangements for equipment, personnel, and facilities.

A complete set of generator manufacturers' itemized packing lists, installation drawings, data, and instructions must be given to the installation contractor before or at the time of turnover to the contractor.

A manufacturers' erection supervisor, to be present during machine erection, is a normal requirement included in this type of procurement. All installation contractor work should be performed under the erection supervisor's direction.

One difficulty encountered with this type of procurement and installation is the problem of obtaining sufficient information from the generator contractor at a time early enough to permit bidders for installation to prepare a complete and proper bid. Because of the lack of specific information from the generator supplier, the preparation of solicitations containing "typical" information may be the only alternative. If typical or estimated information is given to the installation contractor, claims to the effect that installation requirements are beyond the installation contractor's expectations can arise. Claim resolution in the Bureau's favor may be a difficult goal to achieve.

6.4 ADVERTISED AND NEGOTIATED PROCUREMENT

These procedures are used for procurement of generators and generator uprates that can not be completely assembled and tested in the factory. The field erection is considered an extension of the manufacturing process, and acceptable machine performance is heavily dependent upon proper field erection. Therefore, the generator contractor is made responsible for shipment, handling, and storage of the generator components in addition to erecting the machine on its foundation.

Bureau inspection at both factory and jobsite are Bureau options that are usually exercised.

Bureau facilities at the jobsite usually are made available to the contractor. The procurement solicitation must clearly identify the facilities to be made available and state conditions for their use.

Frequently, for completion of a powerplant, a construction contract is usually active simultaneously during the generator erection. Generally, powerplant crane operation is a construction contractor responsibility; the construction contractor must be compensated for any time crane operators assist in generator erection. Care must be taken to differentiate crane time required for generator erection from crane time required for construction contractor activities.

Many times, the generator contractor will subcontract with a powerplant completion construction contractor for some field erection services. Factory trained personnel, under the direction of an erection supervisor, are usually required for special generator erection activities such as armature installation, precision machine work, millwright activities, and testing.

A complete set of manufacturer's instruction books, installation drawings, and data should be made available at the jobsite to assist Bureau inspectors during field erection.

If a pedestal is used for rotor erection, the pedestal should become the property of the Bureau for future maintenance work.

If the solicitation requires the generator contractor to furnish foundation bolt or soleplate placement template, it may be desirable to require that these become Bureau property, although, potential future use is minimal for most jobs. As noted elsewhere, the template is used in a multiunit powerplant and generally fabricated by other than the generator contractor to dimensions furnished by the generator contractor. After use, it may be stored or disassembled.

CHAPTER 7

SPARE PARTS

7.1 GENERAL

Hydrogenerators are almost invariably custom designed for installation at one specific powerplant. The only exceptions, where essentially identical machines would be found at different powerplant sites, would involve small, repetitive manufacture machines. Since most hydrogenerators are custom designed and manufactured, replacements for failed parts must be either custom manufactured following the failure event, or spare parts must be obtained at the time of original manufacture. In addition to probably greater costs for custom manufacture of a few parts, the cost of lost revenue during required machine outage—while obtaining the components—makes postfailure acquisition of replacements an unattractive option. Therefore, any components that have limited service life, is vulnerable to failure, or has long delivery time must be ascertained; replacements may be included in the procurement solicitations.

In addition to actual spares furnished and stored, many solicitations require a manufacturer to retain templates, gauges, patterns, shop drawings, and other records for a period of time following machine completion. Dies used for punching may be included with items that must be retained by the contractor. These requirements may be of doubtful value, when considering the company's possible failure, merger, and change in product lines. Some solicitations have been written to require the contractor to deliver shop drawings and dies to the Bureau after the stated period of time, or for reasons the Bureau can no longer expect to obtain replacement parts from the original source. However, in considering the actual dies' value; punching dies conform to various quality standards; the number of punchings satisfactorily produced by a set of dies is finite. The number possible, from a set of dies, increases with the quality of the die; the cost of the die increases with the quality. For each job, a manufacturer would be expected to fabricate or procure dies of a quality level sufficient to meet only the requirements of that particular contract. The suitability of the original dies to produce additional satisfactory punchings, over and above the original job requirements, has never been made a solicitation requirement; the potential for future die use may be limited or nonexistent. Therefore, if the original dies are required to be delivered to the Bureau—following completion of the generator—a statement should be included in the procurement solicitation that indicates the number of punchings the dies should effectively produce after delivery of the dies to the Bureau. Then, the bidder could include the cost of the required quality of dies in the solicitations offer. Worn-out dies whose useful life has expired are worthless, yet a contractor might like to dispose them to a customer for unknown reasons. Refurbishing worn-out dies may be possible, but costs of refurbishing dies may exceed the cost of obtaining punchings by a different process.

Dies are used to produce rotor rim, field pole piece, and stator core laminations. Of particular interest to the Bureau are those dies used to produce stator core laminations. An armature fault may cause enough damage to core laminations that replacement of some of the laminations is required before damaged armature coils can be replaced. Studies have revealed that production of a relatively small number of laminations required for a core repair is probably more economically achieved by sawing and drilling—or laser cutting—laminations from sheet material rather than attempting to refurbish old dies (or buying new ones) and then punch laminations. Sawing or cutting procedures may be followed if insufficient spare laminations are furnished with the original generator to accomplish all required repairs.

Items included in spare parts list have varied from job to job and over the years. As experience is gained with generators presently in service, the recognition of need for spares furnished with the original equipment progresses.

Spare parts requirments for small generators usually are different than those for large generators. A typical list of spare parts required for a small water-cooled generator equipped with a static exciter would be:

1. A complete set of rotating parts and babbitt metal stationary parts for the thrust bearing.

2. A complete babbitted bearing or bearing liner for each guide bearing.

3. A complete set of field collector rings.

4. A complete set of field collector brushes.

5. One surface air cooler.

6. One cooler or set of cooling coils for each bearing oil reservoir.

7. Sufficient armature winding coils, including all slot materials, installation materials, and connecting materials necessary to completely span one coil pitch of the generator.

8. Three transducers or transmitting devices of each type furnished.

9. One complete set of contacts, springs, and coils for each type of relay, contractor, auxiliary switch, and control element being furnished for one generator.

10. One complete set of all excitation control and voltage regulator parts which require periodic replacement, including one circuit card for each card furnished.

11. One assembled module or tray of rectifiers.

12. Twenty percent of the quantity of silicon rectifiers used in the excitation system other than spare components furnished as one assembled module or tray of rectifiers.

13. One assembled module or tray of firing circuits.

14. Three complete fuse and fuse units for excitation transformer protection.

15. One spare excitation transformer.

NOTE 1.-If the small generator is to be equipped with rotating exciter rather than a static exciter, a complete rotating exciter would be substituted for items 10 through 15.

NOTE 2.-If the generator is of the brushless exciter type, components necessary to replace a complete brushless exciter would be required instead of static exciter items 10 through 15.

In addition to the parts listed above for a small generator, the following spare parts might be listed for a large generator.

1. A quantity of stator core laminations. Some specifications simply list a number of lamination sheets, such as 2,000 sheets for each generator. Other specifications require a volume, such as the number of sheets equivalent to one lamination arc length stacked to 1 foot (305 mm) high for each generator.

2. One spare main field pole and field winding for each generator.

3. One fan unit—including motor for each static exciter cooling unit.

4. One V-belt or one set of matched V-belts for each drive unit using V-belts for each generator.

NOTE 3.-If the large generator is equipped with a rotating exciter, an exciter armature complete with shaft and commutator, one field coil for each exciter field complete with insulation, and one complete set of brushes would be substituted for the static exciter components.

In the Bureau's experience, failures severe enough to require replacement of generator main field poles and windings have been relatively infrequent. However, poles and windings are subjected to strong mechanical and electrical stresses. If a severe failure should occur in the field, repair or replacement could be difficult and time consuming. Therefore, the cost of purchase and storage of a spare pole and winding may be good insurance. Spare main field poles and windings have been required for only a few Bureau powerplants.

Spare parts for a small, air-cooled, repetitive manufacture machine might be even more restricted than the listing above for small machines.

Spares for a small horizontal-shaft machine might be restricted to bearing components, brushes if used, and other components of limited service life. The complete armature (core and coils) for a very small machine may be resin immersed and cured (vacuum-pressure impregnated). This procedure makes replacement of individual armature coils impractical. Therefore, spare armature coils would not be required. Auxiliary devices such as relays and contractors may not be required for such small machines. Excitation control devices may be available commercially as a unit, and the value of main field pole spares may be doubtful.

The required spare parts cost is included in the generators contract price. Spare components delivery is made before contract completion. A powerplant having multiple units usually have unit completion schedules over a time period so that the first unit may be operational before completion of the contract for all the units. In this case, spare parts will be required when the first unit is placed in service.

During the period when warranties are in effect, failures may occur that will require parts replacement by the generator contractor. To correct the problem and return the generator to service the contractor may use Bureau-owned spare parts—available at the powerplant. However, the contractor should be required to replace these spare parts.

Spare parts should be packaged separately for extended storage; each package should be identified clearly as to contents. Some spare parts materials may have limited shelf life; these items should be clearly identified and marked. Special environmental conditions may be required for some materials; these conditions should be marked clearly on the packages. The spare parts should be periodically inspected—to the extent possible—to determine their condition.

CHAPTER 8

COMPONENT PARTS OF A HYDROGENERATOR

8.1 SHAFT, COUPLING, AND COUPLING BOLTS

8.1.1 Introduction

The typical shaft for both vertical- and horizontal-shaft machines is made from a carbon or alloy steel forging with an integrally forged coupling flange. Extra large, vertical-shaft machines may have a shaft fabricated from steelplates, with a coupling flange welded to the shaft body. Small horizontal-shaft generators may be fitted with a heat-shrink and keyed coupling to reduce machine costs. This shaft and coupling configuration facilitates the application of antifriction bearings, which are discussed section 8.2.3.1, and also reduces requirements for shaft machining. Both of these features reduce machine costs. Because the horizontal-shaft machine experiences little or no axial thrust, the heat-shrink and keyed coupling is a practical option. If axial thrust is present, an integrally forged coupling is a better design. Alignment of heat-shrink and keyed coupling is required, and both halves of the coupling should be furnished by the same manufacturer.

8.1.2 Forged Shafts

When specifying machines with forged shafts, the Bureau requires the shaft be continuous (without joints) between the generator guide bearings. The intent of this requirement is to avoid problems that might occur due to misalignment during assembly or reassembly. Configurations disallowed by this requirement include those that contemplate the attachment of stub shafts to either end of the generator rotor.

The diameter of the shaft is not controlled by specifications or standards to permit the manufacturer to select a design that will provide the performance — including stiffness — that is required. The IEEE Standards [1][1] reflect a series of preferred diameters that increase by:

- 1/2-inch increment up to 9 inches,
- 1-inch increment from 9 to 40 inches,
- 2-inch increment from 40 to 72 inches,

whilst shaft diameters larger than 72 inches are not addressed by the standards.

The profile, dimensions, and tolerances of the generator-to-turbine coupling and the coupling bolts; and the tolerances of the bearing journal surfaces and any other surface that would impact shaft runout are closely controlled by these standards.

Forged shafts are required by Bureau specifications to be machined over their entire length. This requirement facilitates inspection and detection of flaws. An axial hole may be bored through the length of the shaft to further facilitate inspection and detection of flaws during manufacture. One industry guide is to bore the hole when generator kV•A divided by rated speed exceeds 75. This hole may be used to route main field leads from the exciter to the field poles. A radial hole intercepting the axial hole is bored into the shaft for the purpose of bringing the field leads out of the shaft. The axial hole may be used to route oil piping to the turbine if the turbine is of the adjustable-blade propeller (Kaplan) type.

Other than the above uses, the axial hole serves no other purpose when the machine is placed in service. The turbine shaft has a similar axial inspection hole; one or both of the holes must be plugged and sealed to prevent water from passing from the turbine, through the hole, and into the generator. The axial hole may be eliminated in shafts for small, horizontal-shaft generators. Rotor hubs, guide bearing journals, and thrust collars may be integrally forged with the shaft.

The thrust block in vertical-shaft generators can be regarded as part of the shaft system—as distinguished from the bearing system. Bureau specifications address thrust block requirements under the shaft paragraphs. The thrust block is required to be forged integrally with the shaft if the thrust bearing is located below the rotor. If

[1] Numbers in brackets refer to entries in the Bibliography.

the thrust bearing is located above the rotor, the thrust block must be a single piece forging, heat-shrunk, and keyed to the shaft. This design tends to minimize the possibility of distortion, fretting corrosion, or misalignment.

8.1.3 Fabricated Shafts

When machine torque demands an extra-large diameter shaft, existing manufacturer's forging abilities may be exceeded or the resultant shaft may simply not be practical because of mass alone. In such event, a fabricated shaft may offer significant advantages. The fabricated shaft could possibly weigh only half that of a comparable forged shaft, while being as much as 40 percent stiffer in both bending and torsion.

A fabricated shaft consists of steelplate pieces rolled into a cylindrical form, and then welded at the seams to form a cylinder. The steelplate pieces may be several inches thick. Forged coupling flanges are then welded to the cylinder to form the shaft. Currently, industry experience indicates that machines developing torques demanding shaft diameters greater than 72 inches are probably better constructed if fabricated shafts are selected.

Differing opinions exist as to whether the outside surface of the fabricated shaft should be machined. One opinion is that machining—to achieve circularity—may reduce the wall thickness more in one area than in another, with possible detrimental impact on the completed shaft. Another opinion is that machining will have a negligible effect on balance or other performance of the shaft. The Bureau has accepted machines with fabricated shafts that have been both unmachined and machined over the entire surface. Performance problems have not been experienced with either of these two designs. However, differences in manufacturer's design and construction may create or eliminate differing concerns; therefore, the Bureau has permitted the manufacturer to select the design. If the manufacturer selects the unmachined option, the Bureau sometimes requires a stainless steel cover for appearance purpose. This cover has not proved to be completely satisfactory because paint, when applied on the fabricated shaft surfaces with fillers, solves the appearance concern—thus eliminating the need for a cover.

It is difficult to properly weld parts to a fabricated shaft body, stress relieve, and machine the final assembly; therefore, a fabricated shaft has been limited to the simplest configuration and profile possible. When the fabricated shaft is used in a modified umbrella machine (thrust bearing below rotor), the rotor hub may become part of the shaft system. A stub shaft—possibly a smaller forging—is used above the rotor if an upper-guide bearing is required. If an upper-guide bearing is not necessary, the only shaft provisions above the rotor are for collector rings and the attachment of a speed signal device, which are necessary regardless of the presence of an upper guide bearing.

8.1.4 Couplings and Coupling Bolts

As stated in section 8.1.2, coupling dimensions of forged shafts having diameters up to 72 inches are closely controlled by IEEE standards [1]. Coupling dimensions for shafts larger than 72 inches are not addressed by the standards; and if such a shaft is required, extra effort will be required to ensure that the turbine and generator shafts are perfectly matched.

The coupling flange diameter is based on the shaft diameter at the coupling. Thus, if generator and turbine shafts have different diameters, a conflict exists in coupling dimensions. The standards resolve this potential conflict for forged shafts by stating rules to be followed if diameter differences exist. Shaft diameter differences may exist because of different requirements for stiffness or different methods to accomplish required stiffness—rather than torque considerations alone.

The method used to transmit torque through the coupling from the turbine to the generator is variable. Different opinions exist, as: "How is this transmission best accomplished?"

Two ways to accomplish torque transmission are:

1. The shear method which requires the bolts to be metal-to-metal fit in the coupling bolt holes. Bolts are tightened sufficiently to prevent opening the coupling due to vertical load. Then, turbine torque transmits through the bolts by shear.

2. The friction method uses bolts that have a clearance or loose fit in the holes. The bolts are tightened sufficiently to transmit all of the turbine torque by friction in the coupling faces.

Other methods include the transmission of torque by a combination of bolt or radial dowel—shear and friction.

A problem encountered in designing a coupling based on torque transmission through friction alone is the establishment of a value for the coefficient of friction. The coefficient of friction is an elusive characteristic that is not a material property such as tensile strength or hardness. The coefficient varies according to surface conditions; i.e., from irregularities and oxidation, contamination by foreign materials, and plastic or elastic material characteristics. Therefore, the designer must decide upon a minimum coefficient value to use in calculating coupling friction force. The minimum value has not been established by a standard nor unanimously agreed upon by others in the industry. A coupling design based on transmission of torque by bolt shear only must assume that differential movement of the coupling faces will continue until all torque is balanced. This differential movement may produce some deformation of the bolt that may impede bolt removal. Torque reversals that occur between acceleration and deceleration may increase the severity of this problem. Designing the coupling by using a combination of shear and friction to transmit the torque may result in the least problems, especially, if the shear is achieved through radial dowels rather than through the coupling bolts.

The standards, for shafts less than 72 inches in diameter, assume that all the torque must be transmitted by shear; the size and number of required coupling bolts are based on this assumption. This does not mean that the bolts will be only tightened sufficiently to close the coupling and carry vertical loading. The machine designer may determine that the bolts be tightened sufficiently to carry all the torque by friction—even though bolts can adequately carry torque by shear. The NEMA Standards MG-5.2 (now rescinded): "Installation of Vertical Hydraulic-Turbine-Driven Generators and Reversible. Generator/Motors," indicated that coupling bolts should be tightened—during machine installation—sufficiently to carry maximum torque by coupling face friction alone, even though the coupling was designed to carry the same torque by shear alone.

In the foregoing, good plant design engineering practice is to specify coupling design considerations if transmission of torque by friction is a requirement. If the friction method is required, a minimum coefficient of friction should be specified. Bureau practice has been to require a coefficient of friction not greater than 0.25, when computing friction. This consideration is especially important when shaft diameters exceed 72 inches and controlling standards are not available.

8.1.5 Shaft Alignment

Factory assembly and alignment of the turbine and generator shafts are required for large machines. Usually, the procedures include reaming or finish boring, fitting, and matchmarking coupling bolts and holes. Factory performance of the alignment offers distinct advantages because of the presence of proper handling facilities, lathes or vertical alignment tables capable of handling large shafts, and the availability of equipment to remachine or otherwise correct problems. The savings in time for field-assembled machinery easily justifies factory alignment. In the field, rotor hub bolt and other holes may be finish bored or reamed and the bolts fitted.

Shaft alignment may be performed in either the turbine manufacturer's factory or in the generator manufacturer's factory—at the Government's option. The factory choice is based upon minimizing the possibilities of damage during shipment, and upon scheduling and cost considerations. Usually, alignment is performed at the generator manufacturer's factory because the turbine is frequently purchased before the generator, and manufacturing of turbine components has likely progressed further. Thus, scheduling delays are minimized by having the generator manufacturer perform alignment. Foreign manufacturer of either turbine or generator, or both, may influence the choice of which factory performs alignment.

Imperfect alignment will produce vibration, noise, cyclic stresses in the machine's stationary parts, and abnormal stresses in the rotating parts. Hence, good alignment is essential to successful generator operation.

The NEMA Standards MG-5.2 (previously noted in sec. 8.1.4) have been rescinded, and have not been replaced. These standards covered field installation and alignment of machines. Because standards do not currently exist, the Government must take action to ensure that field installation and alignment of the combined turbine and generator shafts are coordinated and properly accomplished.

8.1.6 Accessories

Coupling bolts and nuts may be supplied by either the generator manufacturer or the turbine manufacturer. The procurement solicitations must specify which manufacturer will be responsible for the supply.

As noted in section 8.1.4, the coupling bolts may be metal-to-metal fit in the holes, or the torque may have produced enough differential coupling movement to bind the bolts in the holes after operation. In either event, special means may be required to insert and/or remove the bolts. The IEEE Standards [1] address this requirement by stating that the coupling bolts must project beyond the nuts sufficiently to facilitate driving the bolts. Some machines have been equipped with coupling bolts having axial threaded holes that allow for the attachment of devices called "bolt jacks" for removing bolts. This term has been frequently confused with "jack bolts" which is another device discussed below.

Couplings manufactured according to standards have a projecting rabbet on the face of the turbine flange and a matching recess on the face of the generator flange. The fit of the rabbet into the recess is metal-to-metal and serves to ensure that alignment of the shafts is retained. The tight fit also may inhibit separation of the coupling after the coupling bolts have been removed; "jack bolts" are provided in the generator flange to aid in separating the two halves.

Nut guards are provided to cover the projecting heads of the coupling bolts and nuts during operation. These guards are made in halves to help installation and removal. The standards address the provisions on the flange for the nut guards, but do not address the dimensions nor profile of the guards. Therefore, coordination must be achieved between the turbine and generator shaft manufacturers if a matching appearance of the two guards is required. An option often exercised is to have one manufacturer or the other furnish nut guards for both coupling halves.

A shaft deflection monitoring system or a vibration detection system may be required. The shaft deflection system may require a machined band with a smooth finish on the shaft or coupling. A timing device must be used to block operation of the deflection monitoring alarm during starting until temperatures of guide bearing components have stabilized. The clearances of a cold guide bearing may be large enough to allow the shaft and thrust bearing runner to "skate" on the thrust-bearing shoes and produce a false deflection alarm.

A "creep detector" may be installed at a generator flange—or elsewhere on the shaft—to detect unintended shaft rotation. Usually, the creep detector does not require special provisions on the flange or shaft.

8.1.7 Summary

Fabricated shafts do not lend themselves to designs that require many changes in profile. For example, profile changes for coupling flanges, rotor hubs, bearing journals, and thrust blocks require an interruption in the plate/cylinder profile. Each interruption must be addressed by welding of other components to the cylinder—with all the attendant problems associated with welding. Shaft forgings permit a higher degree of precision in machining and alignment, and allow more flexibility in profile changes. Both forged and fabricated shaft construction require factory manufacture and finish, and both require special shipping considerations. However, a forged shaft would probably be longer and heavier and would be somewhat more delicate than a fabricated shaft for the same machine. Therefore, the forged shaft requires greater shipping care.

Forged construction is considered to be superior to fabricated construction for most conventional size shafts. However, it is conceivable that fabricated construction may offer advantages, under certain circumstances, for conventional size shafts. Such circumstances might include a shaft for a close-coupled machine (thrust bearing on turbine head cover) or a machine where no coupling exists between the turbine and generator shafts. A critical-speed analysis might disclose a need for greater shaft stiffness—which could be achieved more easily with a fabricated shaft than a forged shaft—because shaft stiffness increases roughly as the fourth power of the shaft diameter.

When fabricated shafts are specified, as fabricated shafts are not covered by standards, extreme care must be used by the designer to achieve a coordinated turbine generator shaft system. To reduce costs, small, horizontal-shaft hydrogenerators may be equipped with heat-shrink and keyed couplings, rather than integrally forged with the shaft.

Bureau of Reclamation procurement specifications must state the required method for transmitting the torque through a shaft coupling. Specifications must state a minimum coefficient of friction to be used by the contractor if any torque is to be transmitted through the coupling by friction. Although a coupling may be designed to be capable of transmitting maximum torque through bolt shear, the bolts may be tightened sufficiently to cause the coupling to transmit the maximum torque by friction alone.

Alignment of turbine and generator shafts and the fitting of coupling bolts at the factory is an attractive and cost effective requirement. Field installation and alignment—following factory shaft alignment—will require special attention by experienced personnel until new standards become available.

A critical speed analysis of the complete shaft system must be performed. More than one analysis may be required to address different operating modes (turbine coupled and uncoupled).

8.2 BEARINGS AND LUBRICATION

8.2.1 Introduction

The material covered in this section, as in other sections, is written as though limited to hydrogenerators and pumping/generating units. However, extra-large pump motors are constructed to the same standards as hydrogenerators, and bearing systems for these large pump motors are the same as for large generators.

The strengths and weaknesses of various bearing systems from a machine designer/manufacturer viewpoint are discussed in engineering literature; the users of this manual are encouraged to read this literature to develop a technical understanding of bearing design. This section will attempt to reveal characteristics and options of special importance to a plant designer.

Hydrogenerators are built in a wide range of sizes, ranging from a few hundred kilowatts to nearly 1,000 megawatts, and in different configurations—horizontal-shaft, inclined-shaft, and vertical-shaft. Small hydrogenerators may be induction or synchronous machines. The bearing systems used in these machines may vary considerably according to their application. For the smaller ratings, the bearing systems are the same as those found in integral horsepower motors. Larger ratings of generators tend to exclusively use "plain" bearings for the main shaft system, and the large generators may have many small accessory motors for driving fans and pumps. The bearing systems for these motors will not be discussed in this section, although some portions may be applicable.

8.2.2 Terminology

Plain bearing.-A bearing where the relative motion of the primary bearing parts is sliding or rubbing, also known as a "fluid film" bearing.

Rolling element bearing.-Also known as an "antifriction" bearing, this bearing uses some type of rolling element such as a ball or roller between the loaded primary parts. The relative motion is accommodated by rotation of the rolling elements.

Antifriction metal.-This material can be one of many metal alloys. Lead- and tin-base alloys containing various amounts of copper, antimony, aluminum, silver, and cadmium are most frequently applied as an antifriction metal; and are often called "babbitt" or "whitemetal." Antifriction metal is *not* used in antifriction bearings.

Conventional or suspended machine.-This is a vertical-shaft machine with a thrust bearing and a guide bearing above the rotor, a guide bearing below the rotor, and a third guide bearing at the pump or turbine. Machines having long intermediate shafts may be equipped with additional guide bearings between the lower-guide bearing and the pump or turbine guide bearing.

Modified or modified-umbrella machine.-This is a vertical-shaft machine that may have an optional guide bearing above the rotor. The machine has a thrust and a guide bearing below the rotor, and a pump or turbine guide bearing. Occasionally, this arrangement is called an "umbrella" arrangement, but it actually is not the same as the umbrella machine used with Kaplan turbine-driven generators. The true umbrella machine is characterized by drooping rotor arms that place the center of the rotor mass at essentially the same elevation as the thrust bearing.

Close coupled machine.-This is a vertical-shaft machine with the thrust bearing supported by the pump or turbine head cover. The arrangement may have a generator guide bearing either above or below the rotor, but always has a pump or turbine guide bearing.

8.2.3 Bearing Types

All bearings may be classified into two broad types, as distinguished by the relative motion of the parts: (1) One type is the *plain* or plane bearing ("plane" is probably more descriptive, but plain has general usage), and (2) the *rolling element* bearing. Each type has many subclassifications; for example, plain bearings may be of the flat-shoe type or sleeve type.

Bearings, wherein the relative motion is rolling rather than sliding may be called *antifriction bearings*; they are subdivided into ball-bearing and roller-bearing types. Each of these two types have additional subclassifications. Some readily apparent differences of rolling bearings from plain bearings—in addition to the relative motion—include point contact of bearing members in ball bearings and line contact of bearing members in roller bearings, the use of hardened steel in all bearing members (i.e.; antifriction metal is not used at all) and significantly higher bearing loading. Rolling-element bearings may or may not be capable of transmitting axial thrust.

A recent modification of the plain bearing is called a *magnetic bearing*, where part of the load is magnetically supported. As of 1991, the Bureau has not installed a machine with this feature.

8.2.3.1 *Rolling-Element Bearings*.- Rolling element bearings are found only in generators having low kilovolt ampere ratings. This is true mostly because of cost factors that include: bearing and bearing housing costs relative to the total cost of the machine, bearing design costs, machining or shop costs, maintenance costs, replacement costs, operating costs (efficiency), and cost of failure. The cost of failure may be the most important factor when considering potential damage to the rest of the machine if a bearing suffers a catastrophic failure. Rolling-element bearings are more subject to total and catastrophic failure than plain bearings; this fact alone can dictate using plain bearings in large, important, and expensive hydrogenerators. However, rolling-element bearings are capable of controlling a much more precise center than is possible with plain bearings. A design that prevents contact between generator rotor and stator—in the event of bearing failure—is required by the specifications.

In addition to cost, other factors such as: speed, speed variations, load, load variations, permissible deflection, available space, noise restriction, and life expectancy restrictions may dictate choice of bearing type.

Rolling-element bearings are much more sensitive to varying loads or shock than plain bearings; the life expectancy of a rolling element can be dramatically shortened by even brief overloads. Vibrations that are common in hydrogenerators may very well limit the application of rolling element bearings.

Rolling-element bearings generate more noise than plain bearings, and also transmit vibrations and noise created in other parts of the machine more readily than plain bearings.

Rolling-element bearings are manufactured to standards of the AFBMA (Anti-Friction Bearing Manufacturer's Association, Inc.) [2]. These standards have established procedures for evaluating load ratings and for stating the expected life of an antifriction bearing under known conditions.

Rolling-element or *antifriction bearings* are suitable for application over a wide range of operating temperatures. These bearings can be successfully applied at temperatures exceeding 260 °F (127 °C) if they have been heat treated or normalized at a temperature higher than their operating temperatures. An operating temperature of 180 °F (82 °C) is fairly common. Bearings having race temperatures in excess of 320 °F (150 °C) are often found in electric machinery. Bureau specifications have not placed any limits on antifriction bearing operating temperatures. The manufacturer is permitted to select the temperature and proper lubricant for that temperature.

When an antifriction bearing is properly selected, mounted, and maintained, the "life" before failure will be determined by fatigue of the bearing materials. Bearing failure is considered to occur at the first appearance of fatigue in the bearing races or rolling elements. The visual evidence of fatigue failure is usually the fretting or cracking of bearing member surfaces. Bearing life is calculated in terms of hours of operation at a constant speed or in total number of revolutions before failure. The bearing life for a group of identical bearings follows a "bell curve" dispersion, and it is necessary to state whether median life, minimum life, or another measure is being addressed. Bureau practice is to specify a "Rating Life" (AFBMA L_{10}) [2], which indicates a time period that 90 percent of a group of identical bearings will complete or exceed before failure. (Another way to state this: a 10-percent failure rate can be expected within the stated life period.) The presently accepted bell curve dispersion indicates that the median life of this same group of bearings will be about five times the rating life. The rating life of a rolling element bearing will be less than a comparable properly selected, mounted, and maintained plain bearing.

8.2.3.2 *Plain Bearings*.-Virtually all vertical-shaft hydrogenerator bearings are of the *plain* type. The sliding members are separated by a fluid film during operation, which prevents wear.

The fluid film is hydrodynamic, which means that pressure is produced in the film by the shearing motion. The pressure in the film supports the applied load and prevents direct contact of the sliding members. This is an important point because pressure or film will not exist at standstill or at very low speeds; without film, rapid wear or "wiping" will occur and bearing failure will result. Two different forms of fluid film lubrication exist: "boundary film" and "fully developed fluid film." Hydromachinery bearings use the fully developed fluid-film lubrication. Boundary-film lubrication is a condition in which a full fluid film does not support the load—such as at standstill or very low speeds in a hydromachine. Thus, boundary lubrication does not exist intentionally in a hydromachine, but is a condition that the machinery designer has to consider.

In theory, the metal surfaces of a fluid-film plain bearing can approach indefinite life when operating under normal constant load and speed conditions. Heat in the bearing is generated by shearing action in the fluid film; the fluid forming the film is continually replenished with fresh fluid by motion of the sliding members. Thus, if the fluid is maintained in a satisfactory condition, the bearing sliding members should not be subjected to wear. Unfortunately, loads and speeds never remain constant, and wear in the sliding members does occur and is greatest at low speeds when the hydrodynamic fluid film does not exist or is minimal (boundary conditions). Wear also occurs as a result of contaminants in the oil or oil deterioration.

Friction losses are a function of the coefficient of friction of the material of which the sliding surfaces are made. However, the coefficient of friction is not a fixed and quantifiable material property such as tensile strength or hardness. The coefficient of friction is variable and is influenced by several factors. The conditions existing between the two surfaces and the conditions of both the surfaces determine the coefficient. Surface oxidation, adsorbed solids and gases, presence of water or water vapor, surface roughness or irregularities, elastic and plastic properties, and presence of contaminants are factors of the coefficient of friction; small or subtle changes in these factors can greatly affect the coefficient's value.

It has been established that some metals usually exhibit a lower coefficient of friction than others. Generally, these metals are alloys and are called "babbitt," "whitemetal," or simply "antifriction metal." By using an antifriction metal for one of the sliding surfaces of the bearing, three beneficial effects can be achieved:

1. Total bearing friction and wear during starting and stopping can be reduced.

2. The softer antifriction metal for one sliding surface tends to adjust to irregularities in the contour of the other sliding surface. This process occurs over a period of time after initially starting and is called "break-in." Bearing friction usually reduces to a minimum after the bearing is fully "broken-in."

3. The softer antifriction metal for one sliding surface will wear faster than the metal for the other sliding surface; therefore, the antifriction metal should be placed on a part that is most easily removed, renewed, or replaced.

A bearing's capability to support load is a function of the hardness of the bearing sliding members. In hydromachinery, the rotating member is made of high quality, mild steel and is called a bearing journal or runner. The stationary member is called the bearing; this member is the surface to which the antifriction metal is applied. The hardness of the antifriction surface can be varied by using different alloys. The normal loading for plain bearings is about 500 pounds force per square inch (35 kgf/cm² or 3447 kPa).

Fluid-film bearings can tolerate considerable shock loading and function well as a vibration damper.

However, the stress will be transmitted through the film, and fatigue failure of the sliding members or their supports can occur. As loading increases on the hydrodynamic fluid film, the thickness of the film decreases and the sliding members approach each other. Upon reaching overload, the highest projections of the surfaces make contact and the characteristic of the bearing changes from fluid friction to metallic friction. If the sliding members make contact, metallic friction generates a large amount of heat that cannot be controlled, and failure occurs. Under normal conditions of speed and load, bearing friction is a function of fluid viscosity, shear rate, and bearing area. Heat generation in the bearing is a product of friction; excess heat is the source of most bearing failures.

The shearing motion of the sliding members moves the fluid between them. Most plain bearings are constructed such that one of the sliding surfaces is interrupted at intervals to permit the moving fluid to escape and to allow fresh fluid to enter.

The surfaces of the sliding member between interruptions are called "pads" or "shoes." Most of the friction generated heat is carried away from the bearing by the escaping fluid, while some heat is transferred by conduction through the bearing supports.

As noted above, plain bearings function well as vibration dampers. This damping capacity, the bearing stiffness, the bearing bracket stiffness, and the support system stiffness are important factors that must be considered when the machine designer calculates the critical shaft-speed. Stiffness is the amount of bearing journal displacement with an applied load; according, as the fluid in the film will exhibit different characteristics with varying load and temperature, shaft critical speed will vary. Successful performance of the machine depends greatly on a properly performed critical shaft speed analysis.

As previously mentioned, bearing friction is a function of fluid viscosity and shear rate. Viscosity of the fluid varies with temperature—decreasing as the temperature increases. Shear rate varies with load—increasing with speed and decreasing with film thickness. Despite these variations, the rise in bearing temperature can be estimated fairly accurately by the designer if the fluid characteristics and shear rate are known. For hydrogenerators, Bureau specifications limit the thrust bearing temperature to 80 °C maximum, and guide bearing temperature to 65 °C maximum. Thus, the machine bearing designer must know at what loads and speeds the bearing will operate, and also needs to know the characteristics of the fluid or lubricant that will be used. With this knowledge, the designer can specify a bearing that will have a long and trouble-free life. The importance to maintain the lubricant within the limits expected by the designer cannot be overemphasized.

8.2.4 Bearing Applications in Hydrogenerators

Low capacity hydrogenerators can be of the horizontal-shaft type, and may be equipped with either rolling-element or plain bearings. If such a machine is equipped with plain bearings, they will usually be of the split-sleeve type to facilitate removal and replacement. If the bearings are of the rolling element type, they must have dimensions that will permit removal of the bearing over the shaft coupling. Horizontal-shaft machines may not be equipped with any type of thrust bearing. If a thrust bearing is not included, the shaft should have markings to indicate maximum rotor end play limits and the magnetically centered position of the rotor.

Some turbines driving horizontal-shaft machines do not produce an appreciable axial thrust and a thrust bearing is not required. However, if the powerplant designer is aware of the possibility of axial thrust, the machine manufacturer must be made aware of the magnitude, direction, and whether the thrust load is continuous or intermittent. If the loading is a combination of continuous and intermittent, the magnitudes of each and the duration of the intermittent loading must be given to the manufacturer.

The location of the thrust bearing in a vertical-shaft machine is of such importance that it is used to actually describe the machine. Three such locations and their associated machines were discussed in section 8.2.2 along with descriptions of their differences. The location of the thrust bearing not only has a major impact on the machine design, but also dramatically impacts the plant structure and turbine designs.

It is always important to reduce plant structure costs. While pressure may be exerted on the machine designer to permit the structural designer to minimize structural costs, by selecting a physically small machine, it must be noted that an improper machine selection can produce an inoperable plant.

In addition to the loadings previously discussed, the major factor dictating number of bearings and their location is the maximum runaway speed of the unit. The lowest critical speed for the turbine and generator shaft and bearing arrangement must be well above the maximum runaway speed of the unit. Runaway speed is not a factor when a generator is being operated as a synchronous condenser with the turbine uncoupled. However, it is noted that uncoupling the turbine presents a different configuration, and different critical speeds will exist. Also, maximum guide bearing load resulting from a faulted field can occur either while condensing or generating. Therefore, the choice of bearing arrangement must recognize plans for operation as a condenser.

The majority of Bureau of Reclamation powerplants have machines of the suspended type. With this arrangement, the weight of the turbine and generator rotating parts—and the unbalanced hydraulic thrust—are carried by the thrust bearing.

The reactions are transmitted through an upper-bearing bracket to the stator frame, thence from the frame to the generator foundation. The powerplant structure for generators of the suspended type must consider this loading, and also:

1. Lower-guide bearing bracket must pass through the stator bore during assembly and disassembly.

2. Opening in the lower-guide bearing bracket for the bearing must also allow passage of the generator shaft flange.

3. The pit opening below the lower-guide bearing bracket must be large enough to permit passage of the hydraulic turbine parts (i.e., head cover, etc.). Other arrangements have been implemented, such as split head covers or a gallery for turbine removal without having to disassemble the generator.

Generators of the "modified" type, with the thrust bearing located below the rotor, offer advantages when overall generator height reduction becomes a compelling issue. This is frequently the case when the generator unit capacity is large and rotational speed is slow. These factors dictate a large stator diameter that must be spanned by the upper-bearing bracket. If the machine is to be of the suspended type, the loads carried by the thrust bearing dictate a large increase in the massiveness of the bracket and stator frame. Thus, a disproportionate increase in machine height occurs with increasing stator diameter. By moving the thrust bearing to the bracket below the rotor, which must already have the capability of supporting all of the vertical load except for hydraulic thrust, a significant reduction in height for the upper bracket can be achieved. Work space must be provided below the thrust/lower-guide bearing for joining or disconnecting the shaft coupling and other turbine related work. If the machine is equipped with an upper guide bearing, means must be provided for transmitting the maximum forces from the guide bearing to the foundation. If the stator is placed into a concrete air housing or "barrel," structural members can be provided to transmit upper-guide bearing forces through the bracket directly to the barrel walls rather than through the stator frame to the foundation. Assembly and disassembly considerations for a modified machine are essentially the same as those for a suspended machine.

To reduce overall turbine/generator height to a minimum, the "close-coupled" machine supports the unit's vertical load on the turbine head cover rather than on a separate bracket below the generator rotor. This design is fairly common in Europe, and the arrangement reduces the overall height for a powerplant. However, this design introduces concerns that should be evaluated carefully before implementation:

1. Possible operation as a synchronous condenser—with the turbine wheel uncoupled—is virtually impossible.

2. It is almost mandatory that the turbine and generator be purchased as a unit, preferably from the same manufacturer.

3. All vertical loading from rotating parts must be transmitted to the foundation through the turbine stay ring, which may produce undesirable effects due to an increase in size of turbine components.

4. Machine rotational stability is affected by the distance from the center of mass (rotor rim) to

the point of support (thrust bearing) and by the rigidity of that point of support. Therefore, a thorough shaft critical speed analysis and vibration analysis is essential.

5. It is difficult to create a "stiff" support using this design, which makes rotational stability more difficult to achieve.

Variations in the design of a close-coupled machine include a pedestal or cone arrangement for the thrust bearing bracket, thus locating the bearing closer to the generator rotor while still carrying the load on the head cover. This arrangement appears to offer possibilities for improved stability.

As of 1991, the Bureau has not installed any close-coupled machines, therefore, commentary on operating experience cannot be made. Possible applications have been studied, but the results did not indicate sufficient advantages to cause this design to be adopted.

As stated in section 8.2.3.1, various types of rolling-element bearings are suitable for supporting thrust loads. However, thrust bearings used in vertical-shaft generators installed by the Bureau have all been of the plain-bearing type.

Suspended-type generators are equipped with one-piece thrust bearing runners. Modified generators may be equipped with split thrust-bearing runners. The split runner facilitates renewal or replacement of the runner without first removing the rotor from the machine. Split runners are not provided in large, heavily loaded bearings. In a large bearing, thermal distortion can produce movement at the joints in the runner that are greater than the fluid-film thickness, which could produce bearing failure.

A number of different manufacturer's thrust bearing types are available, such as the General Electric spring type, Kingsbury self-equalizing type, Kingsbury adjustable shoe type, and Siemens spring type. These thrust bearings will not be discussed because all have proved to be satisfactory, other than to note that the adjustable types require some means, such as strain gauges, to properly adjust the bearing during initial installation of the generator. Project maintenance personnel have expressed doubts about the usefulness of permanently installed strain gauges after the machines have undergone successful initial operation. A General Electric spring type bearing is shown on figure 8-1.

Bearings in machines that will undergo rotation reversals such as generator/motors and pump motors, which may be exposed to reversal following loss of power, have special considerations. In these machines pivoted-shoe thrust bearings have the pivot placed at the center of the pad. Theoretically, a pivoted bearing with a center pivot would not work because an oil film wedge should not develop between sliding members. Practically, they do work, apparently because uneven thermal gradients in the shoe cause deformation of the shoe surface and a hydrodynamic film results. Rotation reversal—from pumping direction to generating direction—is of concern because theoretically, hydrodynamic oil film does not exist at low or zero speed. Features that direct the flow of lubricating oil must be designed to function correctly—regardless of direction of rotation.

The upper-guide bearing is frequently located in the same oil reservoir with the thrust bearing in a suspended machine, and the outer perimeter of the thrust block may be machined to become the guide-bearing journal. A completely separate reservoir, journal, and support assembly may be furnished for each of the bearings. Forces from the upper-guide bearing are transmitted through the upper-bearing bracket to the foundation. The maximum force to be transmitted through the guide bearing is usually assumed to be the result of a faulted generator field wherein one-half of the rotor poles are shorted, which results in maximum rotor UMP (unbalanced magnetic pull).

The generator lower-guide bearing is supported on a bracket that is placed on a ledge immediately below the stator. Normal lower-guide bearing loading is not necessarily the same as that for the upper-guide bearing, but maximum loading is usually the same (faulted rotor). Generally, the lower-guide bearing is located in the same reservoir with the thrust bearing in a modified machine, and similar to the suspended configuration. The outer perimeter of the thrust block may be used as the lower-guide bearing journal.

The thrust bearing normally operates fully immersed in the lubricating oil, and the guide bearings normally operate partially immersed. The guide bearings are designed so that the portion of bearing surface above oil will be lubricated by normal shaft motion which causes a pumping action of the oil.

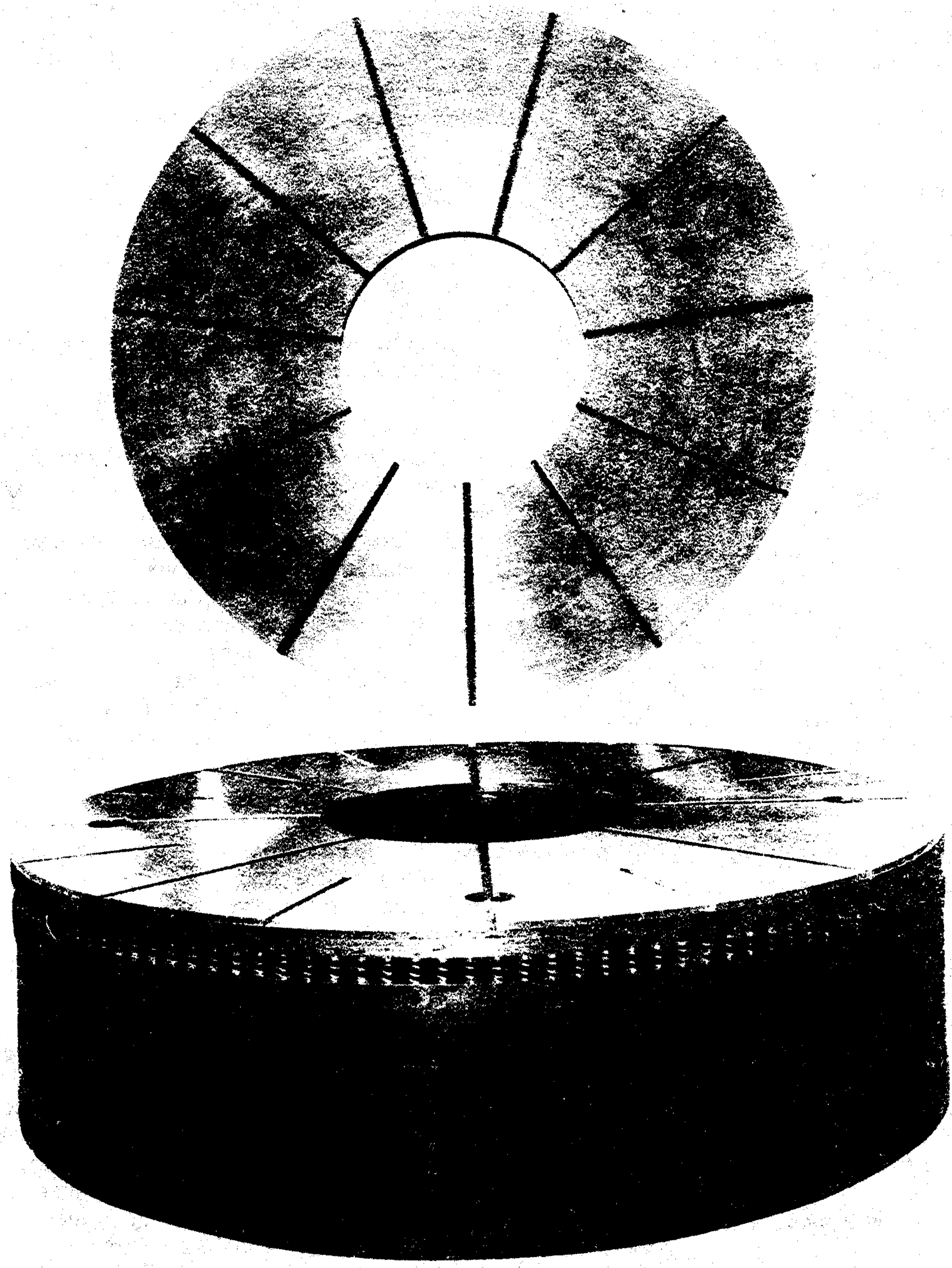


Figure 8-1. — Spring-type thrust bearing [88-in diameter (224 mm)] for load of 1,800,000 lbf (816 metric tons). Hoover Powerplant — one of two vertical a-c waterwheel generators, 82,500 kV•A, 150 r/min, 13,800 volts, 50 Hz, or 180 r/min, 16,500 volts, 60 Hz, type ATI-W, 40-pole. Courtesy of General Electric Company.

Neither the intermediate bearings between the generator lower-guide bearing and the turbine guide bearing, nor the turbine guide bearing itself will be discussed in this section. It is noted that these bearings have a critical effect on successful machine operation. A shaft critical speed analysis must include these bearings and their loadings.

8.2.5 Lubrication

Bearing lubrication has four major functions to:

1. Provide a fluid film that separates the sliding or rolling elements of a bearing,

2. Act as a coolant to remove heat generated in the bearing,

3. Protect the bearing from water, dirt, or other contaminants, and

4. Prevent corrosion.

The lubricant has a controlling effect on the bearing's life and load-carrying capacity as well as an impact on the operating efficiency of the machine. All lubricants can be categorized roughly into three generic types: (1) fluids, (2) greases, and (3) solid films. Hydrogenerators use only the first two types. (Greases are used only in small units with rolling element bearings.) Hydrogenerator fluids are all oils and described as: "slippery hydrocarbon or silicone compound liquids." As a semisolid material, grease is a combination of a lubricating fluid and a thickening agent. Fluids (oils) have several advantages over the greases:

- Ease in filling and draining
- Ease in maintaining proper level
- Efficacy in transferring heat
- Improved operation by extending temperature range
- Efficiently fills all bearing areas
- Effectively carries away contaminants

Grease offers the following advantages over oils:

- Easily contained in a bearing housing because does not flow readily
- Reservoirs and seals are simpler
- Less maintenance because a fluid level is not maintained
- Seals the bearing better than oil to keep contaminants from bearing

Oils exhibit many properties and characteristics; their limitations are described by the ASTM (American Society for Testing and Materials) Standards [3]. Of the many oil characteristics, perhaps the most important is viscosity because it determines the oil's load-carrying capability, bearing operating temperature, and friction loss. Other important oil characteristics that must be considered are:

- Useful life
- Flammability characteristics
- Deterioration products
- Foaming tendency
- Stability
- Volatility
- Compatibility with other oils for replenishment or replacement

The Bureau's policy is to purchase machine lubricating oil having a viscosity specification between 315 and 355 SSU (seconds saybolt universal) at 100 °F (38 °C). Machine purchase specifications state these viscosity limits in addition to the requirement that the bearing be designed to operate successfully with an oil meeting these limits. Deviation of viscosity above or below the specified limits may cause increased heating or reduce load-carrying capability of the fluid film. Therefore, using viscosity modifiers or additives is not recommended unless the bearing is so designed.

As previously stated, the fluid or lubricating oil leaving the bearing sliding surfaces transfers heat generated at the bearing interface. The heated oil is collected and conveyed to the reservoir by grooves, baffles, and ducts. Then, the cooled oil from the reservoir reenters the bearing interfaces.

In smaller machines, heat may be removed from the oil by ventilating air flowing over the bearing housing. Larger machines are equipped with oil-to-water heat exchangers, as discussed in section 8.2.6. A novel system—which may be proprietary—of bearing heat removal was used for the 600-megawatt generators at Grand Coulee Third Powerplant. In addition to the customary oil-to-water heat exchangers, in the bearing oil reservoirs, cooling water was supplied directly into the thrust-bearing shoes. Heat was removed very close to the source of its generation, and lower temperatures resulted at the bearing surfaces. Since the bearing interface temperatures were lower, the oil viscosity remained higher and the load-carrying capacity was improved. As a result, the bearings were loaded to about twice the amount considered practical for conventional bearings.

After the lubricating oil leaves the thrust bearing, its flow is mostly the result of centrifugal action from the bearing runner. Various baffles are provided in oil reservoirs to limit the meniscus effect from centrifugal action and to control the direction of flow. However, the shape of the meniscus and the motion-induced turbulence varies not only because of baffles but also because of different temperatures and loadings. Engineers have long sought for a device to accurately measure the oil level in the reservoir during operation. Because of the irregular and time-dependent varying surface of the oil during normal operation, and because of machine vibrations, their efforts have not been too successful. However, oil levels can be measured accurately while the machine is at rest and the quantity of oil determined. The oil level can fall below acceptable levels due to oil leakage and can rise above acceptable levels if water leaks develop in the heat exchangers. Also, it is possible to install electrodes at the bottom of the reservoir that will sound an alarm if water forms a conductive path between electrode terminals. These devices are most effective at machine standstill when water begins to collect in pools.

Thrust- and guide-bearing reservoirs function normally at atmospheric pressure. In the event of a fire, pressure produced by releasing carbon dioxide might enter the reservoir from the machine air housing and distort the oil surface. As a result, bearing damage could occur, or the pressure could force oil from the reservoir—perhaps along the shaft. Bureau specifications require a unit designed to prevent such an occurrence.

8.2.6 Accessories

The Bureau of Reclamation and many others use a system of "high pressure lubrication" for large machine thrust bearings. This system is intended to prevent bearing failure due to absence of fluid film during machine startup and shutdown. The system may be used during rotation reversal on pumping-generating units or large pump motors. The system has an external pump that injects oil under high pressure directly between the thrust-bearing sliding members. The point of injection is usually a circular groove cut into the face of each bearing shoe surface. The groove is supplied with oil through passages, in each shoe, and connected by flexible tubing to a supply manifold. The high-pressure pump creates a fluid film between the bearing sliding members and maintains this film until machine speed is sufficient to create a hydrodynamic film, or until machine comes to a complete stop. Bearings that depend on an external pressure supply are called "hydrostatic." Since the high-pressure lubrication pump is turned off at higher machine speeds, the thrust bearing changes from a "hydrostatic" type at lower speeds to a "hydrodynamic" type at higher speeds. The high-pressure lubrication system offers many advantages including a nearly zero starting friction, reduced wear, and the capability to carry heavy loads at low speeds. However, this type of system is expensive—requires complicated piping and connections—and is bulky to install.

Bureau specifications require that the thrust bearing be capable to withstand a machine start or stop without damage to the bearing and without benefit of the high-pressure lubrication pump. Primarily, this requirement is intended to permit stopping the machine following a failure of the high-pressure system. Starting also should be possible without the high-pressure system, but interlocks normally would be used to prevent such a start.

The thrust bearing shoes may adhere to the runner during rotor jacking, if not restrained, and become displaced from their proper support. Bureau specifications require a design to prevent the shoes from raising with the runner.

Many machines are equipped with a "creep detector" that sounds an alarm if turbine gate leakage is sufficient to overcome bearing friction and/or brake restraining action. The creep detector may be connected to start the high-pressure lubrication pump and forestall bearing failure resulting from low speed rotation. If gate leakage becomes high enough to start unit rotation, and high-pressure lubrication is applied to save the bearing, friction would be further reduced and rate of acceleration increased. To prevent brake or brake ring damage, brake air pressure must then be released. Brake release would cause an even further increase in rate of acceleration. If permitted to continue, uncontrolled unit speed would occur and major damage could result. However, gate leakage may be balanced by rotational friction and windage; that is, speed may not become high enough to cause concern.

Common practice for starting smaller and larger machines, without activating the high-pressure lubrication pumps, is described as "dropping" and "slugging." Dropping is a procedure where upon the machine hydraulic jacks are used to raise the rotating parts before starting. Oil flows between the thrust-bearing shoes and runner to thoroughly wet the surfaces. When ready to start, the jack pressure is released and the rotating parts permitted to "drop." Approximately 30 minutes will elapse before the oil between the bearing surfaces will be squeezed out, and rotation is accomplished during this time. Slugging is a procedure that follows dropping, where the turbine wicket gates are moved suddenly from their closed position to fully open or nearly so. The resultant rush of water through the turbine, at standstill, tends to slightly lift or float the rotating parts. The oil then flows between bearing surfaces, and bearing damage upon dry surfaces is avoided. Such operating practice is not available to maintain the fluid film during deceleration except to apply the brakes and bring the unit to rest as quickly as possible. Most thrust bearing failures have occurred during shutdown rather than during startup.

Vertical-shaft machines—with bearings above the rotor—and horizontal-shaft machines, particularly those with pedestal bearing mounts, are equipped with insulation to prevent flow of electrical current through the bearing. The source of this current may be the electrical potential resulting from unbalanced magnetic fields, or may be ripple voltages from static exciters induced through the field. If the current flow is not prevented by insulation, the flow can quickly destroy a bearing. The resistance of the lubricating fluid cannot be considered to be sufficient to provide the required insulation. The flow of current passes through the machine shaft ("shaft current"), the stator frame and ground, and back to the shaft.

The normal location for installing insulation is at one bearing pedestal (if present) on horizontal-shaft machines or in one bearing shell. Vertical-shaft machine bearings are insulated if they are placed above the rotor. A suspended machine would then have an insulated upper-guide bearing and an insulated thrust bearing. The insulation is installed in two layers separated by an intermediate layer of steel. This construction facilitates measurement of insulation resistance during rotation while avoiding a situation where a single layer of insulation could be temporarily shorted by a resistance measuring instrument.

Large machine bearing oil reservoirs are equipped with oil-to-water heat exchangers. Usually, the heat exchangers, or coolers, are located inside of each oil reservoir of the machine and are supplied with cool water through a piping system. Exhaust water conveys the bearing waste heat to plant drains. Supply water is usually pumped to the bearing reservoir rather than using penstock pressure. This arrangement allows operation of a generator as a synchronous condenser when the penstock is unwatered. Some bearing oil coolers are located outside of the bearing reservoir.

Location of a cooler external to the oil reservoir presents a problem for the designer as to how to accomplish oil flow through the cooler. The most obvious solution is to use an oil pump to force the oil through the cooler; however, this is not encouraged because it would probably make successful operation of the entire machine dependent upon the oil pump. Bureau specifications require that the bearings be capable of operating at normal speed and rated load for 15 minutes following the loss of cooling water. Machine starts are prevented if cooling water is not available. A second option for establishing oil flow through an external bearing cooler is to use shaft motion to pump the oil. This option is workable; it prevents machine operation being dependent upon an auxiliary.

Hydrogenerator bearings, with occasional exceptions for small machines, are equipped with RTDs (resistance temperature detectors) to facilitate remote monitoring of bearing metal temperatures. The bearings are equipped with thermometers for indication of lubricating oil and bearing cooling water temperatures. The bearing cooling water pressure is monitored and alarms are provided to annunciate potential trouble due to loss of cooling water supply. Devices are provided to shutdown the machine upon excessive bearing metal temperature or loss of cooling water pressure. Bearing oil reservoirs are equipped with float switches to indicate oil levels and to function as a starting interlock. Machine startup is prevented if the oil level is too high (perhaps due to a cooling water leak into the oil reservoir) or if the oil level is too low (perhaps from an oil leak). Float switches also are connected to shutdown an operating machine upon high- or low-level indication, but this practice has met with limited success, as noted in section 8.2.5.

8.2.7 Summary

Rolling-element bearings are well suited for applications where limited space, high load, low speed, constant load, precise centering control, or a need exists to start under full-load conditions.

Plain bearings are well suited for applications where long life, low noise, increasing load with increasing speed, short-time overload, or shock conditions exist. An externally pressurized plain bearing will exhibit the lowest starting friction of either a rolling-element or plain bearing.

It is possible to more precisely position a shaft with a rolling element bearing than with a plain bearing. The running position of a shaft controlled by a plain bearing may vary under different load conditions, but normally will be within acceptable limits for salient pole hydrogenerators. The small airgap in induction generators may demand use of rolling-element bearings.

A universally "best" bearing arrangement does not exist. Each arrangement offers advantages and disadvantages that should be carefully considered for each different job. A judicious evaluation should be made for each application to optimize plant structure costs, machine initial costs, and operational constraints. Usually, information is available from various manufacturers that will assist the plant designer to achieve the best choice. Regardless of the arrangement selected, a shaft critical speed analysis with the turbine wheel connected—and disconnected if condenser operation is planned—should be performed.

Complete details of expected bearing operating conditions should be stated in purchase specifications. These details should include: starting and stopping data, speeds, time durations at different speeds, lubricant characteristics, cooling water volume, pressure, high and low ambient temperatures, and any unusual features known to the plant designer.

Bearing lubricants should be carefully considered. The lubricant that the bearing is designed to use must be maintained within acceptable limits. The use of lubricating oil additives should be avoided, unless their intended use is made known to the bearing designer.

By using a high-pressure thrust bearing lubrication system, many of the problems experienced in the past will be avoided. This system will encourage greater use, including plants with smaller machines, as system automation and remote control becomes more widespread.

Presently, a completely satisfactory method to detect abnormal bearing lubricant levels during machine operation has not been developed. It is noted that the capacitance probe liquid-level detector used at Grand Coulee Third Powerplant shows considerable promise.

8.3 BEARING BRACKETS

8.3.1 Introduction

The bearing brackets of a hydrogenerator perform the vital function of supporting the bearings that control the position of the rotating parts of the machine. These brackets form the structural link between rotor and stator to complete the generator framework. In a small horizontal machine, the brackets may be called "end bells" or a separate pedestal mount for each bearing may be used. Most vertical-shaft hydrogenerators are equipped with an upper-bearing bracket and a lower-bearing bracket. The upper-bracket supports the thrust bearing and guide bearing in conventional suspended machines, and the lower-bracket supports only the lower-guide bearing. The lower-bracket supports the thrust bearing and lower-guide bearing in modified and umbrella machines. Modified and umbrella machines that do not have an upper-guide bearing are equipped with a structural steel framework for support of air-housing cover plates and other equipment at the top of the machine. The framework does not provide significant support to the stator. Bearing brackets in close-coupled machines are located to suit the location of guide bearings, and the vertical loads are not supported by generator brackets.

The upper-bearing bracket in suspended conventional size generators usually derives both vertical loading support and radial support from the generator stator frame. Additional radial support, to counteract the forces of unbalanced magnetic pull, may be required in large machines. This may be accomplished by furnishing structural concrete around the machine and providing extensions from the upper bracket arms to this concrete.

Regardless of type of machine (suspended, modified, or umbrella) the lower bracket is mounted separately from the generator stator frame on the plant foundation. The same is true for close-coupled machines if they are equipped with a generator lower-guide bearing. The brackets are keyed or doweled, bolted, and matchmark to their foundation mountings.

8.3.2 Functions

The bearing brackets of a vertical-shaft machine perform the following functions—many also are applicable to horizontal shaft machines:

- Support entire vertical weight of turbine and generator rotating elements and unbalanced hydraulic thrust during operation and standstill
- Withstand radial forces (unbalanced magnetic pull and mechanical imbalance)
- Transmit torque caused by braking
- Assist in maintaining stator circularity
- Provide structure and support for bearings and bearing lubrication reservoirs
- Support for rotating exciter (if applicable)
- Provide foundation for brakes and lifting jacks
- Support collector assembly and field leads
- Provide framework for air housing cover plates
- Support a variety of pumps, motors, controls, detectors, pipes, conduit, wiring, and other machine accessories
- Provide ducting for cooling air to generator rotor

The bearing bracket that supports the thrust bearing must provide sufficient stiffness to support the machine rotating parts during all operating conditions. Rotational stability can be destroyed by excessive springing or flexing of the bracket.

Both the upper and lower brackets must support the forces incident to maximum unbalanced magnetic pull on the rotor as well as normal rotational forces. Thermal expansion and contraction of the stator frame does not occur simultaneously with, or at the same rate as, the bracket. Because the lower bracket is not attached to the stator frame, thermal expansion forces acting on the upper bracket are not the same as at the lower bracket. Also, the restraining forces exerted by the upper bracket on the upper part of the stator frame are not present at the lower part of the stator frame.

8.3.3 Construction

The bearing brackets are fabricated from steel-plates, and are precision machined at the connection to the hubs and at the points of connection to the stator frame or foundation plates. The brackets may be of radial-arm construction or of the bridge-type. A radial-arm bracket is, as the name implies, one in which the bracket arms radiate from the center of the machine to the stator frame or foundation. A bridge-type bracket has continuous steel beams that span the entire machine, usually in the shape of the letter H. The bearing housing would be located at the cross-bar of the H. A radial arm bracket is shown on figure 8-2 and a bridge-type bracket is shown on figure 8-3.

Small diameter machines may be constructed with bridge-type brackets for both the upper and lower bearings. The H structure may be strengthened by additional lateral legs from the sides of the H to the stator frame. Medium- and large-size machines of the suspended type will usually have a radial-arm upper bracket and a bridge-type lower bracket.

Designers of medium- and large-capacity machines will usually select a radial-arm bracket to improve machine stability for heavily loaded brackets that support the thrust bearing. Therefore, machines having the thrust bearing below the rotor generally will have radial-arm lower brackets. These machines usually have large diameter stators, and the machine designer also will select radial-arm construction for the upper bracket if an upper bearing is present.

Generally, the bracket arms are handled as a complete assembly—by the plant crane—after initial assembly. The "set-down" space required for these bracket arms is considerable, and the plant design must include suitable storage provisions during times when the generator is disassembled. Disassembly of the brackets to facilitate storage is a possibility; however, the requirements for machined surface protection, and precision fitting and realignment of components make this option difficult.

The lower bracket must pass through the stator bore during disassembly. Although it may be

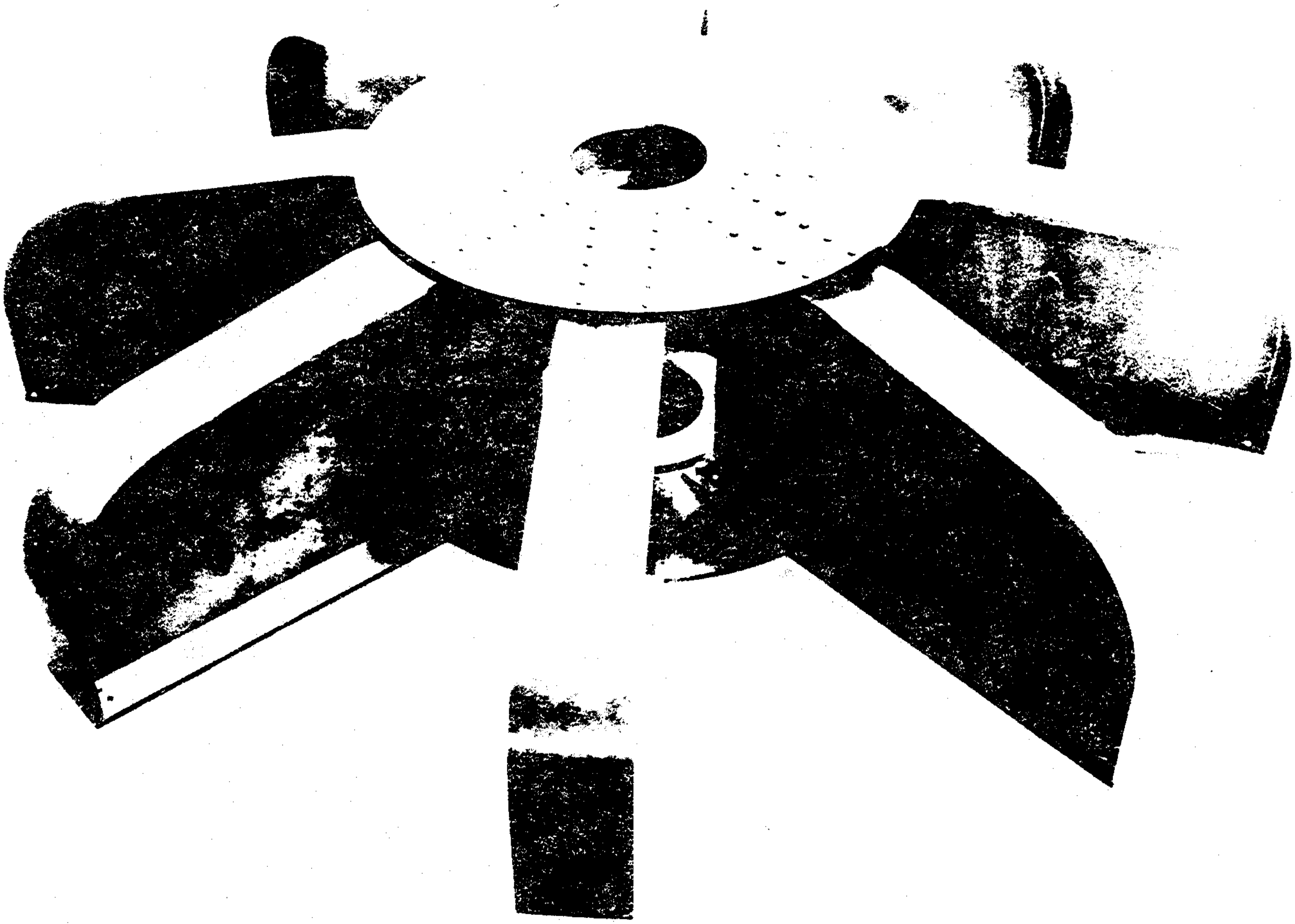


Figure 8-2. — Upper bearing bracket for a generator. Hoover Powerplant 82,500-kV•A generator.

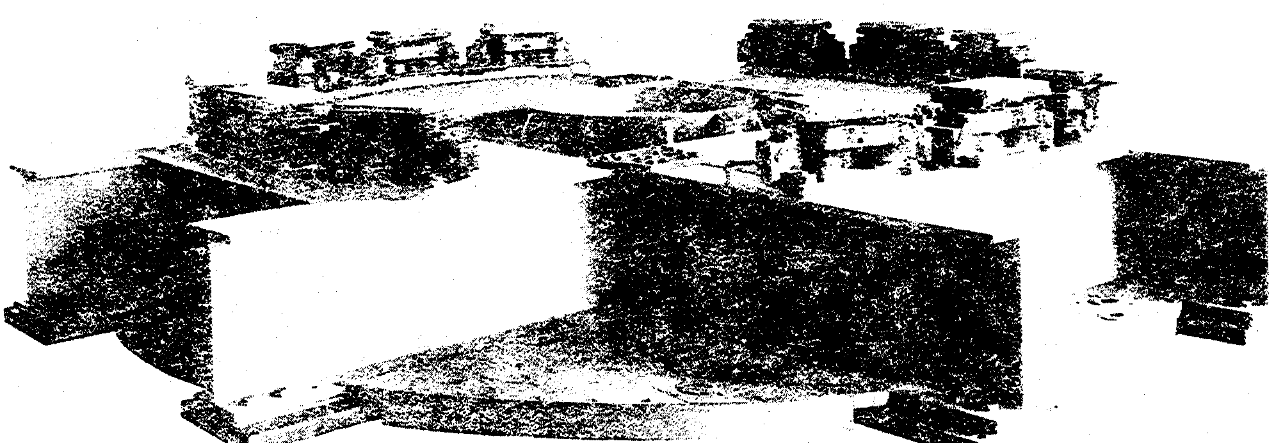


Figure 8-3. — Lower bearing bracket for a hydrogenerator. Bracket with combined brakes and jacks, brake piping, lower-guide bearing support, and air baffle for one of two vertical a-c waterwheel generators. Hoover Powerplant — 150 r/min, 13,800 volts, 50 Hz, or 180 r/min, 16,500 volts, 60 Hz, type ATI-W, 40-pole. Courtesy of General Electric Company.

possible to fabricate the bracket so that it could be partially disassembled to facilitate removal, the concern for proper realignment discourages segmental construction. As a result, the bracket is usually mounted on a ledge above the turbine pit, leaving a foundation opening for the turbine pit that has a smaller diameter than the stator bore. Various concepts have been tested that would increase the diameter of the opening below the generator to allow the turbine designer more latitude in designing the turbine head cover. Conceivably, the pit diameter could be increased up to the stator bore diameter. Unfortunately, these concepts sacrifice the integrity of the lower-bearing bracket; consequently, a successful plan has not been developed.

Disassembly procedures for suspended generators usually require a sequence of: (1) upper bracket, (2) rotor, and (3) lower bracket. To accomplish this sequence, it is necessary first to transfer the rotor's weight from the upper bracket. Following removal of the thrust block and other components of the upper-guide and thrust bearings, the upper-bearing bracket is removed. To remove the rotor from the machine, it is necessary to pass the generator shaft coupling through the lower-bearing bracket. Therefore, the lower bracket configuration must be such as to allow removal of the shaft coupling flange through the bracket.

The lower bracket also is used to mount the brakes. The torque exerted by the rotor on the bracket during shutdown—reaction to inertia and gate leakage—and the torque exerted by wicket gate leakage after shutdown may be considerable. The bearing bracket and its foundation must be capable to withstand these forces. Jacks, mounted on the lower-bearing bracket, are used to transfer the weight of the turbine and generator rotating parts from the thrust bearing to the lower-bearing bracket; therefore, the bracket must be suitable for supporting the entire weight of this assembly.

8.3.4 Instrumentation, Operation, and Maintenance

Bearing brackets are not instrumented and control features are not provided for them. Inspection of bracket condition is performed at routine intervals in addition to special inspections following major machine faults. Particular attention must be given to the condition of bracket interfaces with hubs and foundations. Evidence of looseness, corrosion, distortion, or movement must be thoroughly investigated and the cause corrected.

8.3.5 Summary

A machine's bearing brackets are an important part of its structure. In addition to their prime function for supporting bearings, the brackets provide several other major functions. Although the brackets are static in nature, their functions are vital to machine operation. Therefore, the design and construction of the bearing brackets must be carefully considered; inspections must be performed at intervals (and also as required) to ensure their integrity.

8.4 SPIDER AND RIM

8.4.1 Introduction

The hydrogenerator's rotor is made up of several components including shaft, bearing runners, field poles, amortisseur winding, spider, rim, and accessories. This section discusses the spider and rim. The reason for combining these two components is that in smaller machines these two components may actually be furnished as one assembly. Although this literature describes hydrogenerator spider and rim assemblies, the matter here also applies to large synchronous pump motors and pumping-generating machines. This section does not address induction generators, although many considerations for synchronous machines are equally applicable to induction machines.

Synchronous hydrogenerators are invariably salient pole machines, and some means must be provided to support individual poles. This is in contrast to a smooth-rotor machine—such as a steam powered turbine-generator—where the field winding is installed in slots cut into the rotor. One method for supporting the field poles of a salient-pole machine is by mounting each pole on a radial arm or member attached to the generator shaft. More often, the poles are attached to a rim of metal which, in turn, may be attached to the shaft by spokes. The spokes are called "spider arms;" an assembly of arms is the "spider."

Field inspections have revealed rotor configurations with skewed field pole mounting. Review of manufacturers' drawings and discussions with manufacturers indicate that the skew was not intentional, and the cause for the skew have not been determined. Skew in armatures is a relatively common design, and a preliminary study indicates that field pole skew could produce about the same electrical effects as armature skew—depending on the amount of pole skew. Normal salient-pole rotor design includes field poles installed in-line and parallel to the rotor shaft, without skew. Induction generator rotors are normally designed with skew.

Most hydrogenerators are of vertical-shaft construction which is the specific concern here. However, many features in vertical-shaft machines are equally applicable to horizontal- and inclined-shaft machines. The reader is encouraged to recognize where differences might occur and to develop reasoning as to how those differences can be addressed. Small capacity installations offer the most frequently found occasions where a nonvertical shaft machine is the best choice. These small capacity machines also do not require many of the features required for larger machines.

8.4.2 Functions

The functions of a hydrogenerator rotor and spider-rim assembly are:

- Transmitting torque from machine shaft to field poles
- Locating and securing field poles inplace and furnishing structural support for the poles
- Supporting structure for field leads
- Producing machine ventilation
- Furnishing the major part of required WR^2 (rotating inertia) for complete turbine–generator unit
- Providing a magnetic material path for the pole-to-pole flux
- Functioning as a stable assembly capable of retaining a centered, cylindrical configuration at all machine loads and speeds
- Transmitting combined turbine and generator rotating parts load to foundation when load is removed from thrust bearing at standstill
- Furnishing structural support for brake ring and jack pads
- Mounting devices for balancing weights

8.4.3 Features and Construction

8.4.3.1 ***Small Generators***.-Small generators are frequently horizontal-shaft machines and many of the features in larger machines are not required or included. The rotors may be made from machined castings or forgings and may provide the functions of the shaft, bearing journals, and pole supports.

The application of castings and forgings is usually limited to high-speed, low-capacity machines, or to only part of the spider of larger high-capacity machines. Machining costs can become prohibitive; the problem of material flaws make application of large castings or forgings impractical. Shipping size restrictions also limit the size of castings and forgings. In practice, castings (or forgings) may provide the functions of both spider and rim, or a separate rim may be attached to a forged or cast spider. If the generator shaft is not included as part of the spider casting, the casting is heat-shrink and keyed to the shaft.

Small generator spider-rim construction may be of the "flat-plate" or "punched-plate" design. This design provides the functions required of the spider and rim by using an assembly made up of disks or "plates" of steel. The disks have been punched to provide a center hole for the generator shaft, holes for bolting a stack of plates together, and openings that will form keyways and dovetails in an assembled stack. The openings may be punched to form spokes of metal in an assembled rotor. The punched disks (plates) are stacked to form a laminated cylinder, pressed, and then bolted together. Thence, the assembled, laminated rotor may be drilled, reamed, and machined to dimension, thereupon, heat-shrink and keyed to the machine shaft.

Field poles are attached to the rim using dovetail slots formed in the rim and matching dovetails on the pole bodies. Keys are inserted into the slots to firmly fasten the poles in place. In some small capacity low-speed machines, the poles are attached to the rotor by bolts that pass through the rim; currently, the Bureau has not permitted this type of design. Field leads, for small machines, may be installed directly from the collector rings to the field poles—with minimal support from the spider and rim.

Small generator ventilation may be provided by fan blades attached to the rim or to the field poles, or by a fan mounted separately from the spider-rim assembly.

Requirements for WR^2 may be met by mounting a flywheel separately on the generator shaft to supplement the inertia already provided by the rim-spider-pole assembly.

Small generators usually do not have provisions for jacks to provide support for the rotating parts during extended downtime. If required, a braking system may be mounted separately on the shaft to eliminate the need for provisions on the spider and rim.

8.4.3.2 *Large Generators*.-The rotor spider assembly for large generators is composed of arms that are fabricated from steelplates, or combinations of forgings, castings, and welded steelplates. The spider is attached to the shaft by hub-bolts fitted into reamed holes in the spider arm and shaft hubs, or if a cast or forged spider hub is used, the spider hub may be keyed and heat shrunk to the shaft. All loading, other than vertical, is transmitted through hub-bolt and/or key shear. A rotor spider formed from a solid casting is shown on figure 8-4 and a fabricated steelplate spider is shown on figure 8-5.

The rotor rim is supported vertically by radial ledges machined at the bottom of the outer end of each spider arm. Tangential forces are transmitted between arms and rim by keys installed along the vertical face of each arm. The rim is formed by laying segmental arcs of sheet steel to form a ring and then adding additional rings in staggered, successively stacked layers. Each arc, or "lamination," is punched to provide for installation of spider-to-rim keys, rim bolts, and rim-to-pole dovetails or T-slots. The top and bottom rings of the segmental arcs are formed from much thicker steelplate than the intervening laminations. These thicker plates, sometimes called "press-plates," are used to distribute rim-bolt clamping pressure more evenly to the intervening rim laminations. Laminations, partially stacked on a spider, are shown on figure 8-6, and a fully stacked rim is shown on figure 8-7.

The objective of the laminated rim construction is to obtain as much structural homogeneity as possible rather than to reduce eddy currents. Only a small amount of alternating magnetic flux reaches the rim; therefore, reduction of eddy current losses is not a major concern for rim design.

The rim may be stacked as one continuous cylinder or it may be made of several cylinders or "doughnuts," with spacers between doughnuts to facilitate flow of ventilating air. These spacers also may function as fan blades. The laminations may be pressed together at intervals during the stacking process to improve final rim assembly. After the stacking has been completed, the laminations are pressed to compact the rim as much as practical; then, rotor rim bolts are installed axially through the holes formed in the laminations.

Some designs include reaming the rim bolt holes and installing fitted bolts. This design is considered superior to the clearance-fit-bolt-in-formed-hole configuration. This design is discussed in section 8.4.7.

Pole bodies are attached to the rim by dovetails in the formed dovetail slots. Some designs use two dovetails per pole instead of one; others use T-slots instead of dovetails. Historically, Bureau specifications have restricted designs that propose using bolts-in-tension in any part of the rotor that may be subject to centrifugal forces; this restriction has been interpreted to include designs contemplating a bolted attachment of pole to rim. It is possible that a design proposing attachment of poles to the rim by bolts—with load forces carried through bolt shear—could be proposed. Fatigue failure is a common cause of failure in bolts loaded in tension and vibrations of considerable magnitude are quite common in hydrogenerators. This possible type of failure led to the Bureau's restriction against bolts-in-tension in rotating parts.

Keys are installed in the dovetail slots to prevent any relative movement between pole body and rotor rim. Blocks are welded at the dovetail slot ends to prevent movement or loosening of the dovetail keys.

The assembled rotor's concentricity is of paramount importance and careful attention to detail must be given during rotor assembly. Inelastic or plastic growth of the rotor following initial rotation and subsequent overspeed testing is normal. If this growth changes the concentricity and/or cylindrical shape of the rotor, some action to correct or compensate for the change may be necessary. Rebalancing is a common practice to compensate for mechanical changes to the rotor resulting from overspeed.

Elastic growth of the rotor, as speed and temperature increase from minimum to maximum, is a standard design consideration of machine manufacturers. The airgap at standstill is not the same

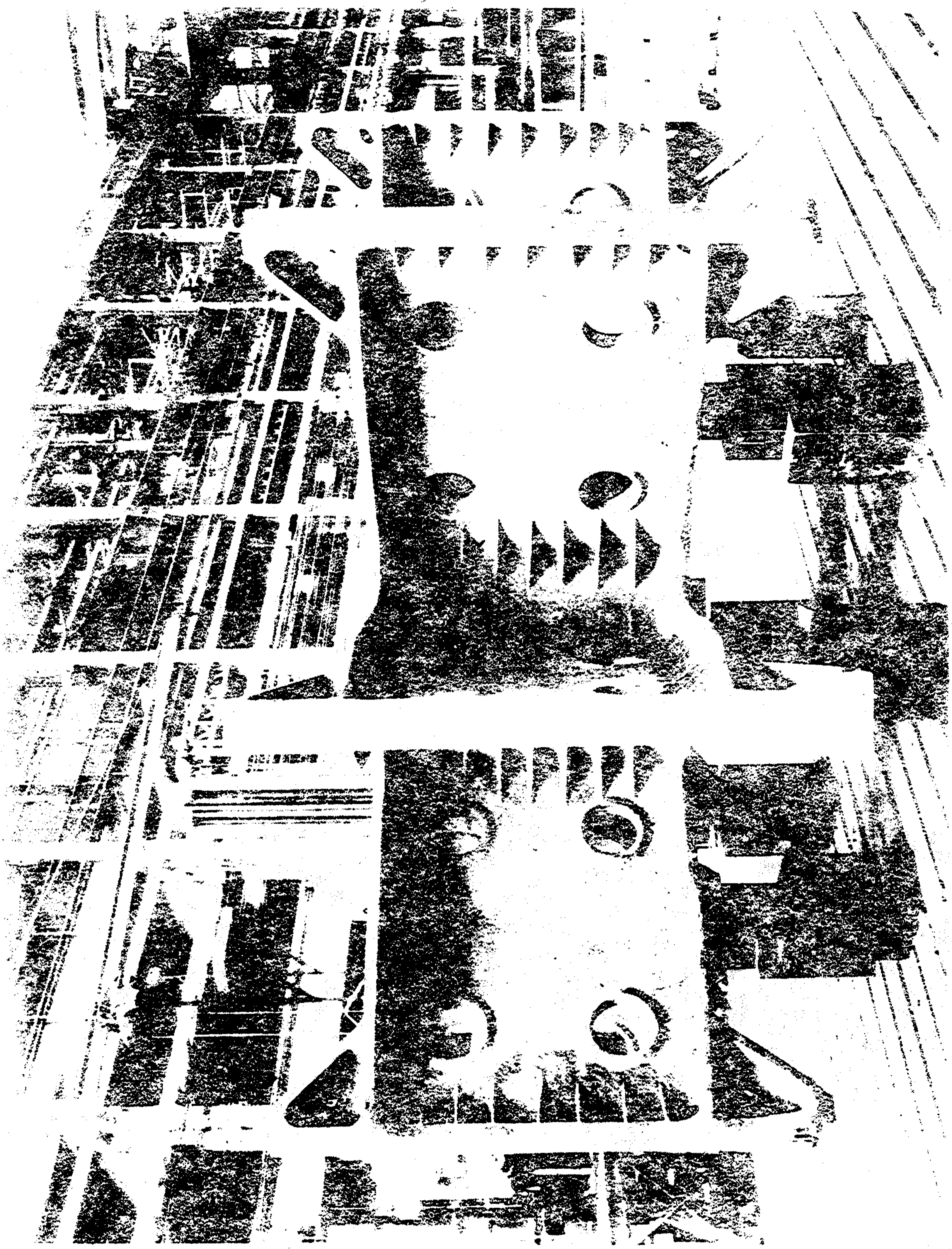


Figure 8-4. — Rotor spider consisting of a solid steel casting. Courtesy of Westinghouse Corporation.

as the gap at rated speed. A significant design concern is the possibility of looseness developing in various parts of the spider, rim, and poles resulting from elastic rotor growth. Deterioration can progress to an unacceptable point, as a result of component looseness at operating speeds, despite relative tightness of the component at machine standstill.

Special attention must be given to rotor imbalance produced by UMP (unbalanced magnetic pull). The UMP forces can be many times the magnitude of those produced by mechanical imbalance; furthermore, they are not necessarily in the same location or direction as the forces resulting from mechanical imbalance. The UMP varies with electrical conditions existing in the stator and rotor. The UMP may act to move or shift the poles and rim with respect to the shaft and spider; moreover, the resulting mechanical imbalance may then aggravate the UMP-produced imbalance. The rim-spider movement may change or correct itself when rotation is stopped. This phenomenon is of particular concern in a machine having a "floating rim" at or near rated speed. Attempts to compensate for UMP-produced imbalance using weights may meet with little success because of the varying nature of UMP. The most successful countermeasure for UMP is a precisely centered and cylindrical rotor—rotating at rated speed—in a precisely centered and cylindrical stator, with uniform and balanced magnetic circuits, and uniform and balanced electrical loading. This idealized concept is practically impossible to achieve, but to strive for it is a worthwhile goal.

8.4.4 Accessories

The following paragraphs are about devices and accessories provided on the spider and rim as well as special features that may be required for some specific machines:

(1) *Field lead mounting*.-This may be in the form of bus pedestal insulators or cable clamps.

(2) *Ventilating air fan blades and air routing baffles*.-Fanning action for the ventilating air may be achieved by centrifugal action of the spider arms or by separate fan blades. The fan blades may be: point-of-attack contoured castings in unidirectional rotation machines, angularly mounted flat blades, radially mounted flat blades, or other blade configurations. Fan blade in bidirectional rotation machines (e.g., generator-motors) present design limits that are not a concern with unidirectional rotation. Multispeed machines also present special fan-blade design problems. Since the windage loss

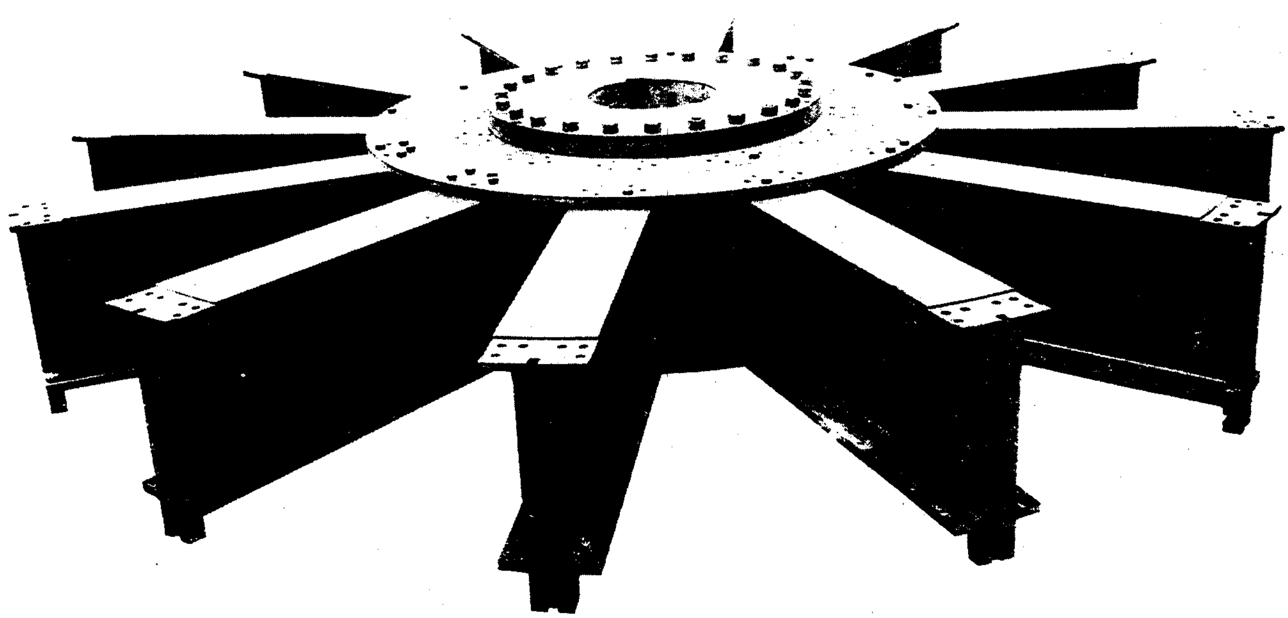


Figure 8-5. — Rotor spider composed of fabricated-steel radial arms attached to a cast hub. Assembly for type ATI-W-72, 16,667-kV•A, 100-r/min, 13,800-volt, 60-Hz vertical waterwheel generator. Courtesy of General Electric Company.

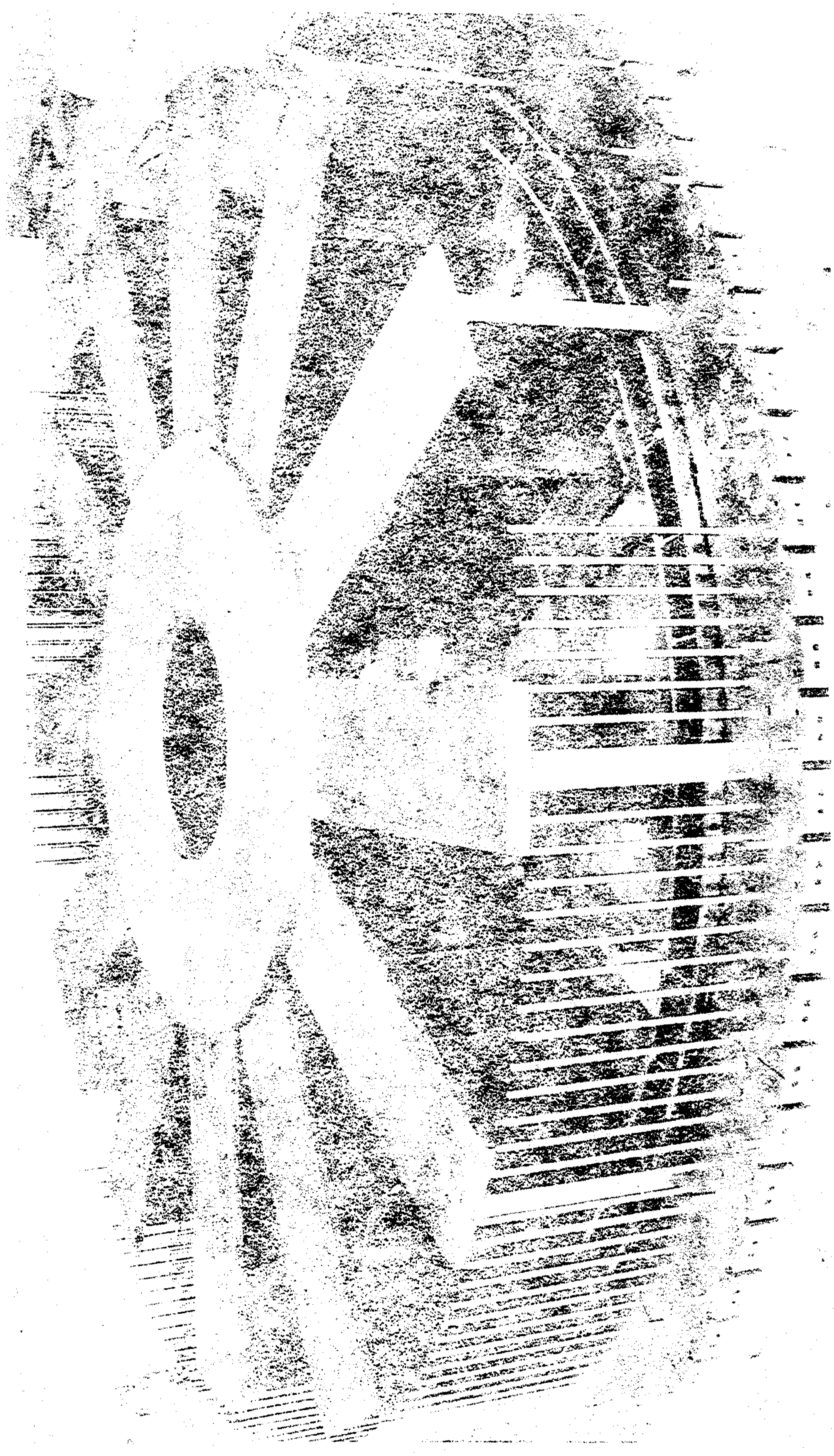


Figure 8-6. — Rotor rim partly assembled on rotor spider. One of two vertical a-c waterwheel generators, 48,000 kV•A, 75 r/min, 13,800 volts, 60 Hz, three-phase, type ATI-W, 96-pole, during installation (April 19, 1937) — hydroelectric power station at Bonneville Dam, Columbia River. Courtesy of General Electric Company.

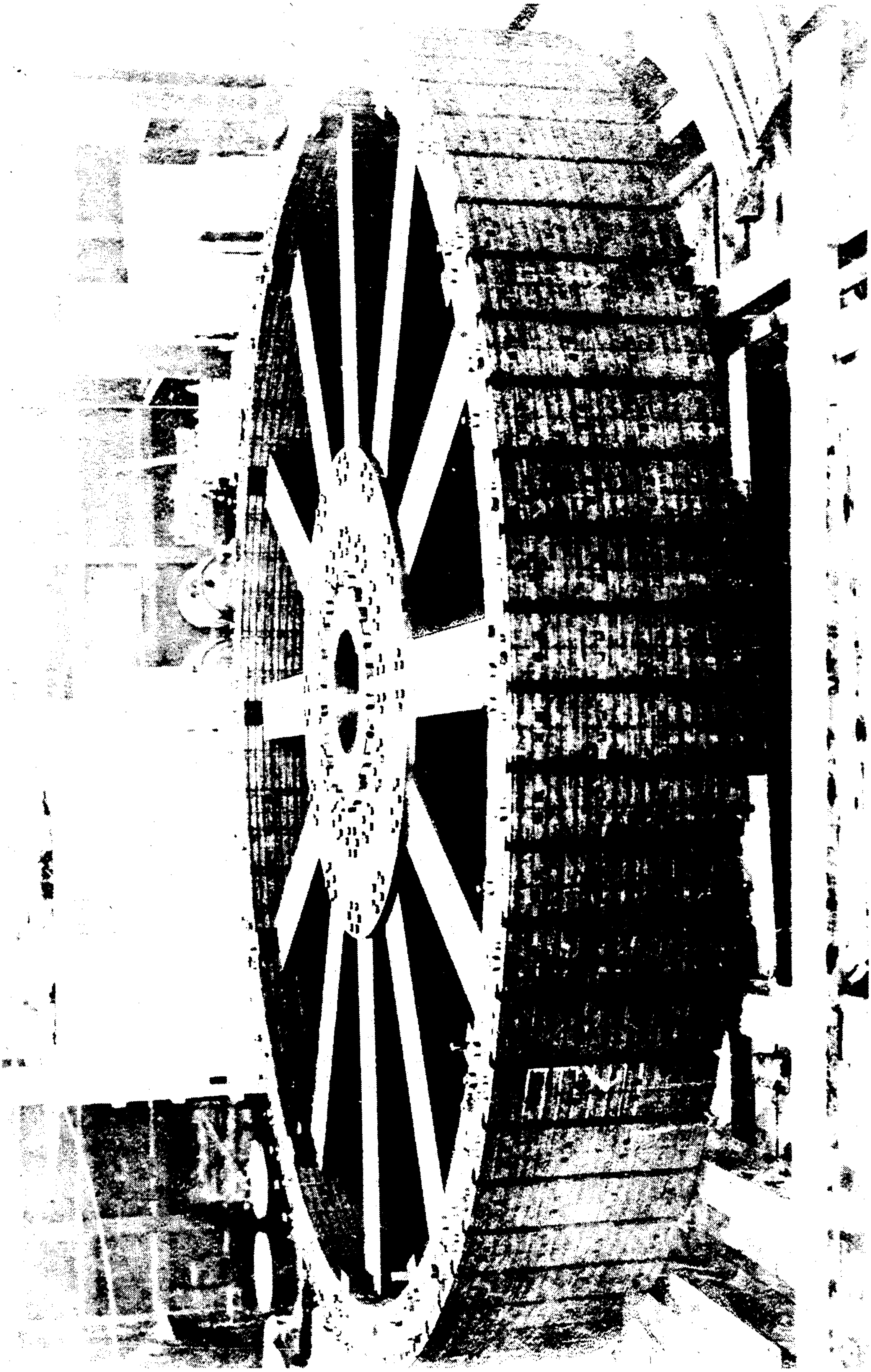


Figure 8-7. — Rotor spider and fully stacked laminated rotor rim. Assembly for type ATI-W-72, 16,667-kV•A, 100-r/min, 13,800-volt, 60-Hz vertical waterwheel generator — at Washington Electric Co., Rock Island Development. Courtesy of General Electric Company.

in a machine is a major factor in determining generator efficiency, the fan blade design is significant.

The ventilating fan blades may not be mounted on the spider-rim assembly. Small machines frequently have a fan assembly mounted separate from the rotor and mounted on the machine shaft; and machines with short axial cores frequently have the fan blades mounted on or between the poles.

Usually, longer cores demand a more uniform distribution of air along the length of the field poles and stator windings than can be achieved with either separate fan blades or pole mounted fan blades. As a result, fan blades mounted on the rim are sometimes used at the top and bottom only or placed between the rotor rim laminations (doughnuts). Rotor rims assembled with spaces between lamination rings, formed by spacers, permit air to flow through the rim and thus achieve a much more uniform distribution of cooling air.

Machines designed with "rim ventilation," where cooling air passes through the rim, may have special features such as baffles and louvers attached to the spider to control the flow of cooling air and reduce losses.

(3) *Brakes and jacks.*-The brakes and jacks, including their location on the rotor, are discussed in section 8.13. The brake-ring segments and jack pads—if separate from brake ring—are usually bolted to the bottom of the spider arms. A design used by several manufacturers uses a ring of steel made up of segmented arcs bolted to the lower edge of the spider arms at the outer ends of the arms. The ring may extend outward radially from the ends of the arms to lay partially under the rim. This design provides a location for the brakes and jacks, effectively under the rim, while not requiring attachment directly to the rim.

Manufacturers may choose separate locations—radially—for the brakes and jacks. Normally, this will move the brakes outward toward the rim and the jacks inward toward the shaft (see sec. 8.13). As the jacks no longer operate against the braking ring, proposals have been made for individual jacking pads on each spider arm. It should be noted that the rotor will seldom come to rest at the same location; the jack pads on the arms may or may not come to rest over a jack. When the jack pads do not coincide with jack locations, manual intervention to move the rotor to a coincident location is necessary. This physical effort to move the rotor may be unacceptable.

(4) *Balancing weights.*-The ideal location to attach balancing weights cannot be determined until after the rotor is completely assembled. Maximum balancing effect can be achieved with any given weight by placing the weight at the greatest radial distance from the shaft. Since this location would be coincident with, or between, pole locations a compromise in radial distance is required. The next most practical radial location for most rotor designs is immediately next to the inside diameter of the rotor rim.

Historically, Bureau specifications have required provisions for attaching balancing weights as close as possible to the rotor rim. Thereupon, the logical location is on the spider arms because attachment directly to the inside surface of the rim, without damage to the rim, would be difficult to accomplish. Field drilling or welding on the arms would pose special problems and concerns for damage to the structural integrity of the spider. Therefore, Bureau specifications require each spider arm to be drilled for possible attachment of weights. This allows weights to be installed or removed from any arm after the rotor is assembled and installed in the generator—without modification or damage to the arm. If possible, the required weights should be distributed so that the total weight on any arm is evenly divided between the top and bottom of the arm.

(5) *Lifting devices.*-Generators that require rotor field assembly and disassembly usually will require handling of a complete rotor by lifting devices attached to the generator shaft. This facilitates simultaneous rotor and stator erection and reduces the downtime for future maintenance work. It is possible that special considerations for handling such as overall weight, crane lift height, or other reasons may make separate handling of rotor components an attractive option. Should a special consideration arise, lifting beams and other devices would have to be provided for the spider and rim. Rim distortion during handling would be of great

concern, and special precautions would be required if it becomes necessary to handle a rim when separated from its spider.

8.4.5 Shipping and Assembly

Complete fabrication and assembly of a generator spider and rim in the manufacturer's plant is preferred. This option is practiced for small and some medium size machines. As machine size increases, the problems associated with shipping and handling become insurmountable, and field erection of the rotor is required. Separate shipping of an assembled spider and rim (from both shaft and poles) has been a feature of some machines.

Various procedures for shipping and assembly of spider and rim will be required by different manufacturers and for different machine constructions. Most frequently, a choice is made that includes an erection bay in the plant and a crane capable of handling a completely assembled rotor.

Assuming that the rotor construction is of the fabricated spider, stacked-lamination rim type most frequently found in large field-erected machines—and that the rotor is erected in a rotor erection bay—the following general sequence of shipping and assembly events could be expected:

1. Spider arms and/or hubs are factory fabricated and shipped as individual components. Pilot holes are drilled where the spider arms will attach to the shaft hubs. Rotor rim laminations are factory punched and shipped in bundles. Other rim-spider components, such as brake ring segments, are shipped as separate components.

2. Following placement of the shaft on an erection pedestal, the spider arms are placed on the hub and the bolt holes in the hub and spider arms are reamed. Then, the hub bolts are fitted and fixed in the reamed holes.

3. Lower rim press plates are placed on the assembled spider arms and rim laminations are placed on the plates in rings, with joints between the laminations staggered to avoid the joints in underlying rings. Separate supports may be required for the rim during stacking.

4. Thence, rim is compressed and rim bolts installed.

5. If the rim is of the heat-shrink type, heaters are used to expand the rim, and keys installed to fix rim to spider.

6. After the rim has cooled, poles are installed using the dovetail or T-slots formed in the rim, and keys are driven to fix the poles tightly to the rim.

7. Accessories such as field leads and brake rings are installed while the spider and rim are in the erection bay.

The extra-large machines at Grand Coulee Third Powerplant do not have shafts that pass through the rotor spider. These machines have stub shafts that are attached to the rotor. Therefore, the above typical procedure does not apply to extra-large machines like those at Grand Coulee.

8.4.6 Plant Considerations

The spider and rim assembly of small generators may not require any special plant considerations because the entire generator may be handled as one assembly. However, as the generator size increases, handling the spider and rim becomes significant. The rim is the heaviest part of the entire rotor; if combined with the spider, the assembly constitutes the major part of the heaviest lift required by the plant crane; that is, the heaviest weight would be a completely assembled rotor.

Obvious savings in plant costs can be realized by eliminating rotor erection bays, and by reducing crane lifting capacity requirements with associated structural support requirements. These potential savings must be balanced against requirements for increased erection time and difficulties encountered in erection, maintenance down-time, and revenue loss.

The most frequently selected plant configuration includes one rotor erection bay, an overhead crane capable of handling a completely assembled rotor, and the capability to pass an assembled rotor by or over other operating units. This plant configuration permits simultaneous erection of stator and rotor, thus minimizing erection time, and permits complete rotor removal to facilitate maintenance work.

Plant layouts requiring spider and rim assembly inplace in the stator have been considered. This plan offers reduced initial costs by eliminating the requirement for a rotor erection bay, reducing crane lifting capacity requirements, and by reducing plant width requirements for passing the rotor over or by other units. Other plans have contemplated provisions for future turbine work to be accomplished without rim-spider removal from the stator bore, and for pole removal from the rim to accommodate stator work.

Some plans have been considered that envision removal of the poles from the rim, and then removal of the rim from the spider-shaft assembly. This procedure would reduce crane capacity requirements. Successful removal and subsequent reinstallation of the rim on the spider would be an extremely demanding accomplishment. Deformation of the rim would be a high possibility, and reestablishment of rim-spider concentricity and cylindrical shape would be most difficult to achieve.

A rotor rim-spider set-down space in a plant, separate from the rotor erection area, is an attractive option that has been considered for multiunit plants. This option facilitates simultaneous work on several units.

8.4.7 Characteristics and Performance

Bureau specifications limit maximum stresses in the spider and rim, when subjected to forces resulting from maximum normal operating conditions, to one-third of the yield strength or one-fourth of the ultimate tensile strength of the material. Maximum normal operating conditions would include load rejection, but not runaway speed considerations. Specifications limits are also placed on materials in the spider-rim assembly that do not have a well defined yield point. Unit stresses in the rim and spider resulting from forces associated with runaway speed are limited to two-thirds of the yield point. The rationale, for these specifications limit differences, is based on the concept that load rejection is a normal event; whereas acceleration to runaway speed can only result from an abnormal event such as equipment failure.

The overspeed testing of a generator is performed as a part of normal commissioning procedures for two reasons:

1. To ensure generator's capability to successfully withstand the forces resulting from runaway speed, and
2. To produce inelastic (or plastic) rotor rim growth up to the point where all clearances between rim bolts and rim laminations have been removed.

This procedure is necessary before final wedging, keying, mechanical centering, and balancing can be properly accomplished. Rebalancing after inadvertent subsequent acceleration to runaway is regarded as good practice. Rim construction using clearance fit of rim bolts will experience considerably more inelastic growth than a construction using reamed bolt holes with fitted rim bolts. Therefore, reamed holes with fitted bolts is the preferred construction. Centrifugal force will move the laminations outward, with only interlaminar friction resisting the centrifugal force, until all laminations rest against the rim bolts. Bolt shear then resists further movement, and the rim becomes stable. Concern has been expressed by some industry individuals that these forces can be sufficient to cause the laminations to cause indentations in the rim bolts, and thus impede efforts to disassemble the rim. However, the Bureau has never had any reason to disassemble a rim, and it is difficult to foresee a reason to do so. Therefore, bolt deformation as a result of lamination movement has not been a Bureau concern.

Normally, the rim will experience elastic growth, which occurs as a result of centrifugal, thermal, and magnetic forces.

Two concepts of rim design exist for large hydrogenerators. One is the floating-rim concept, wherein the rotor rim separates from the rotor spider at some speed; the other is the shrink-fit rim, wherein the rim remains tightly fixed to the spider at all speeds. As rotor diameters increase like those in extra-large generators, designs more frequently envision rim "float" to occur at some speed. Some designs contemplate a floating or non-shrink rim-to-spider fit at rotor standstill.

The compressive forces of the rim on the spider at standstill can be enormous if rotor-rim shrink is required to persist up to and above rated speed. This would require a massive spider just to resist these compressive forces. Capability to retain shrink at all speeds above rated speed can create an unrealistic requirement of spider strength. The fact that maximum UMP may not exist—because excitation will be reduced in the field when rotor speed rises above rated speed—dramatically reduces the value of shrink retention above rated speed. For this reason, rim designs for large diameter rotors usually do not require rotor-rim shrink to be retained above 105 percent of rated speed.

The floating-rim design contemplates separation of the rim from the spider at some speed. As rotor speed increases, the rim expands—due to centrifugal, thermal, and magnetic forces—and moves away from the spider arms; and the spider's capability for retaining rim circularity is lost. The capability of the rim to retain its circular form is then dependent only upon the inherent hoop strength of the rim. This hoop strength is determined by the radial thickness or depth of the rim and in the manner that the rim is assembled.

The UMP-produced rim ellipticity occurs in a different fashion than ellipticity produced by mechanical imbalance. Magnetic pull will increase as the distance between two magnetically attracted bodies decreases. Thus, the magnetic pull between the stator and the major axis of the elliptical rotor will increase as the axis increases, and the amount of ellipticity will be further increased as a result of the reduced distance to the stator. As a result of UMP, a slight eccentricity of the rotor can suddenly become a large eccentricity. To conclude from this discourse, rotor designs that incorporate a floating rim at rated speed or below, require special attention. The rim's inherent capability to retain circular shape is extremely important, and will determine whether satisfactory operation of the generator is possible. Problems with circulating currents, split-phase currents, loose wedges and stator windings, stator core buckling, rotor-stator contact, and many other problems have all been traced to UMP-produced ellipticity of floating rims.

Rotational stored energy of a hydroturbine-generator unit is expressed as the "inertia constant," or "H-factor," and is derived from the equation:

$$H = \frac{0.231 \times 10^{-6}(WR^2)(\text{r/min})^2}{\text{kV•A}_{\text{rated}}} \qquad (1)$$

Typical values of H in equation (1) range from 0.5 to about 5.4, with the higher values associated with large, low speed machines. This H-factor is a major characteristic in determining machine performance in both the hydraulic and power systems. The rated kV•A and r/min (kilovolt-amperes and revolutions per minute) factors in the equation are determined by other considerations—leaving only WR^2 as a variable factor that designers can use to obtain required performance.

Turbine-generator required WR^2 is usually determined from two considerations: (1) the governor time as balanced against penstock pressure change, and (2) power system stability. Short governor times have the disadvantage of higher penstock pressure rise, while offering advantages of better load following ability and reduction of speed rise following load rejection. Increased WR^2 tends to offset the advantages of short governor time. Power system stability is improved by higher WR^2 by using the stored energy to ride through system faults. However, a power system designer has options other than WR^2 to improve system stability.

The turbine contributes only a small part of the total unit WR^2. Of the generator's contribution of total WR^2, the shaft and spider contribute only a small part, and the field pole configuration is determined by other considerations. Therefore, the rotor rim is the major source for overall machine WR^2, and is virtually the only component that machine designers can adjust to achieve different required values of WR^2. Curves showing estimating data for normal generator WR^2 are shown on figure 8-8.

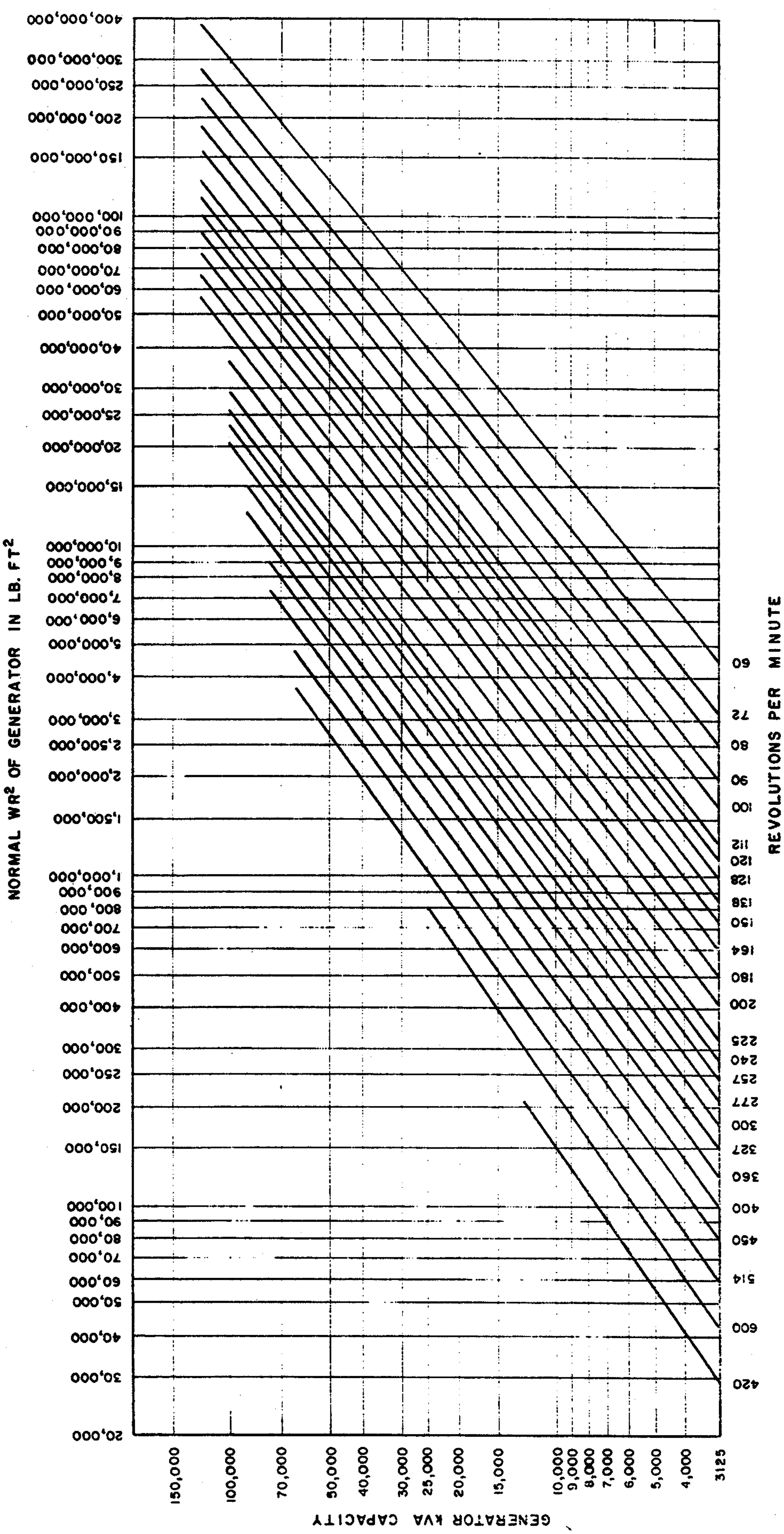
A generator of any given capacity and speed will have a "normal WR^2" that is the result of structural, magnetic, and electrical requirements of the generator. This normal WR^2 is a factor in the size and weight of the generator, and a principle determinate in the generator's cost. The value of WR^2 for any given machine can be increased to as much as three times its normal value if required. An equation for WR^2 from the Bureau's Engineering Monograph No. 20 [4] is:

$$WR^2 = \frac{356{,}000\ (\text{kV•A})^{5/4}}{n^{3/2}} \quad \text{(inch-pound units)}$$

$$WR^2 = \frac{15\,000\ (\text{kV•A})^{5/4}}{n^{3/2}} \quad \text{(SI units)} \qquad (2)$$

where:
WR^2 = product of weight of revolving parts and the square of the radius of gyration, and
n = rotational speed.

The generator designer should design the rim to place the mass at the maximum possible radius



These curves were plotted from manufacturers' data

Figure 8-8. — Generators — normal WR^2 for various generator capacities. Dwg. 104-D-316 of gyration to minimize thrust bearing load and required crane capacity. The thrust bearing friction loss increases with increasing rim weight; excessive increase in rim mass (to achieve required WR^2) can produce reduced generator efficiency and increased bearing bracket size to support the weight. The maximum rim radius is limited by other machine constraints—including rotor peripheral speed and dynamic rotor expansion. The required WR^2 for any given rotor rim diameter may produce a relatively thick, or thin, rim when compared to the overall rim diameter. This relative rim thickness will, in turn, impact the rim's dynamic stability. Thus, an optimized design of rotor rim mass and diameter is necessary.

8.4.8 Tests

The machine manufacturer will conduct a variety of tests on the spider and rim during the factory manufacture and field erection period. These tests will be used to determine material and assembly quality and may include flaw detection, compression, bolt tension, circularity, concentricity, and other tests. These tests are not covered directly by Bureau of Reclamation specifications.

Turbine-generator commissioning tests usually include an overspeed test, to demonstrate machine capability to withstand the forces resulting from overspeed, and to produce initial inelastic expansion of the rim (see sec. 8.4.7). High bearing temperatures following this test may be indicative of test failure. Further balancing tests should follow the overspeed testing.

Acceptance testing of the generator should include tests that will examine the characteristics and performance of the spider and rim. These tests are not intended to identify spider and rim contributions separately from the rest of the rotor structure. These tests are described under IEEE Standard 115-1983 [5], and include the following:

1. A test for windage loss of spider and rim that actually tests friction and windage loss of the entire generator. These losses are not distinguished as to their sources.

2. A short circuit test that determines the capability of spider and rim to withstand forces resulting from an armature short circuit, in addition to other machine considerations. The ability of the spider and rim to successfully pass this test is usually determined by visual inspection after the test. Unusual vibration during subsequent machine operation may be indicative of a test induced problem.

3. Generator efficiency testing to provide a means for checking the manufacturer's calculated values of WR^2.

8.4.9 Maintenance and Inspection

Generator spiders and rims are not instrumented and special control features are not provided. Generally, maintenance is limited to cleaning dust and debris which may collect inside the rim and between the rim and the pole bodies attached to it. Contamination inside the rim can reduce flow of ventilating air through the rim; contamination between the rim and pole bodies can accumulate to the extent that field winding insulation is jeopardized.

Maintenance inspection and corrective action should be performed to recognize the preceding conditions. Also, inspections should be conducted to determine presence of fretting corrosion (particularly at keys, dovetails, hub bolts, and rim bolts), component distortion, and any movement breakage or looseness in all parts of the spider and rim assembly.

Caution: These conditions, if found, can be indicative of far more serious problems.

8.4.10 Summary

The rotor and spider rim assembly of a generator performs many vital supporting functions, and contributes directly to machine performance. The spider and rim design and construction are complex despite their relative simple appearance. The performance of the spider and rim is dynamic and may change for different operating conditions.

Careful consideration of spider and rim requirements must be used during all stages of plant design, machine specifications writing, machine design and construction, and operation.

8.5 FIELD POLES, FIELD, AMORTISSEUR, AND COLLECTOR RINGS

8.5.1 Introduction

This section will not address the many theoretical concepts governing alternating current generator fields because the reader should be familiar with the theories and have an understanding of their relationships. In this regard, some theoretical considerations may be oversimplified to more directly address a subject. Most discourse here will be equally applicable to salient poles found in synchronous motors and generator/motors.

This section discusses salient-pole synchronous generator field considerations that may be of importance from the viewpoint of a powerplant designer, machine applications engineer, machine specifications writer, reviewer of machine manufacturer's design, or possibly a failure forensics expert. All hydro-synchronous machines are of salient-pole construction, as opposed with round-rotor or smooth-rotor construction, due to the inherent low speeds associated with hydraulic turbines and pumps. Nonsynchronous induction generators will not be discussed.

8.5.2 Functions

The function of the field to supply generator excitation is fundamental, but the importance of the field cannot be overstated. The magnetic flux produced by the field is the link that converts the rotating mechanical energy produced by the turbine to electrical energy. Without the magnetic field, turbine power cannot be transmitted to the electrical power system. In general, as the airgap flux produced by the field becomes stronger, the tie between the hydraulic and electrical systems become stiffer. The shock absorbing or damping effect present with low field current will be decreased as field current increases, and disturbances present in one system will be more readily transmitted to the other system.

In addition to the real (active) power produced by the turbine, the field also controls the imaginary (inactive or reactive) power generated by the machine. Loss of excitation in a generator not only separates the real power produced by the turbine from the power system, the power system must then also supply reactive power required by the armature of the unexcited generator. (Excitation supply and control are discussed in sections 8.10 and 8.11, respectively.)

The turbine speed—determined by hydraulic constraints—dictates generator speed. Small capacity, low-head installations may use turbine speed increaser gears to produce higher output shaft speeds. This feature allows the designer to take advantage of the benefits of higher speed generators, although at a sacrifice in efficiency by gear losses. The turbine rated speed dictates the number of generator poles required:

$$T_s = \frac{120f}{P} \tag{3}$$

where:

T_s = turbine rated speed in revolutions per minute,
f = system frequency in cycles per second (hertz),
120 = a constant that converts time in seconds, as used in f to minutes; and to recognize that two-field poles are required for each full cycle: (2 poles/cycle) × (60 s/min), and
P = number of poles.

For a 60 hertz system equation (3) becomes:

$$T_s = \frac{7200}{P} \tag{4}$$

Some pole configurations (namely, 54 and 108 poles) do not allow the machine designer the required latitude for selecting the number of armature circuits. Consequently, machines requiring 54 or 108 poles become both difficult to design and expensive to build. Normally, speeds associated with these pole numbers are avoided.

Field pole magnetic, electrical, and structural requirements determine the physical proportions of the pole. Since the magnetic, electrical, and structural requirements of the pole are fixed by other restraints, the machine designer will not be able to meet requirements for more than normal machine inertia (WR^2) by varying field pole design (see sec. 8.4).

Most field poles are furnished with a damper or amortisseur winding installed in the pole face. The functions of this winding are primarily to provide a damping action to reduce effects of electrical power system and hydraulic system disturbances, and to suppress harmonic voltages. The winding also provides additional starting and synchronizing torque for motor starting. Normally, generator load changes are not considered to be power system disturbances; nevertheless, the amortisseur winding will react to decrease the time of power angle oscillation following a load change, and thus improve machine performance. Pole face heating caused by eddy currents produced during transient conditions is reduced because of the reduced time that the transients exist.

8.5.3 Features and Construction

Because of the pole face proximity to the generator armature, varying fluxes are present in the pole body (particularly at the pole face). Therefore, it is necessary to provide a pole body construction that will minimize the effects of eddy currents. This is accomplished by constructing the pole body using thin laminations of magnetic material. Usually, the laminations are not furnished with an insulating paint or varnish like that used on the stator core laminations. The oxide film created when the sheets, from which the pole body laminations are punched, are hot-rolled usually provides sufficient interlaminar insulation. It should be noted that cold-rolling of magnetic sheet material does not create the oxide film, and an insulating paint or varnish must be applied.

The lamination punchings are stacked and bolted together to form the pole body. The overall length of the stacked pole body may be about 10 percent longer than the gross axial length of the stator core. Features of a pole body are:

1. Dovetails for attachment of the pole to the rotor rim must provide all of the support necessary to resist all forces acting on the complete pole assembly. It is not reasonable to assume that every lamination in the pole body will share an equal portion of the forces acting on the pole. Even the most careful stacking of the rotor rim and pole body laminations, and the most rigorous keying procedures, will not produce uniform load bearing. Therefore, an "overdesign" of the attachment is necessary to compensate for incomplete contact at the dovetails.

2. Pole end plates are added at both ends of the stack of laminations to distribute the compressive action from the bolts. These end plates are of necessity much thicker than the laminations. As a rule, the plates are constructed so that they do not protrude as far into the airgap as the rest of the pole face. The increased distance from the armature reduces problems associated with eddy current heating. Also, the position of the plates is usually above and below the stator core. Despite these efforts to reduce eddy current heating effects, problems with excess heat in pole end plates have been fairly common. One method used to alleviate such problems has been to cut grooves into the airgap surface of the end plates. Small generators may use rivets rather than bolts to clamp the pole laminations.

3. A shoe at the generator airgap end or face of the pole is used to resist centrifugal forces acting on the field winding. The face of the pole is formed by the shoe. The curved surface of the pole shoe will not be such as to produce the same airgap all the way across the pole face; that is, the pole face is constructed with a different radius than the generator airgap. The leading and trailing ends of the shoe will produce a larger airgap than will be found at the center of the shoe. This construction substantially reduces the production of harmonics.

4. Holes for insertion of an amortisseur winding are located at the pole face, usually in a manner that part of the surface of the installed amortisseur bars is exposed in the airgap. This is done to place the amortisseur as far as possible into the airgap, thus giving it maximum exposure to the fluxes present.

A sleeve is placed around the pole body where the field winding encircles it, and a collar is placed to separate the winding from the pole shoe to electrically insulate the winding from the pole body. This sleeve may be cemented to the pole body. A second collar is placed around the base of the pole body between the field winding and the rotor rim for additional electrical insulation. This second collar may be omitted for pole construction of the type where the field winding is bonded to the pole body. A typical pole body having no sleeve or collars is shown on figure 8-9.

In addition to electrical insulation, the sleeve and collars must provide a rigid mechanical support for the field winding. Centrifugal and magnetic action places tremendous compressive forces on the outermost collar, and the innermost collar must provide a snug fit between the field winding and rim to prevent field winding movement on the pole body.

If the sleeve or collars should fail and electrical contact between field winding and pole body

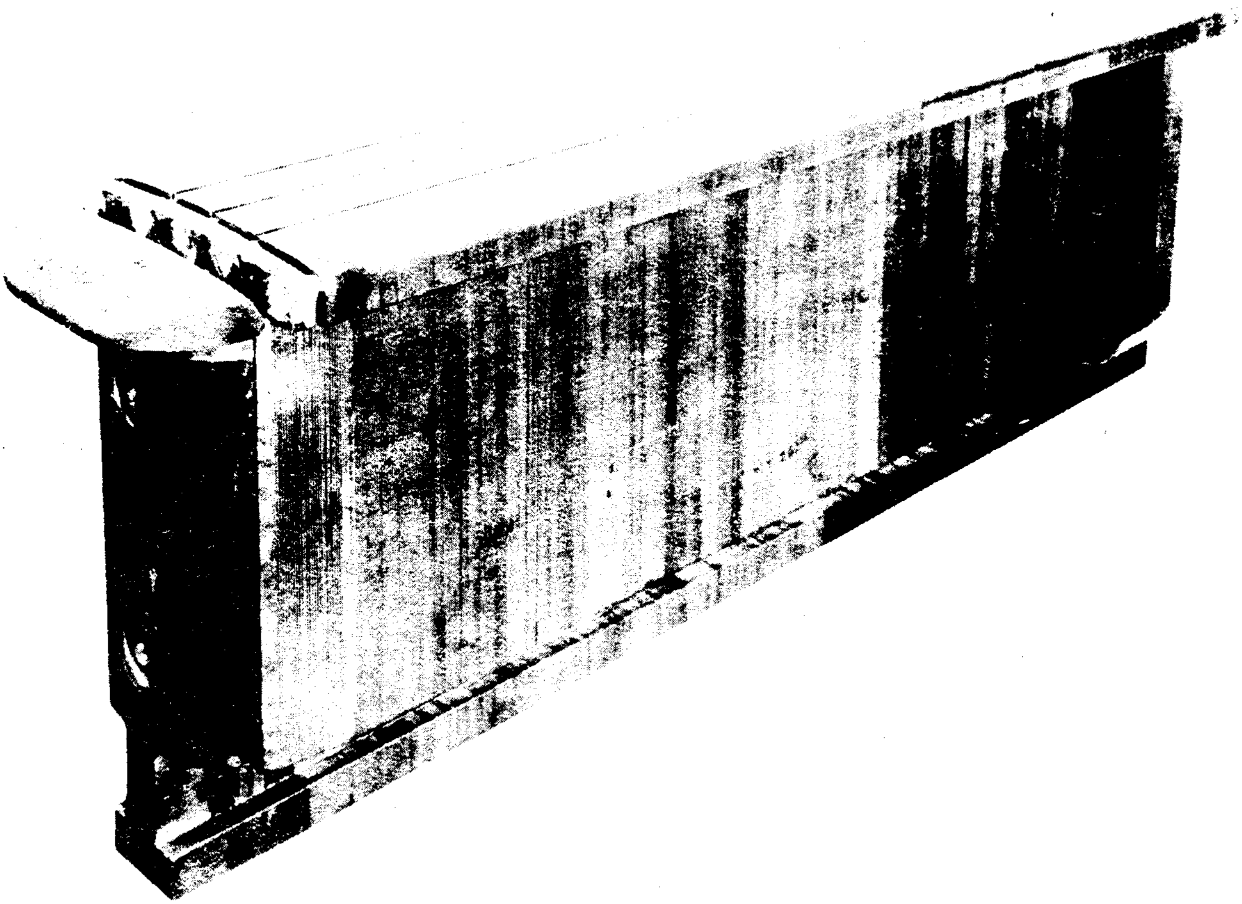


Figure 8-9. — Typical field pole body with amortisseur winding. Courtesy of General Electric Company.

occurs, the possibility of excessive UMP forces acting on the generator becomes a serious reality.

The field winding is made from copper strap and form wound edgewise in either a single or double layer. Insulation is cemented between the layers of copper—leaving the surface of the formed coils exposed to improve cooling. The copper strap is painted to retard corrosion and to reduce the possibility of failure due to bridging of the insulation. This possibility is particularly strong in areas where the installed field pole winding adjoins the rotor rim. Debris may accumulate on surfaces of the rim and pole in areas where the cooling air velocity is low, which makes bridging possible. Bureau specifications require an application of paint because some manufacturers will leave the copper surface bare. The manufacturer must take into account the heat insulating properties of the paint during the winding design.

The field winding is placed on the pole body, over the pole body sleeve, and may be cemented to the sleeve and the collar at the pole shoe. Poles constructed with the winding cemented to the body are described as having "bonded construction." The direction of placement of the winding on the pole body is reversed for one-half of the poles on the machine to achieve opposite directions of coil winding and polarity. If pole construction is such that the winding can be removed from the pole body without damage (nonbonded construction), the polarity of a field pole may be reversed by removing the winding, inverting it, and replacing it on the pole body. Polarity of a pole cannot be easily changed if the windings are bonded to the pole body; spare poles must be obtained for each polarity when required. A typical field winding is shown on figure 8-10.

During operation, breakage of the field winding

Figure 8-10. — Typical generator field coil. Courtesy of General Electric Company.

insulation between layers of copper winding is fairly common. Fragments of insulation may be missing or found migrating outward from the poles. Some maintenance procedures have involved an application of paint or cement to retard further migration or loss of insulation. These procedures do not recognize the probability that the paint or cement will not penetrate to—or provide insulation for—all areas where insulation has been lost. It should be noted that winding turn-to-turn faults are a possibility, particularly when centrifugal forces are acting on the winding at rated speed and voltage. Also, a winding turn-to-turn fault may exist at rated speed and voltage and then disappear as the machine comes to rest.

The magnetic imbalances produced by field turn-to-turn faults and the attendant vibrations can be very destructive to the machine. In addition, the field-short produced magnetic imbalances can cause serious problems in the electrical power system. The machine must be constructed to survive failures of this nature, with minimum impact on other equipment in the plant and power system. Therefore, field winding insulation breakage evidence should be given serious attention even though insulation tests at standstill reveal no breakdown. The replacement of a winding showing physical evidence of insulation failure can be considered good preventative maintenance.

Field insulation levels are quite low when compared to armature windings. Field voltage levels are typically 125, 250, 375, or 500 volts, direct current. Class F insulation is used throughout the field, including accessories [6]. Transformer action will take place during initial armature current inrush associated with a close-in electrical fault. This transformer action can produce abnormally high voltage in the field winding; the field insulation must be able to withstand the high voltage stresses. For this reason, dielectric tests of the field winding are *relatively* higher than those of an armature winding having the same rated voltage as the field winding.

As an alternative (or possible addition) to cooling the field using fan-driven ventilating air, direct cooling of the field winding using a liquid becomes a consideration for extra-large machines. The major benefit offered by direct cooling (or "inner-cooling") is the reduction of rotor diameter. A rotor diameter and overall machine diameter reduction can significantly lessen machine and plant costs. High values of required WR^2 values, with attendant requirements for larger rotor rim diameters, have prevented the Bureau from installing machines with "inner cooled" field windings.

As previously mentioned, typical field coil winding construction facilitates alternate field polarity by simply placing the winding on the field pole body in opposite directions. The terminals for a winding may be arranged so that one terminal is at the top next to the rim and the other is at the bottom—next to the airgap. The next winding, placed on the pole body in the opposite direction, would align its terminals so they could be easily connected to the adjacent pole windings. The connectors used to join adjacent poles are, of course, subject to centrifugal forces, and these forces can be transmitted to the winding terminal in a manner that distortion of the winding can occur. This distortion can cause insulation damage; therefore, special provisions are required to protect the winding at each end of the pole.

All poles on the rotor are connected in series, with final connections made to the field leads emanating from the generator shaft and crossing the spider and rim. Poles partially installed on a rim are shown on figure 8-11; a complete assembly of poles on a rotor are shown on figure 8-12.

Copper bars, or rods, are placed in the semiopen slots formed in the pole faces. Shorting connections are made to connect all bars on the pole, at both ends of pole, to form a copper grid in each pole face. This grid is called "amortisseur winding" or "damper winding." Connectors may be installed between poles to interconnect all the grids on the rotor; this construction is called "continuous amortisseur." If connectors are not installed between grids the winding is a "discontinuous amortisseur."

8.5.4 Accessories

Various accessory devices are provided to support and protect the field poles and windings of large synchronous generators. Many of these devices are not required on smaller machines. Special devices may be required for poles and windings of machines exposed to unusual circumstances such as nearby high voltage direct-current stations, reversible pumping-generating operation, or extra-large diameter rotors.

Several devices for detection and control of abnormal and normal field conditions—and for

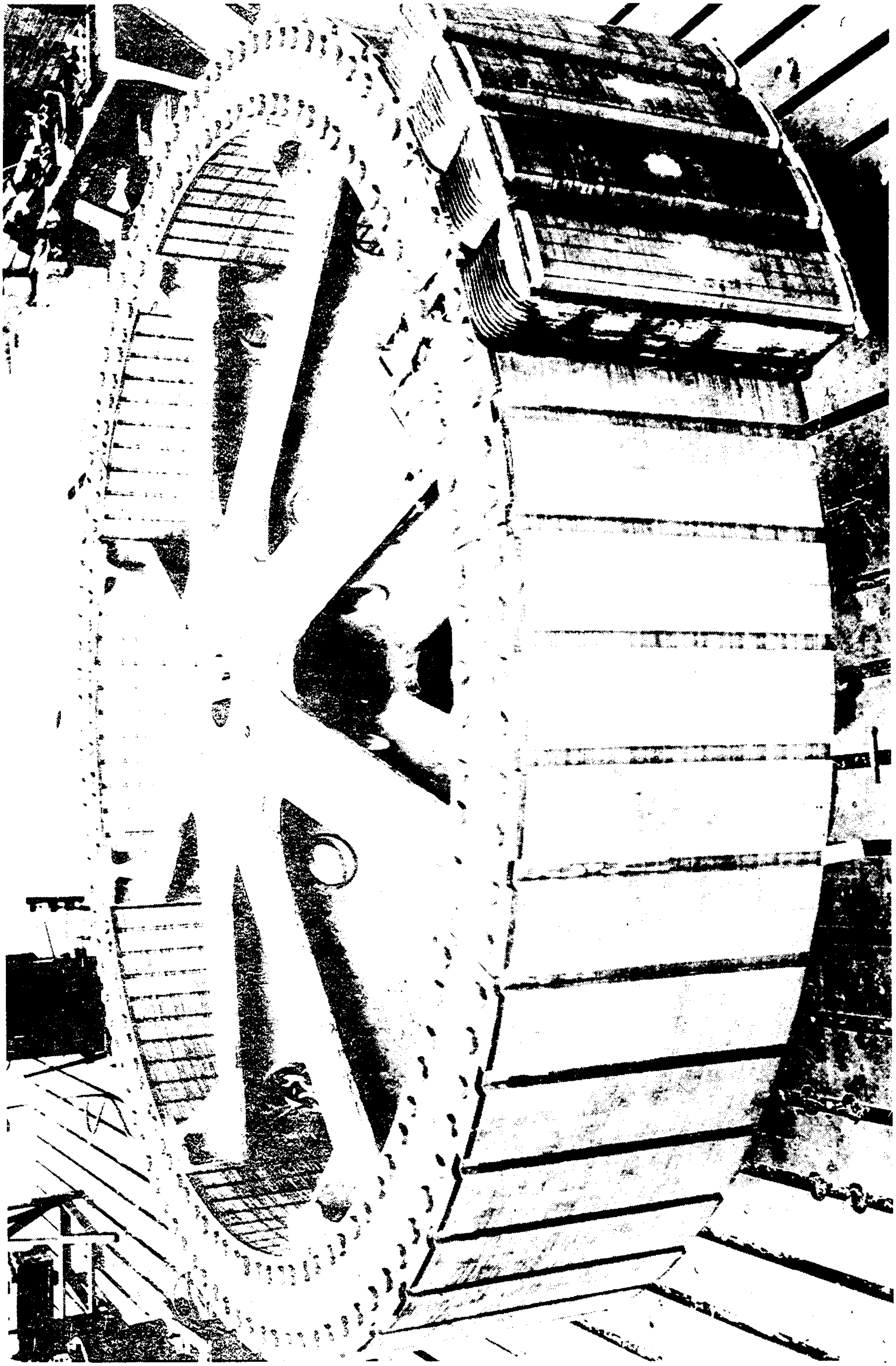


Figure 8-11. — Rotor spider and rim laminations with several pole pieces attached. Courtesy of Westinghouse Corporation.

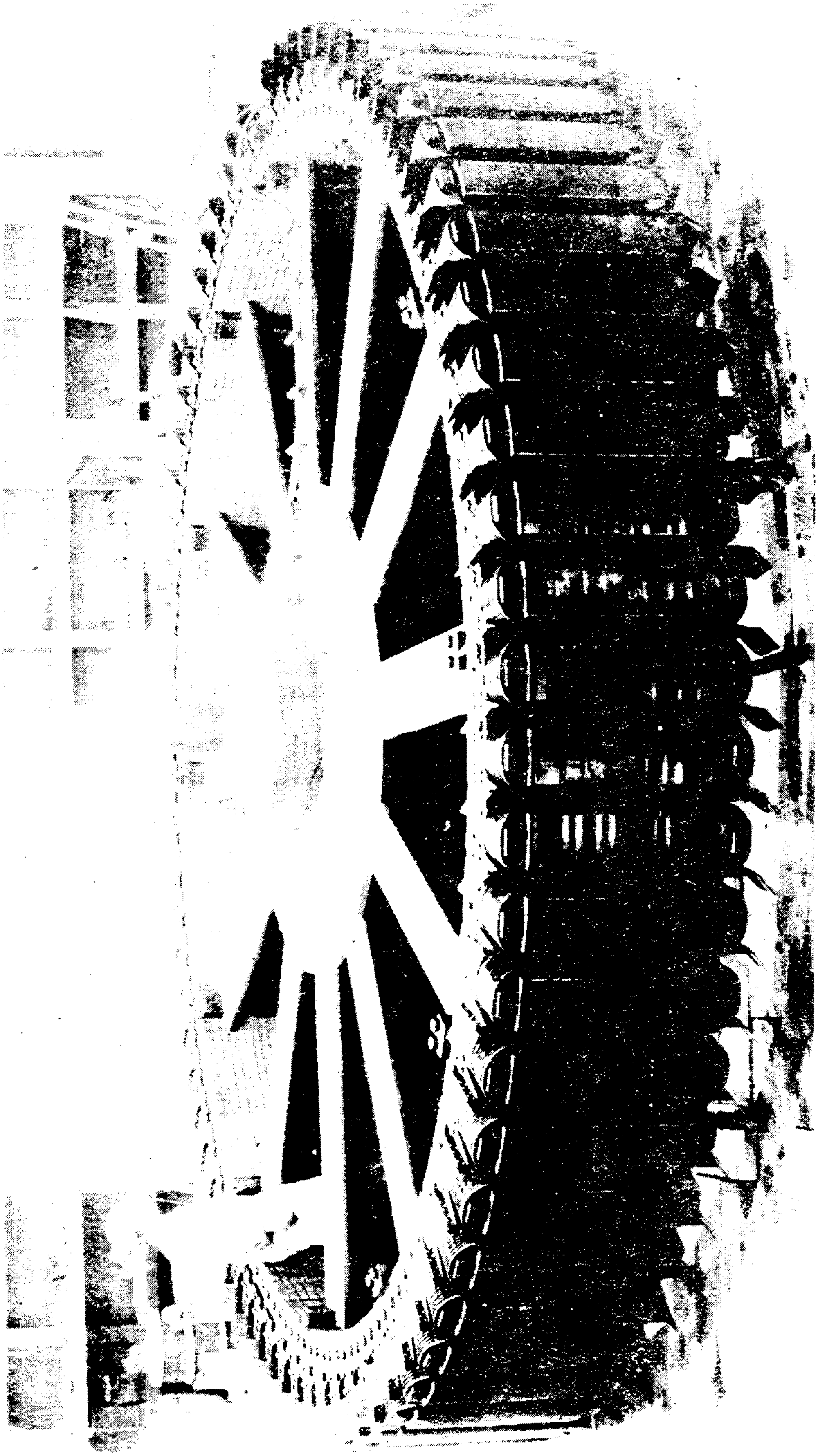


Figure 8–12. — Field poles assembled on rotor. Rotor rim assembled on spider. Courtesy of General Electric Company.

protection from damage resulting from abnormal conditions—are located externally from the field itself. These devices include loss of field relaying, ground detection, temperature determination, field current control, and interruption.

The following devices are located on the generator rotor.

1. Two insulated brushes and brush holders are required for measuring brush loss across the collector rings. These brushes facilitate measurement of field voltage and current for use in field temperature determination. The insulated brushes and brush holders are provided for measuring voltage across the collector rings during operation; the current is measured elsewhere. This measurement facilitates determination of field temperature by calculating resistance from the voltage and current measurements.

2. Collector rings and brushes are necessary for transmitting power furnished by the exciter to the field poles. These items are unnecessary for brushless excitation systems found in small generators. The collector rings may be made of iron, steel, copper, brass, or bronze; however, Bureau specifications restrict collector ring material to steel or bronze. The rings are insulated from the shaft with Class F insulation. The rings are spirally grooved to improve brush performance, enhance collector ring cooling, and facilitate removal of brush wear products. Collector rings in machines that experience rotation reversal (e.g., generator-motors) must be specifically designed for rotation in both directions. The rings are located above the rotor in a place that will facilitate maintenance because frequent brush inspection, adjustment, and replacement may be necessary. Polarity reversal is a required procedure, and extra long field or exciter leads to the collector rings are necessary. Brushes on the positive ring usually wear faster and the negative collector ring usually wears faster than the positive ring. Polarity reversal equalizes the wear and prolongs the lives of the collector rings and brushes. The brushes are installed in a staggered scheme to equalize wear, and provisions are made to separate the brushes from the collector rings during long shutdown periods. If not lifted, etching of the collector rings under the brushes can occur. Brush pressure on the rings must be adjustable because optimum pressure will vary with operating conditions including loading and yearly seasonal changes. Precautions should be observed to ensure that adequate cooling air for the collector rings is available. The temperature rise of the collector rings is limited by the specifications to 85 °C.

3. Leads, either insulted cable or bus, are required to deliver excitation power from the collector rings to the field poles.

4. Interpole connectors must be designed and constructed in such a way to anticipate movement between poles caused by thermal and centrifugal forces and by "pole flexing" and vibration. Special attention must be given to ensure retention of a good electrical connection between poles, and to avoid unusual stresses on the field windings where the connectors are installed.

5. Fan blades may be affixed to the poles, and are formed and placed so as to cause ventilating air to flow between poles and over the field winding before entering the generator airgap. Long-axial length rotors present difficult ventilation and cooling problems; special features may be used to facilitate field cooling.

6. Interpole brackets or supports may be furnished to stabilize pole flexing. A bolted attachment of such devices should be reviewed in regard to the Bureau's practice of not allowing bolts loaded in tension in generator rotating parts.

7. Various bands and other devices for stabilizing the pole body, field winding, amortisseur, and interconnections are also necessary.

8.5.5 Shipping and Assembly

Field poles are factory assembled, and preliminary tests are performed at the factory. The poles may be installed on the rotor rim in the factory and the assembled rotor then shipped to the jobsite. However, size and weight restrictions may not allow shipment of an assembled rotor. Field poles for larger machines, on which such restrictions most frequently occur, may be shipped with the windings separate or installed on the pole bodies. These poles are mounted on the rotor rim at the jobsite either inplace in the stator bore or in the rotor erection area.

As discussed in section 8.4, the rotor rim undergoes inelastic growth or movement during initial operation. This movement may inhibit subsequent removal of the pole bodies from the rim. Movement of rim laminations relative to pole body laminations may be sufficient to make pole replacement difficult and time consuming.

Keys are installed between the pole bodies and the rotor rim so as to ensure that the pole body is compressed against the rim at all speeds. While some rim designs (floating rim) presume movement of the rim relative to the spider, movement of the poles relative to the rim during machine operation is not acceptable in any design.

8.5.6 Plant Considerations

Most plants having large generators are sized so that an assembled rotor, with poles attached, can be handled by the plant crane. Generally, rotor erection and set-down area is large enough to allow work on the rotor with poles in place.

Pole design and construction have special requirements for each size and rating of machine. As a result, off-the-shelf field poles generally are not possible. To avoid excessive costs and prolonged delays required for replacement of failed field poles and/or field windings, it is necessary to specify spare parts at the time of original manufacturer. Failures requiring replacement of field poles with spares have been infrequent—many plants do not have spares—however, the extended outage of a unit, when it is necessary to obtain and install a spare, can easily justify procurement of spare field poles.

Some manufacturers' designs facilitate the use of spare field windings separated from their pole bodies, while other designs (integrated or bonded) require a complete pole assembly for each spare. The field pole construction that uses a separate pole body and winding permits using a single winding to obtain either of two polarities on a single pole body, whilst the bonded-type design requires two complete assemblies to obtain two polarities. The plant design requires adequate storage and handling facilities for spare field parts, if spares are specified.

8.5.7 Characteristics and Performance

Discussions on the characteristics and performance of generator salient-pole fields were covered in section 8.5.3. Power system studies are made to determine parameters that the generator field must have to provide satisfactory performance in the power system.

A hydrogenerator's output in MV•A (megavolt-amperes) when compared to the number of poles on the machine—expressed as MV•A/(r/min)—is generally considered to be an approximate measure of the difficulty of design and construction of the machine. Values of about 10 MV•A/(r/min) are considered to be of extreme difficulty while values of about 2 or 3 MV•A/(r/min) are considered to require conventional design and construction methods. A better measure of difficulty includes the stator core height as a factor, which would be megavolt-amperes per pole per foot of core height. But the problem facing the designer with this latter approximation is that the stator core height is not known until the actual machine design by the manufacturer has been completed.

Generator salient-field poles are designed to operate highly saturated, and as a result, large changes in field current are necessary to effect relatively small changes in flux. Care must be used to avoid overexcitation with consequent overheating. However, underexcitation can produce overheating of generator parts near the end-turns. Evidence of excessive pole end plate heating can frequently be traced to underexcited operation of the generator.

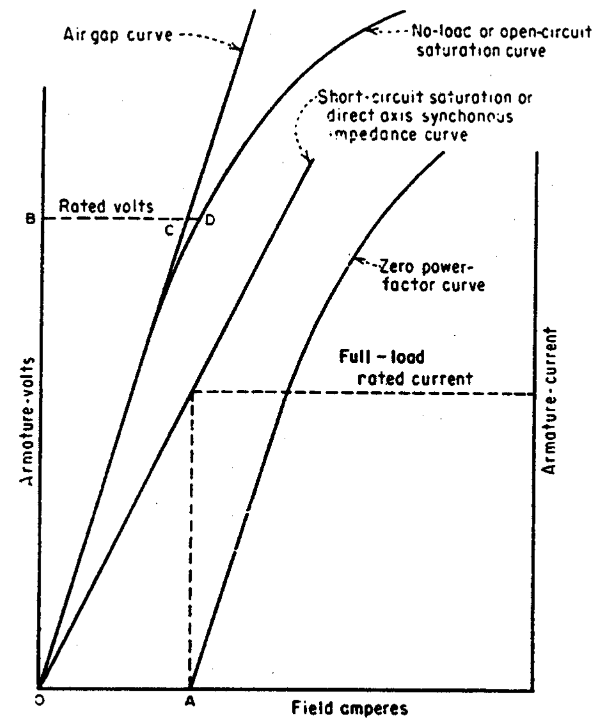
Generally, when performing power systems studies, machine impedances are considered to be the same as reactances. It is recognized that resistance has a major impact on time constants; but time constants are useful in the studies—rather than the resistance. The field resistance does determine the power requirements and losses for machine efficiency calculations, and controls the temperature rise of the field. Since cooling air flows over the field poles before entering the stator, the field temperature is very influential on the overall generator's temperature rise. Changes in field resistance normally occur as a result of the temperature coefficient of resistance. Field resistance changes not associated with temperature change must be regarded as abnormal, and probably occur as a result of connector deterioration, conductor failure, or insulation failure. Any of these conditions must be considered as serious and remedial measures taken.

Machine designers usually consider the worst mechanical stress condition that a generator will encounter (insofar as design of rotor, bearings, brackets, stator frame, and supports are concerned) are the forces resulting from the UMP that is produced when one-half of the field poles on the rotor are shorted. While the possibility of such an occurrence is slight, its impact is extreme. Therefore, the machine is designed to resist the forces associated with a double field-to-ground fault. Regardless of the design, extreme care should be taken to provide sensors that will detect abnormal conditions on the field, and to provide inspection and maintenance that will minimize the possibility of a double field-to-ground fault.

The generator's capability to sustain output or "ride through" system disturbances may be described as "inherent stability." This stability is affected by several characteristics including the SCR (short circuit ratio). The acronym SCR is used also in section 8.11 to describe "silicon controlled rectifier," which is a component that is not related to and should not be confused with the SCR used to describe machine characteristics. The SCR is partially determined by field performance and partially by armature reaction. The SCR should be as high as possible to provide a greater synchronizing power and a lesser drop in system voltage during faults, and should be as low as possible to minimize field pole and overall generator costs. Thus, a balance between generator performance and cost must be selected. A fast acting, high initial response excitation control system permits selecting lower SCRs while still maintaining higher stability (see secs. 8.10 and 8.11).

As indicated above, machine SCR requirements determine to a considerable extent the field pole parameters that determine machine size and construction. Normal power output (rated output) requirements of the generator and overspeed considerations also determine field pole size and construction. Figure 8-13 provides data to calculate machine SCR.

A generator field winding rotating at rated speed and constant load will be in exact synchronism with the rotating field produced in the armature. During such conditions, voltages will not be induced in the field pole amortisseur winding because differences in relative motion do not exist. During armature load current changes or faults, when the machine power or torque angle changes,



Direct axis synchronous reactance $= X_d = \frac{OA}{BC}$

Short-circuit ratio $= \frac{BD}{OA} = \frac{\text{Field amperes at rated voltage on open circuit}}{\text{Field amperes at rated armature current on short circuit}}$

Figure 8-13. — Water-wheel generators typical characteristic curves.

a relative difference in motion between the armature rotating field and the rotor field occurs. This relative difference in motion will induce voltages in the amortisseur, and damping currents will flow in the amortisseur. Naturally, the relative motion between stator rotating field and rotor is large when starting a synchronous motor. In this case, the armature field is rotating at rated speed while the amortisseur is at standstill. Also, turbine speed variations caused by hydraulic disturbances and vibrations create rotor speed differences compared to the speed of the armature rotating field. Thus, amortisseur currents flow as a result of the turbine's hydraulic system disturbances as well as power transmission system conditions. The amortisseur winding and the rotor WR^2 both function to damp power and hydraulic system oscillations.

Amortisseur windings required only for generator stability and harmonic suppression purposes may not have sufficient thermal capacity to permit starting as a motor. Therefore, if synchronous condenser operation of the generator is a planned requirement and if operation with the turbine uncoupled is possible, the specifications must be written and the machine designed and constructed to facilitate starting as a motor. Amortisseur windings for generators that are located electrically close to high voltage director-current converter-inverter stations require a special design because of the harmonics associated with these stations.

In theory, the direct-axis subtransient damping currents flow entirely in the amortisseur grids on each pole face, while the quadrature-axis subtransient damping currents flow between adjacent poles. The circuit for the quadrature-axis currents in a machine having a discontinuous amortisseur would be from grid on one pole face, through pole body to rotor rim, through rim to an adjacent pole body, and then through that pole body to the grid on that pole body. By providing a low impedance connecting path between grids on adjacent poles, the quadrature axis subtransient reactance, X''_q, can be significantly reduced. A well designed continuous amortisseur will have a saliency ratio approaching unity, which is an ideal condition.

As stated, the saliency ratio, which is the ratio of the quadrature-axis subtransient reactance to direct-axis subtransient reactance, X''_q to X''_d, can be reduced if a continuous amortisseur is selected in lieu of a discontinuous amortisseur. The damping action and harmonic suppression functions of the amortisseur improve as the ratio of X''_q to X''_d decreases; normally, X''_q will be somewhat higher than X''_d. Bureau specifications have typically limited the saliency ratio to 1.35 or less. The value of X''_q will decrease if the pole grids are extended further into the pole tips and if the grids are interconnected to form a continuous amortisseur winding. Experience shows that acceptable saliency ratios of about 1.35 (or slightly lower) can be obtained with a discontinuous amortisseur design. This experience, when combined with failures of amortisseur interconnectors, has led the Bureau to specify discontinuous amortisseur windings if reactance ratios permit. The interconnector or failure experiences have involved broken connectors which, in turn, have damaged armature windings. The interconnector failures have been attributed to pole movement, thermal cycling, bolt failure, centrifugal force, vibration, insufficient support, and other causes. If saliency ratios are required by system considerations to be much lower than 1.35, a continuous amortisseur winding may be required. For example, system requirements for a ratio of 1.2 would probably require a continuous amortisseur.

Negative sequence currents, I_2, flowing in the generator armature induce double frequency voltages in both the field and amortisseur windings. Large current flows in the amortisseur winding are produced by the double frequency induced voltage, and severe heating can result. The "integrated product," or I_2^2t, is a specified characteristic that indicates the capability of the machine to withstand the effects of negative sequence current heating. The American National Standards (ANSI C50.12, par. 6) discuss this characteristic [6]. Bureau specifications have required that I_2^2t be not less than 40—according to ANSI standards. The number, size, and material used for the bars in the amortisseur winding are determined by the manufacturer to meet the performance requirements of the specifications.

The actual value of X''_d is extremely important to power system designers who use the reactance to determine the generator bus and circuit breaker momentary and interrupting duty. Calculated values of transient and subtransient reactance are used because actual test values are not available when the system is designed. Also, saturated values are used because they are lower than unsaturated values and saturated values result in higher fault currents. The negative sequence reactance, X_2, is usually assumed to be the average of X''_q and X''_d.

8.5.8 Tests

Generator field poles and windings are subjected to a number of tests, both at the factory and at the jobsite. These tests are performed according to ANSI C50.10, [7], which, in turn, requires testing to IEEE Standard 115 [5]. Specific testing includes:

1. Dielectric test of 10 times the rated exciter voltage for 1 minute. Refer to section 8.5.2 regarding the reason for the magnitude of this voltage level.

2. A test for the resistance of field winding to reveal the condition of the field circuit. Also, the value of this resistance is used to determine the field temperature during operation.

3. An overspeed test to demonstrate the field poles' capability to successfully withstand the forces incident to speeds up to runaway.

4. Tests for short circuited field turns, both at standstill and at speed.

5. Polarity tests on each field pole.

Many other tests performed on the generator will involve the functions and performance of the field. However, these tests do not involve the field alone as they demonstrate field performance in conjunction with the rest of the machine.

8.5.9 Summary

A magnetic field is fundamental to converting rotating mechanical energy to electrical energy. The quality of the electrical power is dependent upon the design and construction of the generator field, and the importance of the field to successfully produce electrical power cannot be overstated.

Many theoretical principles are involved in field pole design, and those theories are not within the scope of this manual. Rather, the intent is to address those concepts that determine successful application of a machine in a plant and system. The required functions of the field pole assembly must be performed in the most reliable manner possible. Therefore, the design and construction of this assembly must be simple and robust. Auxiliaries and accessories are kept to a minimum to ensure self sufficiency.

8.6 STATOR FRAME

8.6.1 Introduction

The stator frame of a suspended, vertical shaft hydrogenerator serves many purposes that include:

- Transmits machine torque to the plant foundation
- Transfers weight and hydraulic thrust of the rotating parts of the turbine and generator to the plant foundation
- Supports the weight of the armature, core, upper-bearing bracket and bearings, and exciter (if a rotating exciter is used)
- Supports and routes the main and neutral leads
- Maintains the armature core in a cylindrical shape, and maintains vertical, horizontal, and elevation alignment
- Provides a base for core clamps and keys
- Provides ducting for cooling air
- Provides mounting provisions for surface air coolers and supports the surface air coolers
- Provides inspection facilities for the back of the armature core
- Provides support for armature circuit rings, coil jumpers, and surge rings
- Provides support for air-housing cover plates and a variety of pumps, controls, detecting and sensing devices, instruments, gauges, terminal boxes, pipes, conduits, and accessories

The above listing shows that the stator frame provides support for all the generator except the lower-bearing bracket and bearings, static exciter (if used), and vertical part of the air housing. Many of the purposes noted above are served also by the stator frame in the vertical-shaft, modified-umbrella, and close-coupled machines. One of the most significant differences between these types of machines and the suspended machine is that the thrust load is supported by the lower-bearing bracket instead of the stator frame. The stator frame of a horizontal-shaft machine also serves many of the same purposes listed above.

Of prime importance to frame design are the strength and stiffness requirements. Strength requirements are determined primarily by unbalanced magnetic pull, short circuit and/or faulty synchronizing torques, and by vertical loading. In general, higher core heights increase frame strength problems. Adequate stiffness usually is not a controlling factor in small, high-speed machines. The larger, low-speed machines do present special problems, and additional design and construction studies are required to achieve proper stiffness.

A problem presented by extra-large machines [having stator frame diameters greater than 30 feet (10 m)] is how to compensate for radial expansion and contraction due to thermal changes. This problem has been addressed by designing a radially free core key system that permits the core to expand and contract radially while still transmitting torque to the frame. Another solution, that has been used in combination with the radially free core key, is to provide a frame-to-soleplate connection which will permit radial movement and prevent circumferential movement. Both of these systems, independently and in combination, present problems with respect to maintaining proper stator centering and circularity. The diametric movement of a stator may be about 0.5 mil[2] per inch (0.5 mm/m) of diameter for a 122 °F (50 °C) change in temperature. Maintenance of a true cylindrical shape during expansion or contraction is essential; therefore, means must be provided to ensure that the top and bottom of the stator move the same amount and at the same rate and direction. Stator core buckling will probably result if proper means are not provided. Thermal movement may not be uniform around the frame, and an uneven airgap or core condition may produce distortion to the circularity and concentricity of the frame.

The magnetic forces acting on a stator core are tremendous. The unbalanced magnetic pull acting on the core and frame has far greater impact on the frame design than normal magnetic forces. This unbalanced magnetic pull usually is considered to be the greatest if it is a result of one-half the rotor poles becoming shorted. Such a condition would tend to distort the stator out of its cylindrical shape, and produce stator core irregularities rotating at rotor speed. A frame that is fully capable of withstanding these forces may be so stiff as to cause problems in compensating for thermal expansion and contraction. That is, a frame robust enough to fully compensate for unbalanced magnetic forces may be the cause of core buckling as a result of thermal changes. Some of the forces may produce inelastic changes (growth or deformation) that occur over an extended time with progressively deteriorating impact on machine performance.

Magnetic, thermal, torque, and mass forces in an extra-large generator may become so great as to make a conventional frame impractical. One solution to such a situation is to transmit the forces directly to the foundation rather than through the frame. An example of this solution is the 600-megawatt machines furnished for Grand Coulee Third Powerplant. The stator frame consists of little more than core supports, air ducting, and a wrapper plate; and the stator forces are transmitted to the foundation by positioning beams. This system has proved to be successful.

8.6.2 Construction

The stator frame is fabricated from steelplates to form a grid-like structure inside a cylindrical outer shell called a "wrapper plate." Frames for larger machines are constructed in segments of a cylinder to facilitate shipment. These segments are bolted together at the jobsite to form the completed frame. The manufacturer will frequently stack the armature core and install the armature winding in the core on each segment—at the factory before shipment. A one-quarter segment of a stator is shown on figure 8-14 and a complete stator frame and core is shown on figure 8-15.

The inner circumference of the frame grid structure is fitted with keys to maintain core alignment, and with supports for the core clamping system. The grid structure forms duct passages to route the heated cooling air leaving the core to the surface air coolers. The wrapper plates on the outside of the grid are fitted with openings and flanges for attaching the coolers, and with removable plates to facilitate inspection and access to the back of the core and to the core keys.

Rings made from steelplates are attached to the top and bottom of the grid to facilitate transfer of weight to the plant foundation through stator soleplates. Some manufacturers will mount the frame directly on the plant foundation, which allows the cooling air to be returned to the rotating parts over the top of the frame and/or through ducts in the concrete under the frame. Other manufacturers may use soleplate extensions to elevate the entire frame sufficiently to permit return of cooling air both over and under the frame. Shrouds made from metal sheets or fiberglass may be attached to the inner perimeter of the frame to further facilitate routing of cooling air.

The stator frame is essentially outside the working magnetic fields of the generator; frame design considerations primarily address the structural integrity of the machine. However, magnetic fields do exist in the frame; differences in the configuration of the frame from one location on the circumference to another are frequently the source of the induced voltages that produce "shaft current." Rather than attempt to eliminate these shaft currents by perfectly balancing the magnetic circuits around the machine circumference, the currents are interrupted by insulation placed near the machine's bearings.

Usually, the main and neutral leads are brought out from the armature over the top of the frame—rather than through a window in the frame. This

[2] A mil is a linear measure equal to 0.001 inch.

eliminates problems that would arise due to current imbalances, which would produce undesirable voltages and currents in any conducting material enclosing the leads. Grounding lugs are provided at least two places on the frame.

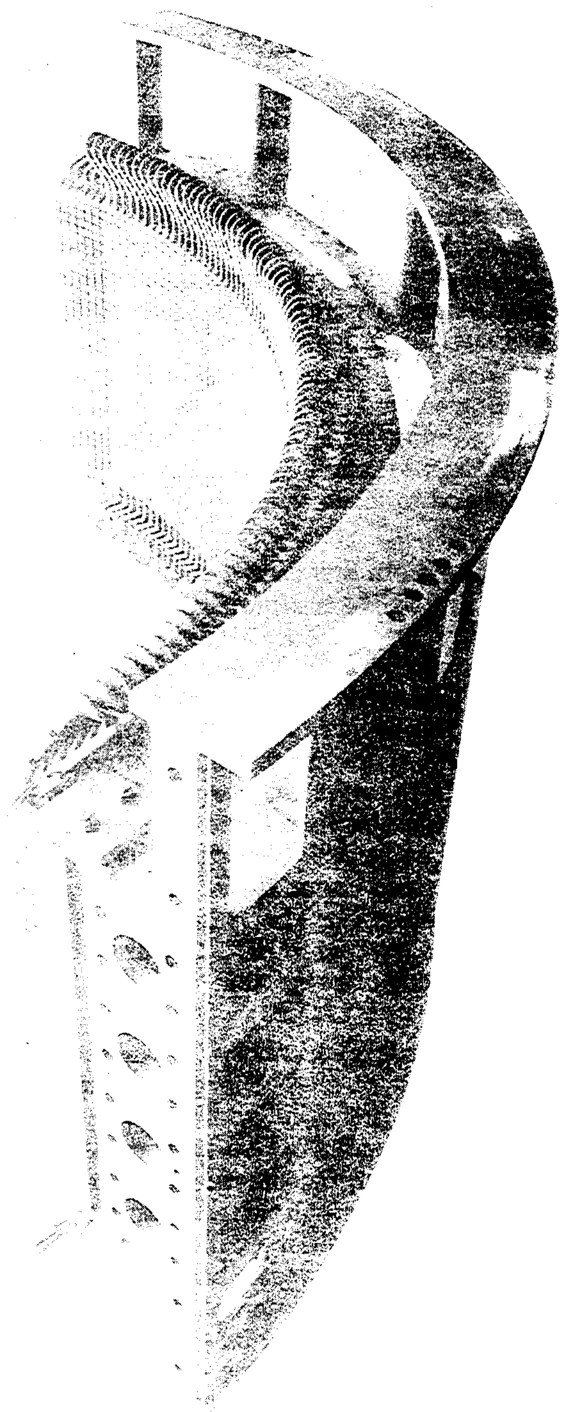


Figure 8-14. — A one-quarter segment of wound stator for a hydrogenerator. Shasta Dam — 75,000-kV•A generator, type ATI-W, 52-pole, 138.5 r/min, 13,800 volts, 60 Hz. Courtesy of General Electric Company.

The frames of most generators are extended far enough above the armature core to provide space for support of surge rings, circuit rings, coil jumpers, CO_2 piping, wiring for RTD (resistance temperature detectors) and other devices.

The frames are prime painted, and the outer perimeter is usually finish painted with a white or other light-colored paint to improve visibility in the area between the air housing and the wrapper plate. The inner frame structure between the wrapper plates and the core has frequently been left without a finish coat. However, finish painting with a color that will facilitate inspection of the back of the core, keys, and air ducting is suggested.

8.6.3 Maintenance

The stator frame itself will not usually require maintenance other the than cleaning of air passages through it. Sensors or detectors are not provided to monitor frame conditions. Devices have been implemented to measure frame movement, although this has been done only on a test basis. The frame-to-soleplate connection for extra-large machines may be lubricated to improve free radial movement, and replenishment of lubricant periodically is required. Any evidence of looseness or movement of the frame's split bolts or core keys should be regarded as evidence of more serious problems in the core itself, and a thorough investigation should be made.

8.6.4 Summary

The stator frame is a vital and dynamic part of a hydrogenerator. While the frame requires little or no maintenance, any frame fault should be regarded as total failure of the complete machine. Continued operation with a defective frame can produce a catastrophic failure.

8.7 STATOR CORE

8.7.1 Introduction

This section will not attempt to cover the many theoretical magnetic, electrical, mechanical, or structural relationships governing the design, construction, and performance of hydrogenerator

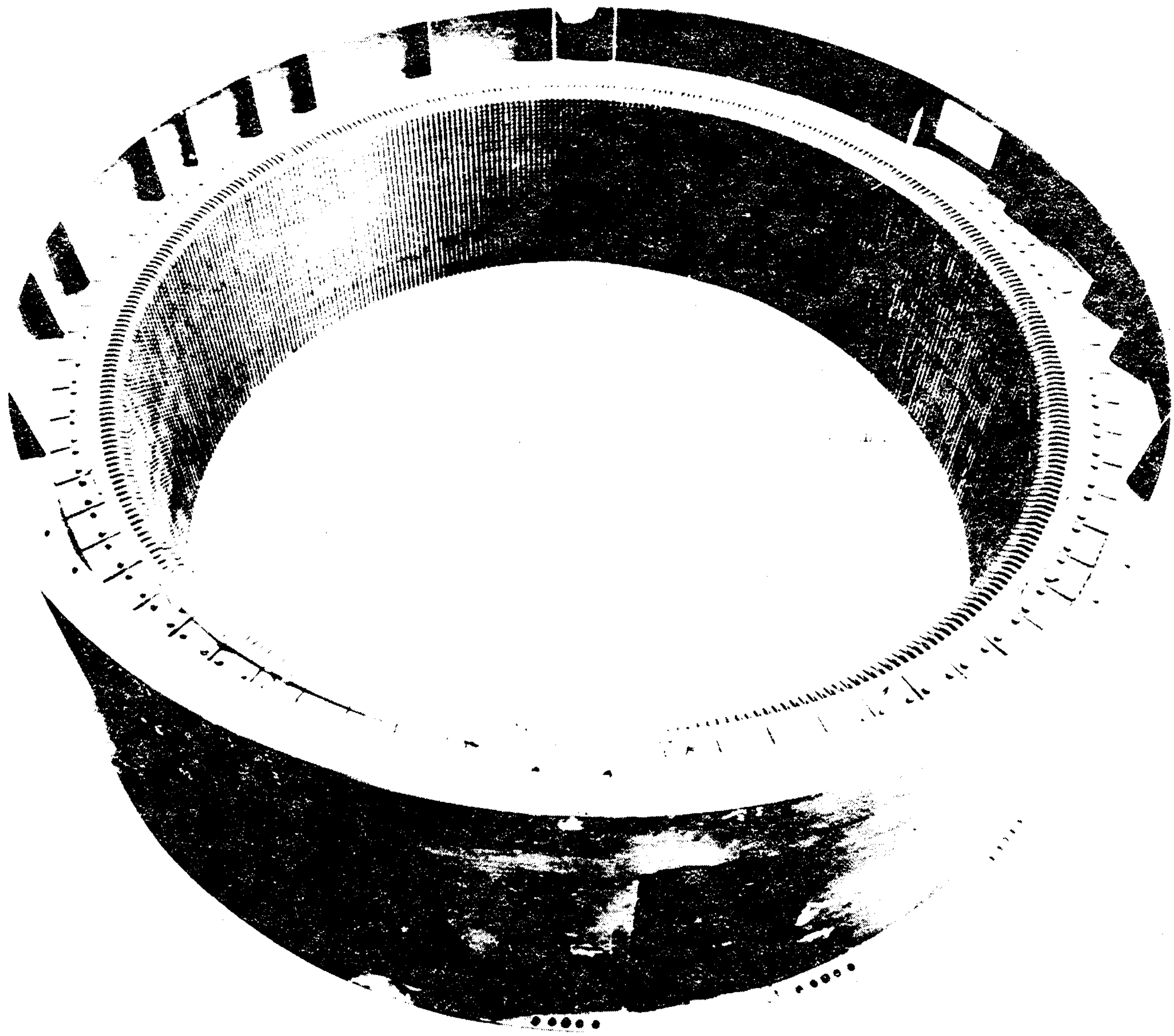


Figure 8-15. — A completely machined unwound stator for a hydrogenerator. Hoover Powerplant—82,500-kV•A generator, type ATI-W, 40-pole, vertical a-c waterwheel, 150 r/min, 13,800 volts, 50 Hz, or 180 r/min, 16,500 volts, 60 Hz. Courtesy of General Electric Company.

cores. These theoretical relationships are covered in depth in the literature; the reader should already have an understanding of the fundamental relationships.

The hydrogenerator's stator core provides the magnetic circuit that, to a great extent, determines the machine's capabilities. The stator core concentrates the magnetic field emanating from the generator rotor to produce the induced voltage in the armature. In addition to the primary purpose for providing the magnetic circuit of the machine, the core provides cooling and structural support for the armature winding. The hydrogenerator core is a massive structure. Regardless of size, the core must retain a relatively precise configuration to produce the required quality of electric power and to avoid operational problems. For example, the stator bore of a 600-megawatt generator at Grand Coulee Third Powerplant is 721.30 inches (18 321 mm) in diameter; this bore must be maintained concentric within a few thousandths of an inch. The core must provide space for magnetic paths, current-carrying paths (armature winding), cooling paths, and structural retainers. The objective of the stator core design is to optimize these requisite conditions.

8.7.2 Materials and Construction

The steel laminations for the stator core are usually manufactured from hot rolled, silicon, electrical-grade steel that may be either grain oriented or nongrain oriented. Grain-oriented steel has superior magnetic qualities with reduced losses and improved permeability in the direction of rolling. At high flux densities, like that present in the teeth of hydrogenerator cores, the advantages of grain-oriented steel are less pronounced. In addition, grain-oriented steel is less economical due to greater difficulty in manufacture and greater waste. Most modern hydromachines use nongrain-oriented steel that is either a low carbon (usually less than 0.025 percent) silicon-iron steel or a silicon-aluminum-iron alloy containing up to about 3.5 percent silicon to which a small amount of aluminum is commonly added. The steel may contain other elements, such as phosphorous, to achieve required punching characteristics, but these elements have no significant effect on the magnetic properties. Heat treating the steel is not required because the required permeability characteristics are developed during mill processing.

The stator core carries alternating flux and is always laminated to reduce eddy currents and core loss. The laminations are segmental and are laid overlapping to achieve the required structural rigidity and as much magnetic homogeneity as possible.

Core steel is identified by a "core-loss type" that establishes maximum core loss limit for each sheet thickness. The core loss is measured in Wb/lb or Wb/kg (Webers per pound or per kilogram). The "core-loss" type is an ASTM designation such as 36F145, which has a maximum core loss of 1.45 Wb/lb (0.66 Wb/kg) at 60 hertz for 14-mil steel.

For 60-hertz hydromachines, there are four standard thicknesses of core lamination steel. The four thicknesses are bare metal measurements: 11-, 14-, 18-, and 25-mil steel. A varnish is applied to each lamination which adds about 0.2 mil (0.005 mm) per side. The 14-mil steel is grain oriented and the 18-mil steel is nongrain oriented. The 25-mil steel is used next to duct spacers. The varnish (or paint) is called "core plate." The core plate functions as an insulating layer between each lamination to reduce eddy currents in the core and is usually an inorganic phosphate type of material. Organic enamel or varnish core plate has been used in hydrogenerators—sometimes with poor long-term results.

The laminations are stacked in groups (or packets) that are separated by spacers which form ventilation passages. A single spacer is used between each slot for machines with tooth widths up to about 1-1/2 inches (38 mm). When the tooth width is more than 1-1/2 inches, two spacers are used. The top and bottom laminations of each packet are usually thicker (25 mil) than those in the center of the packet, and the spacers are welded to the thicker laminations. The spacers may be of either magnetic or nonmagnetic material; their height may vary according to machine size. The arc length of the segments may differ if the stator core is manufactured with shipping splits.

The laminations and duct spacers are stacked on the frame with key bars on the frame providing an alignment and restraining system to form the core. The laminations are stacked in an overlapping fashion to achieve as much of a homogeneous structure as possible. Clamping plates, or "fingers," of either magnetic or nonmagnetic material are placed at the top and bottom of the stacked core and core bolts are used to clamp the assembly into a rigid structure. The assembled core may be supported by flanges at the frame's bottom or suspended through a system from the frame's top. Although this may seem to be of little consequence, the type of system can be of considerable importance if core repair becomes necessary.

The highest and lowest packets of the core may be constructed differently from those in the center portion of the core. The laminations in the end packets may be stepped back from the airgap to decrease flux entering the core axially, and the teeth in the end packets may have radial slits to decrease eddy currents due to flux entering the core axially.

The core may be formed from the laminations such that the armature slots are skewed rather than vertically axial. Usually, that is done by installing the frame keys off-vertical. When the laminations are stacked, using the keys for alignment, a skewed slot is produced on the bore side. Following stacking of the core laminations, the armature slots formed in the core may be painted with a semiconducting compound that serves as part of the machine corona shielding system.

For most hydrogenerators, the stator core is partially factory assembled and then jobsite erected on the machine foundation. Jobsite stacking of the laminations on the frame—in place on-foundation—has been successfully accomplished at several plants (see sec. 8.7.3). However, if an unusually short time is required for complete machine assembly, jobsite erection off-foundation is a possibility. This would probably require additional erection bay space, but probably without additional crane capacity for handling.

8.7.3 Performance

The magnetic circuit path—emanating from a rotor pole of one polarity and across the airgap separating the rotor poles from the core—is through the core teeth adjacent to the rotor pole, through the back of the core, and back through core teeth adjacent to a rotor pole of opposite polarity. The flux density is considerably greater in the core teeth than in the core base; most core loss occurs in the core teeth. For this reason, a machine designer will calculate tooth loss and base loss separately. Machine frequency has a major impact on this loss division. Some of the flux entering a tooth will pass across the slots in the core rather than following the tooth all the way to the base. This crossing flux is called "armature slot-leakage flux" and is responsible for eddy currents in the armature winding.

Magnetic saturation of the core significantly affects machine characteristics and performance. As previously mentioned, core tooth saturation will occur before the core base saturates. Unfortunately, much of the mathematical treatment of machine theory is based on an assumption of straight-line or negligible saturation because of the more basic equations involved. However, practical design must consider the effects of saturation.

Core loss varies directly with machine voltage; the loss increases nonlinearly with increasing core saturation. Core temperature rise occurs as a result of core loss produced by eddy currents and hysteresis. Also, heat may be transferred directly to the core from the armature winding or by ventilating air entering the core from the machine rotor.

Heat removal is accomplished by passing ventilating air through ducts in the core. The ducts are formed by the spacers placed between the packets of laminations. Direct water cooling of the core has been used in some machines, but the Bureau has not used this method. Bureau practice is to limit core temperature rise to 55 °C.

Bureau of Reclamation specifications include an evaluation factor for core loss. The intent of this factor is to obtain the highest machine efficiency consistent with good design. The impact on the core design produced by an increasing demand for higher efficiency is to require thinner laminations and higher quality steel. These requirements tend to make the core less robust structurally while increasing the cost. Thus, the evaluation factors for core loss must be optimized rather than maximized.

Forces existing in the core must be controlled by the stator frame (see sec. 8.6). The core design should be such that it does not require an excessively strong frame to function properly. Several core features can be addressed with this objective in mind.

Most Bureau generator cores were originally stacked in the factory in segments of a cylinder. The segments were either halves, thirds, or fourths of the complete cylindrical core. This segmental construction served the purposes of maximizing factory stacking and meeting shipping size limitations. Field erection was accomplished, in part, by placing insulation between abutting core segments to prevent shorting or bridging of laminations in adjoining segments, and then bolting the frame segments together. Figures 8-14 and 8-15 show cores stacked on stator frames.

Large cores [having diameter greater than 33 feet (10 m)] present different concerns than for more conventional sizes. This is due to the relative difference between the stator bore diameter and the radial core thickness. The effect is to create a relatively thin-wall cylinder that lacks the cylindrical rigidity present in smaller machines. In an extra-large machine, a large diameter core is subject to large radial excursions produced by temperature changes and unbalanced magnetic pull. These excursions require the designer to give extra attention to any factors that may affect the circular shape of the stator. The discontinuities produced by shipping splits are obviously given close scrutiny. Also, most manufacturers choose to locate the splits in the slot area rather than through a tooth; nevertheless, this compounds the problem of noncircularity by introducing concern for coil looseness or crushing in slots with splits. Also, discontinuities produced by the splits represent weak areas in the core, and the UMP of the machine may produce irregular and larger core deflections at these splits. Frame expansion and contraction caused by thermal changes also may upset or buckle the core end packets. This can cause relaxation of clamping pressure at the splits with a degrading impact on machine performance.

The Bureau has experienced problems with core splits that in some instances have required generator core repair or replacement. Usually, the shipment of a completely stacked core is not a factor in repair or replacement—eliminating split joints, when restacking, is an attractive option. The decision to field stack new generator cores should consider the installed cost, longer installation time, and possibly the requirement for erection space. Successful field stacking of generator cores is dependent upon adequate equipment, clean conditions, capable workers, and knowledgeable supervision. Reference is made to *Design Standards No. 4* (ch. 2.7) regarding stator core splits [8].

The frame provides clamping pressure to the core to prevent movement of individual laminations. However, thermal expansion in the core and frame does not necessarily occur at the same time; frame clamping pressure exerted on the core may not be distributed evenly and this may produce some buckling. Other features and support may be furnished to ensure that all core movement occurs as a unit rather than as a differential movement of individual laminations. Buckling can occur in the core that will produce uneven clamping pressure on the laminations. This, in turn, may produce uneven winding support, broken or shorted laminations, and core hot spots.

Clamping pressure on the lowest laminations is greater than for the highest ones due to the weight of the upper laminations pressing down upon those below. Clamping pressure can vary due to uneven thermal expansion of the core compared to the clamping system.

Solutions to compensate for these problems have varied over a time and from one manufacturer to another. Some of the solutions have included floating or moveable frames, flexible (relatively) frames, massive steel structural frames, and utilizing the surrounding concrete foundation to function as part of the frame.

Some machines have been manufactured with the laminations in the end packets bonded together with an epoxy cement. The resulting solid packets then distribute the clamping pressure exerted by the frame more evenly to the rest of the core. Epoxy also has been used to stabilize lamination movement after buckling has occurred. While lamination bonding may appear to have potential benefits for stabilizing the entire core, it must be noted that core repair (due to an armature or other fault) could be severely hampered by such bonding.

High clamping pressure compared to core weight can minimize the effects of increasing pressure due to overlying lamination weight. Supporting the core weight by either flanges at the bottom of the frame or by a suspension system from the top of the frame tends to offset the effects of uneven core/frame thermal expansion. Each machine design must recognize all the conditions that the machine will be exposed to, and proper measures taken to compensate for those conditions. Generic solutions to all problems for all machines, do not exist.

8.7.4 Tests

Factory tests of core laminations include the Epstein test that determines the magnetic properties of the steel and the Franklin test that measures the surface insulation resistance.

Caution: The Franklin test measures resistivity of a single insulating layer tested between applied bare metal contacts and the base metal of the test specimen.

The Franklin test is not interlamination resistance or stack resistance that refer to average resistivity of two or more adjacent surfaces in contact with each other. Typical test specimens for the Franklin test are 2 by 8 inches (51 by 203 mm), and these specimens also may be used for the Epstein test.

The Franklin test is run using a standard apparatus under controlled temperature, barometric pressure, and humidity conditions. The test specimen is placed in an apparatus that measures resistance of the surface at 10 different locations simultaneously. The average value obtained from five specimens, measured on both surfaces, is the value reported. This reported value is the electrical current that ranges from zero to one. The value can be readily changed to electrical resistivity:

$$R = \frac{6.45}{I} - 6.45 \qquad (5)$$

where:

R = resistance in ohms per square centimeter, and

I = current in amperes.

Stack resistance is determined by compressing several Epstein strips together. Wide variations of resistance are obtained from this test; therefore, manufacturers usually try to obtain stack resistances well above (five or more times) the threshold value that will give troublesome stray load losses. The number of strips used and the stack resistance value limits are left to the manufacfturer's discretion.

The Epstein test is performed by arranging a standard number and mass of strips into a frame that is placed into solenoids in the test apparatus. Following demagnetization, a determination is made regarding core loss, volt-amperes, root mean square and peak exciting current, alternating current permeability, and related properties under alternating-current magnetization. Bureau specifications have not required contractors to submit results of the Epstein, Franklin, and stack resistance tests. Although some machine manufacturers recommend that loop tests on completely assembled cores be performed in the factory, the Bureau has not required the submittal of these test results.

Present practice, when rewinding or uprating existing generators, includes two tests that reveal core condition. The first test is the circulating-current test. This test is performed only if a suitable source of power—such as an adjacent machine—is available. The test is performed with the rotor physically removed from the machine and with the armature winding connected to the controlled power source. This test has been performed before removal of the old winding at some plants and may be of significant value in determining the core's condition. The test is designed to detect hot spots in the armature winding rather than in the core. Flux density produced by rated current in the winding under the test condition is lower than machine rated power flux density, and core temperature during the test would be expected to be lower than that under rated conditions. Nevertheless, while examining the winding, an examination of the core may reveal core hot spots.

The second test, the "loop test," is the principal test to determine the assembled core's condition. The Bureau requires the contractor, under rewind and uprate contracts, to perform this test if feasible. The test is performed by wrapping cables around the core, passing alternating current through the cables sufficient to produce the approximate normal flux density in the core, maintaining the current until temperatures stabilize, and inspecting the core from the stator bore with an infrared detecting device. A hand-held infrared digital thermometer is excellent to quickly determine the actual temperatures of surface hot spots. A test loop of cable also is passed around the core and connected to a voltmeter to verify that normal flux density has been attained. It is not unusual to discover that the cables also must enclose parts of the stator structural support frame; allowances must be made for this as a part of the magnetic circuit. About 10 percent of the total flux will flow in the frame. The test duration is 60 minutes or until temperatures stabilize. The temperature measurements are continued for at least 60 minutes after the exciting current has been removed.

Many inspection techniques are available that can reveal core problems such as evidence of discoloration, presence of iron-oxide dust, lamination deformation (i.e., waviness), duct spacer movement, core clamp or finger problems, broken or loose core bolts, and broken or cracked laminations in the tooth area.

The core of a new machine is tested during the field tests conducted to determine if warranties and performance requirements have been met. These field test are thoroughly covered by the standards shown in references [5,6,7]. The generator core has a major impact on the results of many of the machine tests.

8.7.5 Instrumentation

Most hydrogenerators are not equipped with a permanently installed instrumentation or detection system expressly for monitoring the core condition. Devices are installed on a temporary basis while testing the machines. Usually, the test devices include a thermocouple attached to the back of the core.

The extra-large 700-megawatt generators at Grand Coulee Third Powerplant have direct water cooling for the armature winding. When the specifications for these machines were written, direct water cooling of the core was a possibility. The specifications required many special detection and monitoring systems, including temperature detection by RTD of the iron in the core teeth and at the back of the core.

Concerns that any core temperature detecting system would not necessarily be of value for determining core hot spots, troubled areas, or even average temperatures have obviously influenced decisions not to implement such a system routinely. The possibility that the core temperature at the spot of detection would be influenced by the presence of a detector has raised doubts regarding any such system. However, the possibility still exists that valuable information about the machine could be derived from such a system. While the actual readings might not be significant, *changes* in values obtained during the machine's life might well be indicative of incipient problems. The cost to install devices and to monitor their output (using existing monitors) should be relatively low. Plant designers should consider the merits of monitoring core temperatures when developing their control system.

Extra-large machines may be equipped with a system to detect airgap variations that are produced by either rotor or stator irregularities. One such system monitors current in each parallel of the stator winding; a comparison of these currents can reveal an indication of stator eccentricity or irregularity.

Inspection ports are frequently installed in the frame to allow inspecting the back of the core. Various substances, such as corrosion or wear products, may be moved through the core ventilation ducts and they may collect on the outer periphery of the core. Visual inspection may not reveal the substances' source, but sample collection and laboratory examination should furnish enough information for diagnosis. An inspection of bore face, clamping fingers, core bolts and nuts, frame keys, and supporting features should indicate the core's condition. Paint color and temperature-sensitive tapes or paints may be used to indicate the core's condition.

An armature fault to ground can severely damage a stator core; such a fault is not uncommon. To limit the damage from this fault, an armature neutral grounding system is used. The system requires the armature neutral to be brought out of the machine and passed through a high impedance before being connected to ground potential. Fault current magnitude is limited to a low value by the high impedance, and the low current reduces core damage, "iron burning", while still facilitating fault detection.

8.7.6 Summary

The stator core is an important part of a hydrogenerator that serves several purposes. The electrical, mechanical, and structural performances of the machine are dependent upon proper functioning of the core. The core is expected to perform these required functions during all possible normal and abnormal conditions without the need for operator intervention. The only normal condition requiring automatic external control is the removal of heat from the core; all other core performance requirements are furnished as an inherent part of the structure. An abnormal shutdown condition is provided to protect the core from excessive damage due to an armature ground fault or detection of core eccentricity. Possibilities for acquiring knowledge of core aging through temperature monitoring are possible. (Information derived from Grand Coulee Units G22, 23, and 24 may be useful in development of this possibility.)

For small machines, factory assembly of the core usually produces an excellent installation. As cores become larger and shipping becomes a problem, partial assembly at the factory and final assembly at the jobsite is a better option. With extra-large machines and when replacing the core of an existing machine, field assembly of a completely homogeneous core (no core splits) is considered to be the best practice.

8.8 ARMATURE WINDING

8.8.1 Introduction

This section presents a brief overview of synchronous salient-pole alternator armature design and construction. Much literature is available that covers the theoretical aspects of this subject—particularly from a manufacturing viewpoint. From an application engineer's viewpoint, documentation of design considerations is not too prolific; this section attempts to address application considerations. The literature on armature windings abounds with terms relating to armature characteristics, materials, design, and construction. Unfortunately, these terms are not universally consistent. This section considers that the reader is familiar with the terms and their usage—at least as customarily applied within the Bureau of Reclamation. Discussing considerations involved in actual design of the armature winding including slot size, length, and number of slots is beyond the scope here.

8.8.2 Configurations

The emf (electromotive force) induced in a single coil side of an armature winding is not of sufficient magnitude to be useful in electrical power production. Several coil sides must be connected in a series string, with the voltage induced in each coil side additive to the others, to build up voltage to the required level. The current carrying capacity of each coil, and the series string in which it is connected, may not be adequate to deliver the required amount of machine power. In this case, several series strings may be connected in parallel to produce a series-parallel combination with both the required voltage and current capability. Such a series-parallel connection of coils constitutes one phase of a three-phase winding.

Hydrogenerators are invariably connected in a "wye," configuration, with the neutral connection grounded to reduce line-to-ground voltage stress on the armature insulation. However, the insulation is not graded. Each coil is insulated for full-line voltage and is usually identical to the other coils in the same machine.

Series voltage build-up may be accomplished by passing a conductor around through the same slots several times. This most frequently found type of winding is called "mulitum" winding. Although the voltage induced in each successive pass of a conductor through the slots is added to the voltage induced in the preceding pass or turn, the voltage difference between adjacent turns is relatively low. Any given coil may be series connected anywhere from the neutral end of the winding to the line end; therefore, each coil must be insulated from ground for full-line voltage.

Series voltage build-up also may be accomplished by a single pass through of a conductor through a slot with subsequent series connection to other conductors—each making a single pass through another slot. This configuration is called a "single-turn" winding, and each single conductor is usually called a "bar." Industry terminology may describe single-turn winding as "bar winding." Each bar constitutes one-half of a full coil. Another industry term for a bar or one-half coil is "coil side" (rather nondescriptive) and may be used to describe the side of a coil as compared to the top or bottom of the coil.

The connectors required to join coils in a series string are called "series connectors," "pole jumpers," or "coil jumpers." Similarly, connectors used for parallel connections between series strings are "parallel connectors," "circuit rings," or "ring bus." The jumpers and circuit rings are located at the top of the armature in vertical-shaft machines to facilitate assembly. The ring buses are connected to main lead extensions to take line-voltage power out of the machine, and to take the winding neutral main leads to the neutral or "wye" connection. The CTs (current transformers) are placed in the main and neutral leads, and in series strings of larger machines, and usually are located on the stator wrapper plate, inside the air housing. The PTs (potential transformers) and surge protection are connected to the main leads, usually outside the air housing. Some machines are equipped with housing extensions or blisters to permit installation of PTs, surge protection, and exciter taps within the air housing.

Bus connection points are silver plated to ensure a low resistance connection. It should be noted here that silver is used not only because of its inherent low resistivity and chemical stability, but also because the common oxides of silver are also low resistivity.

Hydrogenerator windings are of the "distributed type," wherein the coils are distributed at locations around the stator core. The coils in any string are connected to form groups. For example, an 11-coil multiturn series string might be formed by connecting 2 coils, with a side of 1 coil installed in a slot immediately adjacent to a slot containing a side of the other coil. These two coils would form a group of two, be jumpered to a second group of two—then to a third and a fourth group of two—and finally to a final group of three coils.

Thus, the series string would be 2+2+2+2+3 for the 11-coil string. Obviously, coils installed side-by-side cannot share precisely the same position relative to a rotor pole at the same instant of time. Therefore, the magnitude and wave shape of the series string voltage is a resultant of the voltages induced in each coil side. Similarly, hydrogenerator armature windings are usually fractional pitch, which means that the span of slots encompassed by one coil ("coil pitch") is not the same as the span between centers of adjacent poles ("pole pitch"). Thus, one side of a coil is not located so that it is opposite precisely the same part of a rotor pole as the other side of the coil. As a result, each coil side is exposed to a different flux from the poles, and a resultant of coil side induced voltage magnitude and wave shape is produced. By properly selecting coil grouping and pitch ratio, the machine designer can produce a winding with improved wave shape and low harmonics. The overall quality of the wave shape is controlled by specifications limits of "Deviation Factor of Open Circuit Terminal Voltage Wave," which is the ratio of the maximum difference between corresponding ordinates of the voltage wave to an equivalent pure sine wave when the waves are superimposed to make the difference as small as possible, and by specifications limits of TIF (telephone-influence-factor). The TIF is the weighted sum of all harmonics in the voltage wave; it is a reflection of the relative objectionable effect produced by inductive coupling of the voltage wave with telephone communication circuits. Both the Deviation Factor and Telephone-Influence-Factor are defined by ANSI Standards [7], with permissible limits upon each. Bureau specifications require machines to meet the standard limits. It should be noted that harmonics are caused by many factors other than pitch ratio and coil grouping. The slots in the core are one of the major factors influencing the presence and the fundamental frequency multiplier of the harmonics.

A winding may be "skewed" to reduce the effects of ripples in the airgap flux produced by the slots ("slot ripple"). The skew is accomplished by placing the stator core keys out of the plumb, which causes a small displacement of each succeeding layer of core laminations. Typically, the skew is one full slot pitch in the core length.

Armature windings in hydrogenerators are usually of the "lap" type because this configuration lends itself to form wound coils and also tends to minimize the required number of coil jumpers. "Spiral" windings are not used due to the requirement for different sizes and shapes of coils for the various turns of each spiral. Using single turn coils tends to make "wave" windings more advantageous.

8.8.3 Materials and Construction

The ANSI Standards C50.12 [6] permits indirectly cooled hydrogenerators to be furnished with either Class B (130 °C hotspot) or Class F (155 °C hot-spot) armature insulation systems. Bureau specifications limit manufacturers to Class F materials only, and specifies the maximum permissible temperature rise—as measured by embedded detector—over a specified ambient air temperature. In addition to the armature winding, all materials in the slot section including wedges, under wedge springs, side fillers, and spacers are required to be Class F. Although this requirement has not been placed on materials used for supporting the armature in areas outside the slot, most manufacturers have used Class F materials in those areas as well.

It is not practical to actually measure maximum hot-spot temperatures because the hottest spot in a wound stator may change with different loads and conditions. Therefore, ANSI Standards C50.10 [7] requires that the temperature detectors be located *between the coils in a slot* and along the length of the slot usually having the highest temperature. An expected or calculated difference between measured temperature and maximum temperature is called the "hot-spot allowance." The main purpose of an RTD is to indicate the temperature of the winding as compared to the rest of the wound stator. The hottest copper, or strand, temperatures always occur in those strands closest to the airgap.

8.8.3.1 *Conductors*.-Magnetic flux in a stator core is not uniformly distributed. The irregularities produced by the slots and the air ducts induce different emf in various areas of the conductors in the slots, while rotor eccentricity and ellipticity create a nonuniform airgap. These factors create a nonuniform current flow.

To reduce eddy current losses to a minimum practical value, the turn conductors are stranded with individual strands insulated from each other. Then, the stranded conductors are twisted in a manner so that the individual strands conduct current through as many different levels in the slot as practical.

Most hydrogenerator windings are installed so that one side of each coil is placed in the bottom of the slot and the other side is placed in the top of the slot.

Multiturn coils are frequently made with a 180-degree twist in the conductor somewhere in the coil—usually in the shoulder area of the coil. Although this construction does not completely transpose each strand in each coil, it is fairly effective. The coil end connections should be solid, which facilitates installation and repair.

Another method of transposing multiturn windings is to continue strand insulation integrity through the coil lead connections, and then transpose the strands in the coil jumpers. This method is fairly effective, but the installation time and cost is higher than for the previous 180-degree twist method. Strands making up a coil side, or bar, of a single turn winding are formed in a way so that each strand forms a "zig-zag" current path across, up, and down as it passes through the slot. This construction is called a "Roebel" transposition. Bureau specifications require a minimum transposition of 360 degrees in the slot section, which means that each strand will provide a current path through every strand position in the bar. Transpositions of 540 degrees are common in some long core machinery like that found in turbo-alternators. The special forming of the zig-zag shaped conductors for a Roebel transposition and the necessity for skilled, hand-application of strand insulation make this configuration expensive to manufacture.

Coil connections between bars of a single turn winding are rather basic because strand insulation integrity need not be retained between different bars. Bar connectors are frequently flat copper plates brazed to connect all strands in both bars. Hollow or solid copper tubes, or formed flat bars, may be used for series connection of coil groups.

Solid copper tubes or bars are most frequently used for circuit rings. Some machines are furnished with laminated conductors that facilitate forming and reduce "skin effect" loss. The solid construction offers great mechanical strength and low construction cost. Bureau specifications require circuit rings to be of solid copper construction.

Considerable difficulty has been experienced from using lead-tin ("soft") solder to complete connections in armature windings. The joints secured by soft solder tend to deteriorate with age and develop excessive heating at the joint. The excess heat adds to the problem, and winding failures (including fires) have resulted. To prevent such failures, the Bureau has placed a requirement in purchase specifications that all connections be brazed using a filler material having a melting temperature above 800 °F (427 °C). This requirement permits manufacturers to use silver solder; it is a brazing alloy containing silver and does not contain lead or tin. The various lead-tin alloys used for "soft" solders have melting temperatures below this specified temperature.

Bureau specifications have not placed restrictions or requirements on the copper used in making strands, series connectors, circuit rings, or connector fittings. The copper is selected by the manufacturer to meet performance requirements. Some hydrogenerators have been manufactured with aluminum conductors; however, the Bureau has not permitted conductors to be of any material other than copper.

The copper wire used for forming strands is drawn from large reels during manufacture. Some manufacturers splice wire from a nearly exhausted reel to a new reel to make one continuous wire. However, such a splice creates a weak spot and strand fracturing has been found to occur after coil formation. To prevent this possibility, Bureau specifications require the strands to be continuous and without splices in the coil. Lengths of wire, at the end of a reel, that are of insufficient length to complete a coil or bar may not be used in Bureau machines.

8.8.3.2 *Insulation*.-Armature winding insulation has a low impulse strength compared with transformer insulation and other equipment insulation exposed to power system surges. As a result, special machine surge arresters and surge wave shaping capacitors are connected close to the generator terminals for winding protection.

The armature insulation of a hydrogenerator is undoubtedly the "weakest link" of the components that compose the machine. The insulation is vulnerable to damage resulting from chemical and/or mechanical changes because of temperature and time relation (normal aging), chemical attack (environmental conditions), excessive thermal conditions (overheating including fire), mechanical distress (fatigue, flexing, abrasion, foreign object intrusion), and excessive voltage stress (outright breakdown, partial discharge). Any one of these, or any combination of these changes can lead to a catastrophic failure.

The ANSI Standards C50.10-6.1 [7] define an armature insulation system as inclusive of the coil insulation, coil connector insulation, coil support insulation, and the coil support system (wedges, fillers, blocks, ties, etc.). This subsection describes materials used for various parts of an armature insulation system.

Industry-wide experience indicates that armature insulation failures are the principal source of unscheduled outages. Because of this, more articles have been written, more standards exist, more detailed specifications have been developed, more procedures explored, more testing performed, more concerns addressed, more opinions stated, and more attitudes expressed regarding "proper" insulation than for any other machine component. Consequently, considerable progress and improvements have been achieved, especially in the material used to bind the insulation into a solid mass.

In older machines, insulation was usually formed of mica and bound with asphaltic bitumen compounds. This insulation became somewhat plastic when heated, which facilitated installation in the slots during machine fabrication. The material also tended to flow sufficiently to form bulges at the air ducts, which limited vertical movement or slippage in the slots. Unfortunately, this thermoplastic tendency also created problems of tape separation, binder loss leaving voids, and other deterioration that led to inservice failures. Groundwall working dielectric stress levels with asphaltic bound mica were about 35 or 40 V/mil (volts per mil) of groundwall thickness, with 40 V/mil being a nominal average and 50 V/mil being a maximum stress. In comparison, thermosetting binder groundwall insulation permitted design stress levels up to 75 V/mil, with 60 V/mil being the most common.

Polyester and epoxy ("thermosetting") resins have demonstrated superiority over asphaltic bitumen binders, and widespread availability in the industry has permitted the Bureau to limit specifications requirements to polyester and epoxy resins. The epoxy resins have proved to exhibit slightly higher voltage endurance characteristics over the polyester-resin binders, but may produce a harder, "slicker" surface, which may prove to be a handicap if not properly installed.

The initial "hard-insulation" windings installed used polyester resin binders. Manufacturers have gradually adopted various epoxy resins to replace the polyester resins (circa 1970). Some manufacturers use a hybrid combination of these two types of resins.

Generally, polyester resins create a slightly more flexible, softer insulation than can be achieved with epoxy resins. However, epoxy resins can be formulated to produce cured insulation with differing degrees of flexibility. Some insulation systems provide greater flexibility in the insulation used for the end-turn diamond portion of a multiturn coil than in the slot portion of the coil. This design is permitted by Bureau specifications—provided a proper joining of the different resin systems is made. The type of resin (polyester, epoxy, or in combination) is not restricted in Bureau specifications.

A Bureau memorandum included[3]:

> "Most of the epoxy and polyester resin systems used as bonding and encapsulating materials in conjunction with modern insulation materials do emit toxic gases when severely heated and/or burned. The toxicity of these gases and decomposition products vary with the rate of burning, temperature rise, original cure time, and various manufacturers' anti-oxidant and stabilizer additives. Generally, such toxic materials as fluorides, chlorides, cyanides, formaldehyde, aromatic esters, alcohols, amines, peroxides, styrenes, and others are commonly released.
>
> "During field installation of windings, many of these toxic materials are released in concentrations at or near the threshold limit values until initial curing has been completed. However, under normal operating temperatures the release of these materials is not significant.

[3] Memorandum from the Chief—Division of Safety to: Chief—Electrical Branch on the subject: "Epoxy or Polyester Resin-Type Insulation Used in Generator Armature Windings and the Toxic Gases Given Off Under Fault Conditions," June 8, 1978.

"Employee exposure to these toxicants is maintained within permissible limits during field applications through the use of skin creams, protective clothing, respiratory protection, and ventilation systems. The controlling of fires involving epoxy and polyester resin bonding systems, as in any electrical insulation fire, requires the use of self-contained breathing apparatus and adequate training to protect employees against exposure to high concentrations of toxic materials.

"Realizing the need for such procedures and training, Reclamation O&M bulletins require self-contained breathing apparatus and adequate fire fighting training for employees at all powerplants and major pumping plants. Additionally, all generating units are equipped with automatic fire suppression systems."

Exclusive use of polyester and epoxy ("thermosetting") resins solved some performance problems; however, they created some new problems not encountered with the older systems:

1. The smooth, hard surface of the coils does not lock into the slots like the older soft insulation. As a result, the coils tend to slip downward within the slots during operation.

2. It is necessary to bend the coils (multiturn configuration) for installation into the slots, and the hard, more-or-less brittle insulation tends to crack when bent.

3. If the coils are not tightly packed into the slot for the entire length of the slot, the coils will vibrate against the slot side and erode the protective coverings.

The problems cited above with thermosetting resin systems are primarily because of mechanical rigidity. However, their overall superiority has caused asphaltic bitumen binder systems to virtually disappear from the market. If careful attention is given to proper installation and maintenance of the thermosetting ("hard insulation") system, a satisfactory winding life can be realized. The above problems indicate proper design, and installation are both critical to successful performance.

Proper design provides a margin in average insulation strength, to compensate for installation variations, but not enough to provide protection from failures resulting from installation damage or from operational deterioration.

Polyester or epoxy resins may be used to fill the caps surrounding the bar end connections of single-turn windings. Usually, the caps are of molded fiberglass construction that are made specifically for the purpose. The resin is placed in the reservoir formed by the caps and is cured to securely bond the cap to the bar groundwall insulation.

Some Bureau generators—equipped with hard insulation systems—were furnished by the manufacturer with air-dry solvent type varnish as a binder for jumper and circuit ring insulation and armor coverings. The armature coils for these windings met all specifications requirements, but the specifications did not indicate that the jumpers and circuit ring insulation had to meet the same restrictions as the coils. The air-dry varnishes were thermo-plastic and flowed from between insulating tape layers when exposed to normal inservice heating. The exposed varnish proved to be quite flammable, and presented a significant fire hazard. This situation led to the present Bureau specifications language that does not permit solvent-type varnish in any part of the armature winding.

Mica usually forms the basic insulation for most systems; however, glass, dacron glass, asbestos, or other inorganic materials have been used. Various classes of electrical grade natural mica, such as "phlogopite" or "muscovite," may be used for armature insulation, with phlogopite having slightly better electrical characteristics. The mica may contain various organic and inorganic inclusions, which can affect its suitability for electrical insulation; therefore, the mica must be graded and classed before use. Bureau specifications limit mica splittings to a NEMA grade C classification as given in standards for Manufactured Electrical Mica (F1-1-1983) [9].

Synthetic mica is available, but its use in hydrogenerator insulation systems has not been documented. Synthetic mica appears to be primarily considered in high temperature applications, over 1832 °F (1000 °C).

Mica is mechanically strong in compression, but relatively weak in tension and bending. Fractures or creepage paths are the most common dielectric failure sources. Mica has high thermal stability, chemical inertness, good physical properties, low dielectric loss, and high resistance to corona attack (voltage endurance). All solid insulation has electrical strength characteristics, which are time dependent. That is, the insulation's life is shortened by exposure to increasingly higher voltages—an exponential characteristic. An insulation material may at first have apparent indefinite life at one level; secondly, a reduced but measurable life at perhaps twice that level; and then suffer virtually instantaneous failure at twice the second level. This characteristic is the basis for some opinion that excessively high or frequent hipot testing can reduce an armature winding's life.

Electrical grade mica may be attacked by various acids including carbonic acid, which is water containing carbon dioxide, and it may delaminate if contaminated by oil.

Mica may be formed into tapes by backing mica splittings or platelets with glass or polyester tapes, or it may be formed into a paper like material called "mica paper" or "mica mat." Mica paper contains only mica, and it is relatively weak mechanically. This paper may be strengthened by resin impregnation or by attaching it to a backing material. Tapes, using either mica flake splittings or mica paper bonded by resins to polyester or glass cloth, are widely used by the industry. The Bureau prohibits using mylar tapes for backing material because mylar is subject to degradation in the presence of corona, and mylar may not permanently bond with the resins.

The tapes may be "B-staged," which is a process whereby the mica paper or splittings are attached to the backing tape with a semicured resin. These tapes may be described as "resin rich" tapes. Final curing is accomplished after the tapes are applied to the coils. The surplus resin flows from the tapes during curing to fill voids that would otherwise exist in the coil insulation.

Asbestos was used for many years as one of the components in an insulation system. The most frequent uses were in strand-separation insulation, as an overall armor covering on the outside of the coils in the slot section, as coil separators, and as slot filler material. Present Bureau specifications prohibit asbestos in any part of the insulation system, or in any other part of the generator.

Glass and/or polyester binder tapes are used to provide an overall cover over an insulated coil, jumpers, circuit rings, and main lead extensions; however, the Bureau has not limited the manufacturer's choice between the two tapes. The polyester tapes absorb the bonding resins better than the glass tapes, and produce better bonds with the mica tape insulation. The polyester tapes are also said to provide better scuff and abrasion resistance when installing coils in the slots.

Glass or polyester-glass fibers may be used to insulate individual conductor strands. Usually, these material are applied as filaments wound around the conductor, fixed in place with resin, or they may be fused to the copper strands. Some manufacturers use a semicured resin to saturate the filament covering. The resin is completely cured after the strands are formed together to make a coil turn.

8.8.3.3 *Protective and Supporting Materials*.-Three different types of paint are applied to the outside of an insulated coil. The coils' slot section is painted with a relatively low resistance or semiconductive material. The paint extends beyond the slot a few inches above and below the core, and provides corona protection in the slot. A second semiconductive paint, "grading paint," having a somewhat higher resistivity than the corona protective paint, is applied to the coils in the areas above and below the core. The paint extends several inches from the corona paint toward the end-turn portion of the coils. Some manufacturers use a grading paint that has an inverse voltage gradient characteristic. As the voltage gradient increases, the resistance of the paint decreases. This permits a relatively uniform voltage change over the grading area. A third covering of synthetic enamel, usually red, is applied to the coils' end-turns and to the coil jumpers and circuit rings.

All coil-supporting material in the slot except wedges and under-wedge springs are required to be semiconducting. The RTDs installed in the armature slots are required to be coated with a semiconducting paint before installation. Using semiconductive materials permits discharge of corona without shorting the stator core laminations. Actual resistance of semiconductive materials can vary from less than 10 to more than 10,000 ohms—depending on the manufacturer's selection.

A silicone elastomer, RTV (room temperature vulcanizing), has been used as slot filler. Some manufacturers have used nonconductive (RTV) material in various configurations with conductive (CRTV) material. The manufacturers' reason for not using side filler composed of 100 percent conductive elastomer is cost. Apparently, the conductive material's cost is appreciably higher than nonconductive material. The success of armature windings packed with CRTV has been much better than windings using CRTV in combination with RTV. Actually, CRTV-packed windings are much better than any other winding packing method. The intent for future Bureau specifications is to require a semiconducting paste material that will solidify at room temperature on the one-half coils of a bar winding. The bar and paste are to be placed in a semiconducting envelope or "shield" having a U-shape to enclose the bar; then, the assembly is inserted into a slot before the paste solidifies. The semiliquid paste forms bulges at the air ducts, and after paste solidifies, locks the coil sides into place in a manner similar to the old asphaltic binders.

Another possible acceptable practice would be to permit the coils of a multiturn winding to be installed with an "interference fit" in the slots. This scheme would allow using mica sheets that are driven between one side of a coil and the slot side to firmly force the coil against the other side of the slot.

Blocking material, between coils in the end-turn area and attached to coils next to the top of the core in older generators, was usually maple wood or micarta blocks. Current practice uses phenolic laminate or polyester glass laminate covered with a material such as dacron felt that is impregnated with polyester or epoxy resin.

Glass cord, roving, or tape is used for support ties, and slot filler paper may be made from various polyester materials that have been impregnated with a carbon (graphite) material. The under-wedge ("ripple") springs are made from fiberglass material. These springs may be strips having a general sinusoidal undulation when looking at the edge of the strip, or the wedge itself may provide the spring force acting on flat filler strips. This latter configuration uses a drive wedge between the bore side wedge and flat filler strips next to the top of a coil side. Although this system is not technically an "under-wedge spring," it provides the same function which is a continuously applied radial force to the coil.

Coils in older machines were secured by wedges made from various materials such as micarta. Current Bureau specifications require these wedges to be made from glass matte base laminate conforming to NEMA grade GPO-1 or GPO-2. At least three wedges in each slot are required to have holes drilled at the appropriate spacing to permit measurement of under-wedge spring compression by gauging spring deflection. Wedges may be either single-piece or "two part radial-pressure type." The two-part system uses a drive-wedge method to develop radial pressure on the coils. Some systems meeting this intent have been described as "Three-Part Radial Pressure Wedges." Notches are formed along the edges of each wedge. The notches are spaced to match the air ducts in the stator core, and when driven into the core slots to the correct position, help to direct the flow of cooling air into the air ducts. The notches may be placed along one edge only in unidirection rotation generators and along both edges in reversing pumping-generating units.

The Bureau requires a final overall coat of light blue-, or buff-colored epoxy paint be applied to the completed armature winding and core. The purpose of this paint is to facilitate inspection for contamination and corona activity. Manufacturers have shown a preference for black paint to improve the radiation of heat to the cooling air. Black may reveal the presence of corona activity, but it tends to obscure the presence of contamination and other deterioration. The buff-color paint has not caused any protest from manufacturers regarding heat radiation characteristics.

8.8.4 Installation and Assembly

Many design engineers' opinion is that most armature failures in machines having multiturn windings originate as turn-to-turn failures that evolve into groundwall failures. A considerable amount of evidence supports this theory. The evidence has led to current Bureau practice requiring single-turn windings to be furnished wherever practical. Strand insulation failure also has been identified as a probable source of undetectable hot spots which evolve into ground-wall failure. Unfortunately, from a failure forensics viewpoint, most armature failures produce enough damage in the failure area that the exact source of the failure is destroyed or indiscernible.

Faulty installation has been positively identified as the source of many armature winding failures. This has been particularly true with thermosetting resin-bonded windings. Installation design and the procedure for installing the coil in the slot is critical to successful operation. Proper design requires considerable manufacturing experience and expertise, and skilled craftsmen are required to perform the job expertly.

Usually, Bureau specifications require factory installation of the coils to the greatest extent possible to take advantage of the proficient skills at the factory. Contractor field personnel seasoned in factory training can provide a professional installation.

8.8.4.1 *Multiturn Coil Fabrication*.- The individual strands that make up a turn may all be insulated separately, or every other strand may be insulated. This second option, with every other strand insulated, theoretically provides separation of every strand while permitting reduced cost through the use of uninsulated wire for one-half the strands. However, extra care must be taken to ensure that displacement of one stack of strands, as compared to an adjacent stack, does not occur. Should a displacement occur, corners of strands in adjacent stacks may come in contact with each other and thwart the purpose of insulated stranding. Such displacement frequently occurs at bends made during the forming of a coil. The strands may be bonded before coil forming to prevent strand movement; a filler may be used to even-up the turn sides before application of turn insulation.

After the required number of strands are assembled to turn size, insulation is applied to obtain the required turn insulation level; thence the conductor is formed into loops to obtain the required number of turns. Then, a spreading machine is used to form these loops into the basic coil shape. Presses may be used to achieve proper turn shape and positioning. Groundwall insulating tapes are applied to the assembled turns and overall armor tapes are placed over the groundwall; then, the assembled coil is cured.

The Bureau has experienced inservice coil failure wherein, subsequent dissection of coils identical to those that failed revealed that the manufacturer had trimmed or "shaved" the turn insulation off formed turns-of-coils before application of the groundwall. Apparently, this procedure evened up the sides of the coil sufficiently to permit application of minimum groundwall without encroachment on the maximum cross-section of finished coil that could be placed in the slot. The turn insulation between adjacent turns remained intact, and full groundwall insulation between the virtually bare sides of the turns and the slot was applied. However, a creepage path was formed bridging the insulation left between adjacent turns, and turn-to-turn failures resulted. Bureau specifications now prohibit shaving or reducing the cross-section of the turn insulation for any reason. Prior to groundwall application, using a filler to even up the surface of assembled turns is acceptable.

Currently, manufacturers have been permitted to determine the voltage stress magnitude for the turn insulation. Specifications are now being written to limit turn-to-turn voltage stress to no more than 3 volts per mil of insulation thickness.

Various processes are used by different manufacturers during coil formation. Some manufacturers use semicured resin bonded tapes (B-staged) that have been impregnated with sufficient excess resin to ensure that flow occurs—during the curing process—to displace all gases and to fill all voids. Other manufacturers may use a VPI (vacuum-pressure-impregnation) process; whereby, the assembled coils are placed into a tank—vacuum drawn and held—the tank and coils are flooded with resin and pressure applied. The VPI system objective is to achieve a void-free insulation. Because many different methods are capable of achieving the same quality of end product and because some of these methods are proprietary, the Bureau requires that coils comply with the objective for eliminating voids regardless of the method. Previous specifications wording required a "void-free" insulation, but some manufacturers objected that this the wording as to restrictive. The phrasing was changed to "minimal voids or air pockets." The presence of voids in an insulation has been identified as being one of the basic sources of partial discharge and armature winding failure.

During the period when "thermosetting" insulation was available from some sources and not from others, and while asphaltic binder systems were still acceptable, the Bureau was concerned that the thinner groundwall thickness of the thermosetting coils might actually have less basic insulation (mica) than was present with the asphaltic binder systems. The possibility was considered that a manufacturer might take advantage of the higher dielectric strength of resin binders (higher than asphalt) and reduce the amount of the relatively expensive mica insulation. To counter this possibility, Bureau specifications were written to require a minimum net mica thickness. Following the exclusion of asphaltic binders in 1967, the net mica thickness requirement was removed from the procurement solicitation specifications language.

The groundwall tapes may be machine applied in the slot section, and hand applied in the shoulder and end-turn areas. This procedure leaves a joint or transition between the two taping systems; care must be taken to prevent possible leakage paths from forming at the joint. Bureau specifications include a design drawing that shows acceptable methods and places for making such joints.

8.8.4.2 Single-Turn Coil Fabrication.- As indicated (see sec. 8.8.3.1), the strands making up a coil side, or bar, of a single-turn winding must be carefully hand assembled. Special pieces of insulation are placed at the strand crossovers to avoid creating spaces or voids. The Roebel transposition of strands occurs only within the slot section; strands in the shoulder and end-turn areas are of straight, nontransposed configuration. The strands are formed into the bar shape and a semicured resin applied to hold the strands in position while the groundwall is applied. Bureau specifications require strand bonding of the slot portion before applying groundwall insulation. Machine taping of the groundwall is frequently over the entire bar—except for end connectors.

Two bars, or coil sides, compose a single coil may be connected either before or after installation in the stator slots at the manufacturer's option. If connected before installation in the slots, the Bureau requires that the connection be made at the bottom of the stator core and that groundwall insulation be applied continuously over the two coil sides and their connection. The connection must be brazed to ensure complete connection of all strands. If the bars are installed in the slots before making coil side connections, the bars are brazed and the connections insulated by using caps filled with a resin that bonds to the factory applied groundwall insulation.

8.8.4.3 Multiturn and Single-Turn Winding.-Following the groundwall application to either a multiturn or a single-turn winding, armor tapes are applied and the coil is pressed and cured to final shape and cross section. Close dimensional control of the slot portion of the coils must be achieved during this procedural step to ensure proper fit and slot space usage.

Corona and grading paints are applied to the slot section and end-turns, and various tests are conducted to determine coil quality. It is considered good practice to install coils having higher acceptable power factor tip-up test results near the neutral ends of the winding.

Bureau specifications require coils to be wound into the stator slots in the factory to the greatest extent possible. Stators that are too large to be shipped in one piece are made in sections to facilitate shipping; extra-large machines have stator cores that are field stacked and require complete field installation of the winding. The slots adjoining splits of sectional stators are left unfilled until the stator sections are erected on their foundation in the field. Proper coil installation procedures must be established by the manufacturer, and controls observed to ensure correct successful performance.

As discussed (sec. 8.8.3), RTDs are located between the two coil sides occupying a slot. The ANSI Standards [7] require at least six RTDs to be installed in an armature. Good practice is to place at least one RTD in each series string in each phase. This practice is not noted as such in the specifications; more precisely, an actual number of RTDs is required. This quantity of RTDs is based on the Bureau's estimate of the probable number of strings to be supplied, and then increased to ensure that spares are installed to compensate for functional losses of RTDs during service.

Spacers, of the same thickness as the RTDs, are installed between the coils in slots where no RTDs are located.The coils are installed in slots using either the U-shaped shields or are interference fit into the slots, under-wedge filler and springs are installed, and wedges tightly driven to fix the coils into the stator slots. Care must be taken to avoid damage to the corona paint when inserting the coils into the slots.

Wedging of the coils into the slots of older machines was accomplished by driving wedges into the slot-wedge grooves, with strips of filler material placed between wedge and coils, to develop radial pressure on the coils. Experience indicated that thermosetting resin-bonded coils undergo a small amount of volumetric shrinkage during the first few months of operation. This shrinkage caused relaxation of pressure exerted by the wedge and under-wedge filler, and allowed the coils to become loose in the slots. Using spring-type under-wedge filler has effectively solved this problem.

The radial electromagnetic force acting on the coils is a function of the rms (root mean square) current, slot width, and number of turns in the coil. The wedge and spring are required by the specifications to exert a force at least 150 percent greater than the maximum radial electromagnetic force acting on the coils. Also, the amount of spring compression is required to provide at least 150 percent of the amount of shrinkage expected in the insulation over the life of the coils. The first value (electromagnetic force) can be readily calculated once the armature winding configuration has been selected by the manufacturer. The second value (shrinkage) is more difficult to determine because the amount of shrinkage to be expected is dependent on the materials used and the degree of curing accomplished before wedging is completed. It should be noted that *maximum radial electromagnetic* force probably occurs as a result of short circuit current.

The following actions may not necessarily be performed in the sequence listed. Following wedging and end-turn connection, coil spacers covered with resin soaked felt material are inserted and tied into position between adjacent coil end turns. The resin cures after installation and ensures complete contact with and bracing between the coil end turns. The end turns are then tied to supports that are frequently in the form of metallic tubular rings located between the coil end turns and the stator wrapper plate at both ends of the stator core. The rings are, in turn, supported from the machine frame. These rings (surge rings) provide resistance to the electromagnetic forces acting on the coil end turns during normal operation and short circuit, and support the weight of the coils. The rings are frequently covered by insulation that is not necessarily the same insulating materials or voltage insulation level as the winding, and the ring metal is completely grounded.

Circulating currents may be produced in the metallic surge ring, and detrimental heating can occur. Insulated joints are placed at intervals around the ring to prevent flow of such current. Blocks are attached to the sides of coils where the coils exit the stator core at the top. Usually, the blocks are fixed into position using resin soaked tapes or cord. After attachment to the coils, the blocks prevent downward movement of the coils in the slots. The cord is weaved in a "figure 8" configuration around the coils where the coils exit the core at the bottom. This cord configuration or other device is installed about 1/2 inch (13 mm) below the stator core. This location will permit any loose slot filler material to move downward until it is blocked by the cord configuration. This limited amount of migration should facilitate inspection for loose material while still preventing sufficient material movement to cause damage. Several occurrences of slot filler movement, where the material moved downward and air movement caused the material to vibrate or slap against a coil side and erode away the groundwall, has caused the Bureau to require the "figure 8" tie.

Connections to the series connectors and parallel rings are brazed and insulated. Bureau specifications do not permit the use of preinsulated jumpers. Connecting points between coils to be connected are usually close together, and the required jumpers are fairly short. Usually, some adjustment or bending of the jumpers is required to make the connections; any insulation on the jumpers probably would be damaged by the twisting and bending action if the jumpers were preinsulated. Also, brazing heat conducted along the fairly short lengths of the jumpers could damage the bond between jumper insulation and conductor. Therefore, jumpers are required to be insulated after the conductor connections are made.

The circuit rings are formed in a circular shape from solid copper bars, usually with the long axis of the rectangular cross section of the bars in a horizontal plane. Solid copper bars with a circular cross sections also have been furnished. The radius of the circuit rings is selected to facilitate mounting the bars in the machine. The location most frequently selected for mounting is the inside perimeter of the stator wrapper plate near the top of the generator. Circuit rings are insulated—using the same mica tapes as used on the armature coils—after the copper bars have been formed to their final shape. Forming the bars after application of insulation would undoubtedly create fractures that could lead to failures.

The insulated circuit rings are installed in the machine on brackets attached to the wrapper plate.

Blocking material is located on both sides of the rings, and then clamped firmly in position. Usually, the rings are too large to be handled in one piece so splices must be brazed between arcs of the bus making up the rings. The splices are insulated after installation in the machine. Connections from the various series strings are similarly brazed to the rings and insulated after installation. Because of the high currents carried in the circuit rings, extremely high forces act on the bars; and deformation of the rings have caused machine failures. The supporting and clamping system, as well as the arrangement of the circuit rings, is critical to machine endurance during close-in short circuits.

Usually, the main lead extensions are connected to the circuit rings by bolted connections rather than by brazing. Polyester or epoxy putty is used to smooth the contour of the bolted joint, and hand-applied insulating tapes are applied over the joint. Main and neutral leads may be reversed by removal of the insulation and unbolting the connection. The shape of the main lead extensions, or removable links in some cases, is such that by repositioning the pieces of extension the relationship of the main and neutral leads are reversed. Usually, main lead extensions are preinsulated before installation.

Reversal of the main and neutral leads may be determined necessary to extend the service life of a winding. Corona activity or other damage near the line end of a winding may have placed the machine in jeopardy of a destructive inservice failure. By reversing the main and neutral leads, the voltage stress on the deteriorated portion of the winding is reduced and the portion that had previously experienced low voltage stress, and probably less deterioration, is operated at line voltage.

Large machines, having several series strings per phase, may have leads from the strings or groups of strings in parallel brought out through circuit rings to facilitate installation of current transformers. This configuration is used to facilitate "split-phase" relaying; it allows detecting turn-to-turn failures in multiturn windings. This configuration may increase the complexity of the ring bus installation.

Generally, the main lead terminals are arranged so the voltage for each phase (A, B, C) reaches a maximum in sequence of direction of rotation, when viewed from rotor looking down on machine. For horizontal-shaft machines, the viewing position is from end opposite from turbine.

The winding may be operated at low voltage following complete installation to completely cure field-insulated joints. This operation is similar to the "dryout" run required for the older asphaltic binder insulation systems.

8.8.5 Tests

Armature windings are tested during factory assembly, during field assembly, following machine erection during commissioning, during acceptance testing, and at various times during operation for the life of the winding. Various tests are performed by the manufacturer and the manufacturer's suppliers on materials and combinations of materials used in the winding. Also, manufacturers may select random samples of coils and subject them to destructive testing. Results of these tests are not usually required by the Bureau; however, the tests are required according to ANSI and IEEE Standards.

The following factory tests and their results are required by the Bureau:

(1) *Strand test*.–This test determines the integrity of the strand insulation; it is performed using a procedure and voltage level determined by the generator contractor. The procedure and voltage level is reviewed by and must be approved by the Bureau of Reclamation. Successful passing of the test verifies that the insulation between individual strands in a coil has not been broached during coil assembly. Typical test levels are about 120 volts alternating current.

(2) *Turn-to-turn surge test*.–If multiple turn coils are furnished, the manufacturer is required to submit a procedure for this test for approval. The test voltage level is required by the specifications to be 21 times the turn-to-turn operating voltage of the coil, multiplied by the *effective number of turns* in the coil. The effective number of turns is defined as: the number of turns in the coil minus one. The time duration is required to be at least 3 seconds, but not more than 10 seconds. The actual time is determined by the manufacturer and submitted with the procedure for approval.

(3) *Dielectric test of each coil.*-Each coil is subjected to an alternating-current overpotential test having an effective level rms of twice rated machine line-to-line voltage plus 1000 volts, the sum multiplied by 1.5, for 1 minute. The 1.5 factor is used to conservatively approximate the crest value of the final proof voltage. For example, a coil for a 13.8 kV winding would receive an rms voltage of 1.5 [2 (13,800) + 1000] = 43,000 volts. Many manufacturers actually test each coil several times during coil assembly and installation in the core. The best test, from the client's viewpoint, is the one performed after the coils have been wedged into the slots.

(4) *Power factor tip-up tests.*-These tests are made as a measurement of the voids in the insulation, and are done according to IEEE Standard No. 286-1975 [10] or its latest revision. The recommended test voltages of this standard are 25 and 100 percent of the rated phase-to-ground voltage. The Bureau has used test values of 2.5 and 10 kV for a 13.8 kV (7960 volts, phase-to-ground) winding. The test voltage levels may be increased or decreased in proportion to the difference between 13.8 kV and the voltage rating of the machine being purchased. The power factor at each voltage is expressed as a percent; the numerical difference between the two values is used to determine the acceptability of the coil. Differences greater than 1 percent are a basis for rejecting the coil. The actual value of power factor tip-up is marked on the side of each coil. Some specifications have required that coils having higher, but still acceptable power factor tip-up be installed near the neutral end of the winding.

Failure of a coil to pass any of the above factory tests is a basis for rejection of the coil. Some manufacturers have indicated their desire to remove the flawed insulation from the copper conductors of a failed coil, reinsulate the coil, and retest until the coil hopefully passes. The Bureau has not permitted this practice as the possibility of damage to fused strand insulation or to the copper strands themselves, during reworking, is too great. Also, the residue left on the strands inhibits successful application of new insulation. Therefore, specifications are written to prohibit furnishing reworked coils.

Failure of coils to pass the factory dielectric test normally occurs at a rate of 2 or 3 failures per 1000 tests. Any increase in this failure rate would probably be indicative of an inherent problem in design or manufacture. A failure rate of 1 percent may be the maximum tolerable rate.

Many manufacturers have used d-c (direct current) high potential tests to determine the dielectric strength of the group of coils installed in a stator during each work shift. This type of testing limits the amount of disassembly required to remove a faulty coil; this procedure may be used in either the factory or the field during erection, or both. Industry-wide experience indicates that d-c testing is less damaging than a-c (alternating current) overpotential testing, it may reveal characteristics that can not be determined when using a-c "go-no-go" testing. The d-c "hipot" levels are selected at 1.7 times the a-c level.

An armature winding is subjected to many tests during acceptance testing. A discussion of these tests is in another chapter of this manual. However, it is noted (in this ch.) that two of these tests are made at the time of unit commissioning to determine the quality of the installed armature winding. These two tests are: (1) dielectric test—performed at twice-rated machine rms voltage plus 1000, and (2) the armature resistance test, which—in addition to its use in performance calculations—may reveal faulty brazed connections. The latter test is made on each phase separately, and noticeable differences between measured values may be indicative of a bad connection.

8.8.6 Performance

Ongoing experiences by the Bureau have indicated that one of the most frequent failure sources occurring in hydrogenerator armatures is a dielectric failure of the turn insulation of multiturn windings. This type of failure is not possible in a single-turn winding; however, a single-turn winding is more expensive to manufacture. Generally, competitive bidding will favor the multiturn configuration if bidders are given the option of furnishing either winding. The advantages to the Government of the single-turn configuration appear after the bidding, in the form of lower winding losses, elimination of turn-to-turn failures, and ease of replacement. These advantages quickly offset the initial cost savings offered by the multiturn configuration. Therefore, the Bureau has made a practice of restricting bidding to the single-turn, Roebel-transposed configuration if other machine parameters will permit. Factors such as core length, current density, terminal voltage, and slot size are used to determine if single-turn configuration is practical. These factors are determined by the manufacturer, and not available to the Bureau before bidding. However, manufacturers who may become bidders can be questioned regarding any limitations before the bids are solicited.

The Bureau has experienced generator failures produced by the failure of connecting joints in armature windings. As indicated (see sec. 8.8.3.1), some of these failures were produced by failure of lead-tin soldered joints. Other failures, including perhaps the most disastrous generator failure that the Bureau has suffered—the Grand Coulee Third Powerplant Generating Unit G21 Fire—were produced by the failure to properly braze a connection. Various procedures have been proposed to ensure that such conduction failures do not happen, including the exclusion of lead-tin solders. Testing for hot spots and measurement of winding copper resistance are also used to detect bad joints. The use of infrared thermography is considered to offer great assistance in locating hot joints and conduction failures.

Corona discharge is frequently involved in armature winding failures. Corona is an electrostatic discharge that usually occurs at voltages over 5000 volts. During corona discharge moisture in the air combines with nitrogen to form nitrous acid, which decomposes the winding insulation. Ozone, a powerful oxidant that can accelerate deterioration, is also produced by corona.

The number of turns per coil and the number of coils per string are other parameters of a multiturn winding that the manufacturer determines. Coils having relatively few turns must be series connected with considerably more coils to build up line voltage. A coil with relatively few turns would be expected to suffer fewer failures from turn-to-turn dielectric failure; however, the coil would require more series connectors, with the potential for joint failure, and would have high I^2R losses due to the length and number of series connectors. The coil with relatively few turns per coil may offer some advantages over the coil with many turns in that it may permit the coil to be bypassed or cut out without overly impairing machine output. This is a somewhat nebulous advantage because the possibility of a turn-to-turn failure is lower with the low-turn coil.

As discussed above, there are advantages and disadvantages that can be realized by different selections of turns per coil and coils per string. Bureau engineers have considered placing restrictions in purchase specifications that would limit the number of turns per coil to possibly improve some maintenance considerations, but industry reaction and efficiency factors have caused such considerations to be dismissed. Present specifications that permit multiturn coils do not place any restrictions on this choice by the manufacturer.

Armature windings for hydrogenerators are custom designed for each application. Off-the-shelf replacement parts can not be expected to be available after original manufacture, except for materials such as resins and some glass or polyester tie materials. Therefore, it is necessary to purchase sufficient spare parts and material from the original equipment supplier to ensure availability. Bureau practice has required sufficient spare coils to span one coil pitch as a minimum. If a manufacturer's design uses coils of different types in the winding, a minimum number of spares for each type of coil is required. In addition to the coils, sufficient mounting and supporting materials—including coil end connectors and series connectors for installing the spare coils—are required to be furnished.

Many forces act on the armature winding during normal operation and under fault conditions. These forces include mechanical, thermal, and electric potential (voltage) stresses. Electromagnetic forces acting on the coils are primarily radial, and considerable coil slot and end-turn supporting features are designed to resist such radial forces. Normal load and short-circuit radial forces acting on coil sides are a function of current flowing in each coil side in a slot, number of turns in each coil, and slot width. Coil sides having current inphase with each other develop the greatest radial forces. Coils connected in different phases of the winding, but occupying the same slot, exert radial forces that are a function of the sine of the 120 degree angle between the currents in each coil. In addition to the radial forces acting on each coil that must be resisted by wedging, radial forces act on the series connectors and the ring buses. Resistance to these forces is provided primarily by the surge rings in the end-turn areas. Vertical and tangential forces act on both the coil sides in the slots and on the winding components in the end-turn areas. End-turn bracing is shown on figure 8-16. Slot side fillers, and various blocks and ties

Figure 8-16. — Stator winding showing the bracing of end turns to prevent vibration under short-circuit stresses—asphaltic-type coils. Courtesy of General Electric Company.

are installed to resist the forces acting on the winding in those areas. Electromagnetic forces acting on the coil end turns tend to force the end turns into a semicircular form. Vertical forces, as a result of gravity and vibration, act on the entire winding. The tangential forces are produced by action between the rotating fields of the rotor and stator. Vibrational forces may result from any number of sources in the machine and the rest of the plant.

Thermal forces within the winding are primarily the results of I^2R heating in the strands of coil produced by normal loading. However, eddy currents also produce I^2R heating. Heating occurs primarily in those strands nearest the airgap, and is a result of slot leakage flux and differences in iron saturation at the tooth corners. Eddy-current heating is virtually independent of load current. If extreme, eddy-current heating can seriously degrade insulation and a dielectric failure can result. A rule of thumb would be that a winding's remaining life is reduced by one-half for each increment of 18 °F (10 °C) in temperature. Bureau specifications limit the temperature rise of an armature winding at rated load to 80 °C over a 40 °C ambient (120 °C maximum temperature. Leakage flux in the end-turn areas may produce emf that cause eddy current and circulating current heating that vary with load conditions on the machine. End-turn heating can be particularly severe during periods of low excitation.

Any force that produces damage to the corona shield on the coil in the slot section can be the source of a dielectric failure. A hot arc, called "slot discharge," may develop because of the loss of contact between the corona shield and ground. This arc may cause further loss of corona shielding paint, development of corona, and ultimate dielectric breakdown.

Any force that causes sufficient movement of the coil to produce a fracture in the relatively brittle insulation can also be the source of a dielectric breakdown and failure. Many forces, whose source is elsewhere in a generator or plant, may well culminate in action on an armature winding and produce a failure.

8.8.7 Summary

A complete discussion of armature winding theory, design, construction, application, testing, operation, and failure diagnosis is beyond the scope of this manual. The reader is referred to the literature for any matter of particular concern.

The armature winding of a generator may be described as the "heart" of the machine, and although it is designed and constructed with perhaps the greatest amount of care and attention given to any one component of the machine, "heart failure" remains the most frequent cause of generator problems.

8.9 AIR HOUSING

8.9.1 Introduction

Generators equipped with surface air coolers must have an enclosure, air housing, to ensure recirculation of chilled air without excessive leakage within the machine. The air housing is formed by the concrete foundation, metal plates installed on or between bearing bracket arms, and a concrete or metal wall around the machine. The housing may enclose the exciter of the machine. A generator may be installed in a concrete pit or barrel, which will also function as part of the air housing.

Outdoor plants, or plants that permit exposure of the generator to severe weather conditions, require a more complicated air housing design and construction than is necessary for indoor generator air housings. The collector rings, exciter and pilot exciter (if so equipped), PMG (permanent magnet generator), and other machine components may be housed within the air housing of outdoor generators. These components may be self-cooled, and are not covered by the air housing for indoor machines.

8.9.2 Functions

The generator air housing provides the following:

- Limits loss of chilled air to surroundings
- Routes ventilating air within the generator
- Minimizes entrance of dirt, moisture, and other contaminants
- Mitigates escape of ozone from the generator
- Limits loss of fire suppressant (CO_2 or other) during emergencies
- Retards loss of heated air during generator shutdown
- Provides support for accessories

- Provides for personnel access to various parts of the machine
- Suppresses machine-generated noise
- Provides physical barriers to limit access to hazardous areas

8.9.3 Features and Construction

The metallic parts of the air housing are made of steelplates that are supported by a metal framework. The plates are attached to the upper and lower-bearing bracket arms to complete the housing in those areas. Machines not equipped with an upper bearing will require a supporting structure, which resembles a bearing bracket, for the air housing deck plates. The vertical metal parts of the air housing are anchored to the concrete foundation.

Foam seals are installed at all conduit, piping, ducting, and other entrances to the generator to preserve air tightness. Gaskets are used to seal the air housing plates to the framework, bearing brackets, and foundation. Seals and gaskets required for generators installed outdoors must obviously meet different standards than those for indoor generators. The seals and gaskets not only prevent loss of chilled air, CO_2, and ozone; they prevent the entrance of dirt, moisture, and other contamination. Also, the gasket and seal material may function to assist in suppression of noise emanating from the generator. The material used for gasketing is selected by the machine manufacturer.

Ducting and baffles are provided to route the chilled air leaving the surface air coolers to the rotor-mounted fans. Some machines, such as small single- and two-cooler generators, also require the air housing to route the heated air leaving the stator to the coolers. This may produce an air housing that is nonconcentric with the stator. Any cooling system can be badly impaired if seals, ducts, or baffles become loose or damaged.

Eddies in the air stream can occur, and if they develop in areas around heat-producing parts, overheating of the parts can result. Special attention is required in the end-turn and ring-bus areas to prevent air-stream eddies.

Ozone is a chemically active gas that is considered to be toxic. Bureau specifications place limits on the amount of ozone permissible *within* the air housing, and also require tests to demonstrate that these limits are not exceeded. A tightly sealed air housing prevents the escape of any machine-created ozone into the plant to reduce danger to personnel.

The generator air housing alone greatly reduces the fire hazard presented by the machine. The air housing makes possible the installation of a fire suppression system for the machine, which would not be possible with an open air-cooled configuration. The CO_2 fire suppression systems used by the Bureau are discussed in section 8.15.

The air housing must be sufficiently tight to maintain a CO_2 concentration of 30 percent by volume for 30 minutes after initial discharge. Generator air housings have many doors, hatches, removable covers, terminal boxes, and other features that make CO_2 retention difficult. Machines equipped with static exciters located in the generator air housing have many instrument and control panels that are viewed or accessed from outside the machine. These panels have proved to be especially difficult to seal. The axial hole in the generator shaft, when used for routing field leads, has been occasionally overlooked when sealing the machine.

A well-sealed machine presents other concerns that must be addressed. The internal pressure rise associated with CO_2 release can cause distortion of the oil surface in the bearing reservoirs that can lead to bearing damage. Also, the air housing itself may be distorted by the pressure rise. Pressure-relief doors are required to prevent such distortion, and the bearing reservoirs are configured in a way that the pressure rise will not adversely affect the bearing—even if the relief doors fail to operate. These doors must reclose automatically, before internal and external pressures completely equalize, to retain CO_2 concentration.

Heaters are installed in most generators to prevent formation of water condensation on sensitive parts of the machine during shutdown periods. Obviously, escaping heated air must be replaced with cool plant air that brings moisture with it. A well-sealed air housing not only reduces the amount of moisture-laden cool air entering the machine, but also reduces the cost of operating the heaters. Heaters are discussed further in section 8.20.

Personnel access inside the air housings of smaller machines may be limited to periods of major machine maintenance. The air housings of these machines are usually constructed in a manner that the coolers can be serviced or removed without disassembling the entire air housing. Similarly, the center air-housing framework and deck plates may be removable to permit generator rotor removal without complete air housing disassembly.

Larger machines are built to permit personnel access inside the air housing—even during machine operation. It should be noted that proper clearance procedures, including CO_2 clearance, must be provided before one enters an operating generator. If access inside the machine is planned, various features such as doors hatches, lighting, barriers, gratings, and passage ways must be provided.

Two doors, located diametrically opposite from one another, are installed on each generator. These doors are equipped with "panic hardware" that permit personnel to exit the air housing quickly without the need for keys or special devices. Loss of interior lighting is a possibility; dependence upon one's ability to see clearly should not be a prerequisite. Interlocks are installed at each entrance door or hatch to indicate door position. The access doors are lockable from outside the machine, but the interior door hardware must permit personnel to open the doors from the inside regardless of the position of the locks. Panic hardware is described in National Fire Protection Association Code No. 101: *Code for Safety to Life from Fire in Buildings and Structures*, paragraph 5-2.1.5, "Locks, Latches, Alarm Devices," and paragraph 5-2.1.7, "Panic Hardware and Fire Exit Hardware" [11].

In addition to the access doors, access hatches or trapdoors may be provided through the air housing from below. Ladders, either removable or permanently installed, may be required to gain access to the trapdoors from the turbine pit.

Lighting is provided inside larger air housings, and the control switches are provided at each entrance door. Convenience outlets are provided. The inside of the air housing and the outside of the stator wrapper plate may be painted white to improve lighting and to help reveal possible contamination within the machine. Lighting is discussed further in section 8.20.

Barriers or shields around the main and neutral leads are provided to prevent inadvertent contact by personnel. Other potentially hazardous areas may be barriered. These barriers become especially important when considering possible conditions and personnel reaction during an emergency.

Many machines have cooling water manifolds, or "ring headers," located in the walkway area inside the air housing. Gratings may be required to facilitate personnel movement over the ring headers, valving, and other obstructions in the passageway.

The passageway inside the air housing should provide at least 30 inches (762 mm) of clearance space completely around the machine—including spaces between air housing and coolers and barriers.

Various pumps and motors may be located within the air housing, and access to these devices should not be restricted by the housing design. Also, features to contain or control oil leakage from these devices should be provided to prevent contamination of the generator cooling air.

Access to all valves, switches, instruments, and controllers should be made as convenient and safe as possible.

The outside of the air housing may be painted, and it may be fitted with metallic bands to improve the appearance of the machine.

Isolating barriers are provided on the air housing for the generator main leads to prevent loss or exchange of cooling air and to maintain the integrity of the electrical insulation system. The barriers must be made from nonmagnetic material to prevent hysteresis heating.

Similar to the features provided for small machine air housings, deck plates over surface air coolers on large machines should be removable to permit the removal of the coolers without disassembly of the entire air housing. Also, deck plates and framing over the center of the machine should be removable to facilitate rotor removal. Removable deck plates may be required to facilitate thrust bearing maintenance on umbrella or modified umbrella machines.

Stairways may be provided, either by the Government or by the manufacturer, to facilitate access to the top of the generator. Handrails may be required. The stairways and handrails must be of the safety type and must be according to Bureau and OSHA standards.

The deck plates on top of the air housing may be used by personnel for access to various parts of the machine; these plates may be required to support various loads on a temporary basis. Deck plates with a raised pattern should be provided to improve safety for personnel. A requirement for live-load support capability of the top deck plates is stated in procurement specifications.

Terminal boxes, accessible from outside the machine, are provided for low voltage wiring. Separate boxes are required for current transformers. Attention should be given to ensure integrity of the air housing sealing system at these boxes (see sec 8.19).

The generator nameplate should be mounted on the outside of the air housing in a location to be the most visible to the public. Nameplates for the turbine and governor may be mounted on the generator air housing because of the relatively good visibility at that location compared to the turbine pit or governor gallery. Usually, this location has been negotiated between the various manufacturers with Government concurrence. In some cases, joint use of the air housing for mounting all nameplates has been found to be attractive by the Government in advance of procurement. Grounding of the air housing is discussed in section 8.19.

In some Bureau powerplants generator air housings have been equipped with special doors that permit heated air to escape from the air housing to be used for plant heating. Additional doors are required to permit entrance of makeup air. All these doors are equipped with CO_2 activated pistons and cylinders to close the doors when the CO_2 is released into the air housing. Filters are installed to minimize entrance of contamination into the machine. Escape of any machine-generated ozone into the plant is a possibility with such systems. Charcoal filters at the heated air outlets could possibly alleviate this concern.

8.9.4 Tests

Testing is performed to determine air housing design quality. In multimachine plants, only one machine is tested. The test measures the machine's capability to retain a CO_2 release for a period sufficient to ensure fire suppression. The concentration is required to be at least 30 percent CO_2 retained for 30 minutes after release.

An ozone test is conducted to determine the amount of ozone generated by the machine and retained within the air housing. This test does not determine the amount of ozone permitted to escape from the air housing.

8.9.5 Summary

Generator air housings provide many functions in addition to their prime function purpose of confining cooling air. These functions include fire protection, safety features, access, and appearance.

8.10 EXCITATION SUPPLY

8.10.1 Introduction

The term "excitation system," as used in this manual, refers to the supply of controlled direct current for excitation of a synchronous machine; it includes the exciter, automatic excitation control, and manual excitation control. This section discusses the source of d-c (direct current); section 8.11 discusses the means of controlling this power.

The prime function of an exciter is to supply d-c power to magnetize the main generator field. The importance of this d-c power is fundamental to generation of power by the main generator, and the importance of the exciter cannot be overstated.

Excitation theory and technology has advanced probably more rapidly and further than any other synchronous machine aspect. The advancement has been necessitated by the need to interconnect isolated systems and has been facilitated by the availability of high-power, fast-acting solid-state equipment.

Exciters in Bureau powerplants vary in size and technological advancement from the unsophisticated, low-capacity equipment found in older, small plants serving only local loads, to the large and powerful state-of-the-art static exciters found in extra-large plants such as Grand Coulee Third Powerplant. Such large plants operate in large interconnected network grids. The exciters in these plants serve to control the main generator in such a manner as to control power swings and oscillations for the entire network, in addition to the main generator's prime purpose of supplying vast amounts of power to the network.

Small machines serving only local loads may experience relatively small, slowly changing loads; and as a result, relatively slow response excitation serves adequately. Manual or motor-operated rheostats function to control basic exciter output. Disconnecting devices, with features to discharge the main field current, serve to apply and remove excitation from the synchronous machine. Automatic voltage regulators, to adjust exciter output above or below the setting of the rheostat, adjust excitation to meet changing generator loads. Many smaller plants now have static regulators or exciters without field rheostat.

The shaft speed of the main machine has a major impact on exciter capacity. Higher speed machines require relatively less exciter capacity for a given main machine kV•A (kilovolt-amperes) than that required for a low speed machine having the same capacity. This is explained by Faraday's *Law of Induction*, which states that induced emf is proportional to the ratio of change in magnetic flux to time, or $e = - d\phi/dt$. For this discussion, this means that the same amount of field flux rotating at a higher speed will produce proportionately more power.

The capacity of an exciter is dependent upon the requirements of the main generator field. Generally, larger capacity generators have more responsibility for power system control, and therefore, may require more exciter capacity proportional to main machine kilovolt-amperes, than would smaller kilovolt-ampere capacity machines. The capacity of the exciter is determined by the manufacturer to meet requirements for overexcited kilovolt-ampere operation of the main machine. Therefore, the main machine design must precede the exciter design.

When initially started from a cold condition, a generator stator core will expand fairly rapidly to a diameter determined by a temperature produced by armature and core losses. The rotor rim of the same machine under the same condition will expand more slowly to a diameter determined by the temperature of the cooling air passing over the rotor rim. Thus, the airgap of the machine varies from a maximum value, with a hot stator core and a cold rotor rim, to a lesser value after the stator core and rotor rim temperatures stabilize. The exciter must be capable of delivering the required excitation, regardless of airgap dimensions, under all possible machine operating conditions. Therefore, the capacity of the exciter may be required to be significantly higher than would be expected solely because of airgap variations. The above example of airgap excursions caused by thermal expansion differences can be compelling in extra-large diameter low-speed machines.

As the capacity of the exciter is dependent upon machine design, the Bureau does not specify the kilowatt capacity except to require that it have a stated excess capacity over that required for main machine rated output. Exciter capacities vary from about 5 percent of small generator rated capacity to about 0.2 percent of large generator rated capacity.

Nominal voltage ratings for exciters vary from 125 volts d.c. for small machines, through 250 and 375 volts d.c., to 500 volts d.c. for extra-large machine exciters. Usually, the voltage rating of the exciter is limited by specifications to one or two of these voltages.

In addition to restricting the nominal voltage rating, the specifications restrict the exciter characteristics by specifying limits for (see sec. 8.10.2):

- Excitation System Voltage Response Time
- Excitation System Voltage Response Ratio
- Excitation System Ceiling Voltage

Other performance requirements for the excitation system are also covered in the specifications under purchase solicitations for new machines. The manufacturer must use these performance requirements to determine required exciter design and construction.

ANSI Standards C50.12 (4.13) [6] indicates that if excitation power is taken from the machine terminals, the machine output power must be determined on the line side of the excitation power taps; that is, generator losses include excitation power requirements. Also, ANSI C50.12, 7(5) [6] indicates that excitation power requirements are not included in generator efficiency calculations if the exciter serves more than one generator.

The Bureau requires field testing of the overall excitation system—including tests of the exciter itself. Exciter field tests have included voltage response time, ceiling voltage, and response ratio. Factory test results of static exciter temperature rise may be accepted in lieu of field test results. Tests on static exciter transformers, bus, circuit breakers, and the static exciter itself are usually performed in the factory; however, the contractor may be given the option to perform these tests in the field. Factory testing of direct connected rotating exciters requires special machinery to mount and drive the exciter because it has no bearings of its own. Field testing of these exciters would have added difficulty of determining the temperature rise and efficiency; therefore, all tests of direct connected rotating exciters are required to be performed at the factory.

In addition to supplying d-c power for normal, steady-state conditions on the main field, an exciter may be required to force a rapid change in field current. Such a condition occurs when a generator suffers a close-in fault making it is necessary to rapidly force the main field flux to a low level to minimize damage. This situation could require the exciter's capability to actually reverse field voltage. The capacity of a static exciter—deriving its power from the main leads of a generator—is reduced during a close-in fault condition because of the rapidly falling bus voltage.

Main generator field poles operate highly saturated; therefore, relatively large changes in field current are required to produce small changes in the airgap flux. Compounding this problem is the inductance of the main field that requires a relatively strong forcing voltage to produce a change in field current. The time required for a main generator to respond to a power system's demand for a loading change is dependent upon:

- Time required for sensors to detect that a change has occurred, and to initiate corrective action
- Time constraints of the excitation control equipment
- Time constraint of the exciter
- Time constraint of the generator field
- Time constraints of main generator and various components, such as transformers, in the main power system

The exciter's capability to force a change in generator field current is a major factor in power system considerations.

Generators serving isolated, close-in loads do not present a difficult system stability problem. Similarly, small capacity generators connected in large power systems cannot function to control changes in the large system. However, maintenance of stability during transient conditions is of prime importance to successful operation of a large electrical power system. Loss of excitation on a large machine or the inability of an exciter to supply sufficient excitation soon enough to satisfy system demands—during transient conditions—can cause loss of system stability. Generator reactances provide inherent stability. When the limits of a machine's inherent stability are exceeded, a rapid change in machine excitation can operate to maintain stability. This is described as "dynamic stability." A high-initial-response excitation system can be extremely effective in improving power system dynamic stability.

Because of the essential nature of the exciter; that is, the source of d-c power supplying the generator field, the design and construction of the exciter must be robust and simple and have adequate reserve capacity to serve during emergencies.

8.10.2 Terminology

Terms used to define various components and characteristics of excitation systems have not kept pace with developments in the systems. The literature have attempted to develop a listing of terms, but these attempts have had difficulty in receiving universal acceptance. As a result, the Bureau has found it necessary to develop a listing—for use in purchase solicitations—to ensure that both the contractor and the Bureau interpret the terms to mean the same thing.

The ANSI/IEEE standard 421.1 [12] consists of a definition of terms used in excitation systems that is in fairly close agreement with the definitions used by the Bureau. The minor differences between this standard and the Bureau are presently being resolved, and future purchase solicitations will probably refer only to [12] for excitation system definitions.

8.10.3 Exciter Configurations

Many different exciter configurations exist, and most are not used in hydroelectric powerplants.

The Bureau has used or permits the following types of configurations in its powerplants:

- Type 1: Exciter bus (d-c bus supplying several machines)
- Type 2: Separately driven d-c generator
- Type 3: Exciter direct connected to main generator shaft
- Type 4: Brushless exciters
- Type 5: Electronic or static exciters

The above configuration types are so designated for use in this manual only and are not necessarily used by any other entity.

Types 2, 3, and 4 are described as "rotating exciters," as distinguished from the type 5 "static exciter." Each of the above types may have several subtypes or variations in design, construction, and performance that are sufficiently different to make them distinct from other subtypes. Because of numerous different types and subtypes now installed, and because of the availability of many more different configurations, this manual will address only the major features of the types listed above.

8.10.3.1 *Type 1: Exciter Bus*.-This configuration was used in some of the early Bureau powerplants, such as for units 1 through 6 at Minidoka Powerplant in the State of Idaho. A d-c bus serves essentially constant voltage power to several units simultaneously. Power is served to the bus by a motor-driven d-c generator. One variation of this system uses a storage battery floating on the bus. In the event of d-c generator failure, the battery has the capability to supply the main generator fields for a short time. With the battery, this system can provide "blacked-out-plant" startup; without the battery, startup is not possible unless the d-c generator is not electrically driven (possibly turbine or engine driven). This system functions in a manner similar to a modern-day UPS (uninterruptible power supply) system.

Each main generator field is served though a breaker and a rheostat. The rheostat is adjusted to vary the voltage and current delivered to each generator field. A field discharge resistor is required to shunt the generator field when the field breaker is opened. Motor-driven field rheostats present options for remote adjustment, and perhaps more rapid adjustment.

Since the basic design of this system includes sufficient capacity to serve the needs of several generators, this system may have sufficient reserve capacity to provide additional excitation power during transient conditions, particularly if not all of the generators are in service at the time.

Since the exciter bus voltage is essentially constant, the main field excitation voltage must be changed using the rheostat, and high rheostat I^2R losses usually result. These losses become unacceptable with larger machines, and this configuration becomes impractical. Considerable rheostat maintenance presents a problem with this configuration.

8.10.3.2 *Type 2: Separately Driven Direct-Current Generator*.-This configuration uses a d-c generator dedicated to supply excitation to only one main machine; that is, each main machine has its own exciter. The exciter may be driven by: induction motor, synchronous motor, hydraulic turbine, gasoline- or diesel-powered engine. The Bureau has only used a-c motor drives.

The exciter armature is direct connected to the main machine field. Field discharge resistors are not required because circuit interrupting devices are not connected between the exciter armature and the main machine field.

This configuration offers the advantages of a variable voltage supply to the main field, the supply being independent of the main machine speed, and of a dedicated supply. A rheostat connected in the exciter field circuit suffers relatively low losses because of the relatively small current there.

The major disadvantage of this configuration, if a-c motor drives are used, is its dependency upon a reliable source of station service a-c power. This makes "blacked-out-plant" startup a difficult procedure.

This configuration was used for the initial generating units (G1 through G6) in Grand Coulee Left Powerplant and for the first six pumping units (P1 through P6) driven by the first three (of six) of those generators. The last six pumping units are pumping-generating units that use static exciters rather than separately driven exciters. This configuration was selected at Grand Coulee to permit synchronous starting of two pumping units by one generating unit. The motors were connected to the generators at virtually standstill, to reduce brush/slip ring burning, with controlled excitation applied to both generator and motors. Then, the generator turbine gates were opened and the generator and the connected motors were accelerated to speed synchronously.

The exciter drive motors for the Grand Coulee machines were synchronous motors supplied from either of two sources of a-c power. Excitation voltage control was accomplished using a motor-operated field rheostat, a voltage regulator, and an exciter field breaker. The exciter armature was direct connected to its associated main machine field.

8.10.3.3 *Type 3: Exciter Direct-Connected to Main Generator Shaft*.-The majority of all Bureau generators use this configuration. The exciter is mounted on top of the main generator, with the exciter shaft coupled to the main shaft. A pilot exciter for control of the main exciter field may be mounted on top of the main exciter with the pilot exciter shaft coupled to the main exciter shaft.

This configuration offers the advantages of a dedicated d-c excitation supply for each main generator and variable voltage to the main machine field. "Blacked-out-plant" startup is possible because exciter field residual magnetism will facilitate voltage buildup once the main shaft rotation is accomplished. Rotating exciters, direct connected to the main generator shaft have proved to be rugged, simple, and relatively reliable.

Disadvantages of this configuration include:

- Relatively slow response when compared to a type 5 exciter
- An increase in overall machine height because of the location on top of the main generator
- A more massive upper-bearing bracket is required for the exciter's weight
- Brush/commutator wear and wear product (dust) problems

Also, low voltage stability of self-excited exciters is a concern, and if a problem is perceived a pilot exciter may be necessary.

Exciters in this configuration are exposed to all speed conditions of the main shaft, including runaway speed, and the exciter must be constructed accordingly. The commutator is especially vulnerable to damage resulting from overspeed.

Instances of exciter field demagnetization have occurred, and exciter field flashing from the station battery has been required to restore residual magnetism.

Similar to the "separately driven" exciter configuration, a main generator field discharge resistor is not required because the main field and the exciter armature are direct connected without intervening disconnect devices.

Rheostat losses are low due to the rheostat location in the exciter or pilot exciter field.

8.10.3.4 *Type 4: Brushless Exciter*.-This configuration retains the advantages of the Type 3 configuration while eliminating the major disadvantages of brush/commutator wear and sparking. Unfortunately, this "brushless" configuration is restricted to relatively low capacity exciters. The brushless configuration is particularly attractive for application in machines having a sealed housing, such as bulb-turbine generators, or other applications where brush sparking, maintenance, or brush wear products present major problems.

As the name implies, this configuration does not use brushes for commutation, and slip rings are not required. All generation of d-c power occurs on the rotating shaft of the main generator, and control of this power is exercised through control of a stationary exciter field.

"Blacked-out-plant" startup may not be an easily accomplished procedure because the exciter field current is usually rectified from the a-c station service supply. If the powerplant is to be equipped with a station battery, emergency startup exciter field power may be derived from the battery.

Brushless exciters have made their appearance on the market relatively recently and operating experience is limited. However, the rugged design and construction and the absence of brushes provide promising signs of minimum required maintenance for this configuration.

8.10.3.5 *Type 5: Static Exciter*.-The development of high current capacity silicon rectifiers has made construction of exciters having high power, quick response, high ceiling voltage, and field forcing capability a reality. These features are important when considering the performance of a large generator in an interconnected power system. As a result, large modern generators are almost exclusively equipped with static exciters; generators in older plants are frequently retrofitted with static exciters upon major renovation.

The a-c power is taken from the main machine leads and stepped down to exciter voltage using a transformer. A circuit breaker may be used to connect the excitation power transformer to the static exciter. The a-c power is rectified by thyristors in the static exciter, and controlled d-c power is supplied to the field of the main machine from the exciter.

Usually, station battery power is required to "flash" or polarize the main field, which then will permit main generator voltage buildup and supply of a-c power to the exciter from the generator main leads. Flashing is required during normal startup because the action of the excitation system, during normal (and emergency) shutdown, will function to lower the residual magnetism in the main field to such low values that induced generator stator voltage will be too low to operate the static exciter. The ability to build up main machine voltage, and thus build up full excitation power, also permits "blacked-out-plant" startup with static exciters.

Static exciters eliminate the problems associated with rotating exciter commutation, but the requirement for slip rings and brushes to transmit excitation to the main machine field remains. Also, component failure in the static exciter itself is a concern, but static exciter maintenance is usually limited to cleaning.

The static exciters offer real advantages when considering applications such as at pumping-generating plants. These installations require significant amounts of controlled excitation at low main machine speeds and static exciters serve this requirement.

8.10.4 Construction Features of Exciter Configurations

8.10.4.1 *Type 1: Exciter Bus*.-As indicated (sec. 8.10.3.1), this configuration uses a separately driven d-c generator that supplies excitation power to several main generators through a bus and various switching and control devices. The losses of the exciter bus system are not usually charged to the generators when calculating efficiency of each generator. The exciter losses are factored into overall plant efficiency. The d-c generator is of essentially the same construction as described for the following Type 2 configuration.

8.10.4.2 *Type 2: Separately Driven Direct-Current Generator*.-This type of exciter is almost exclusively of horizontal-shaft construction. Although the Bureau has only used a-c motor drives for exciters using this configuration, there are many possibilities for other driving systems. A discussion of drive mechanisms is beyond the scope of this manual. The exciter and its drive motor are mounted on a common structural base close to the main machine. The d-c generator and its a-c motor drive are direct coupled.

The Bureau has only used this configuration in indoor plants; the exciters in those plants have been of open, self-ventilated construction.

The exciter armature is supported by pedestal sleeve bearings, with one bearing pedestal electrically insulated from the base to prevent shaft currents.

The exciter armature is series connected through the commutator and brushes to a commutating field. This field is wound on interpoles mounted between the main-shunt field poles. The purpose of the communtating field is to nullify the effect of leakage flux existing between the main shunt field poles. By canceling this flux, induced voltages are reduced to near zero at the instant of armature polarity reversal, and commutator/brush sparking is minimized. The airgap end of the interpoles are tapered to, in effect, concentrate the flux in the commutating zone. Usually, the interpoles are precision set in the factory to achieve the proper reluctance of the airgap from the interpole to the exciter armature. More than one commutating field may be used. The commutating field is comprised of relatively few turns with large ampere capacity.

Total elimination of brush/commutator sparking under all conditions of load is not a practical goal because some sparking under various conditions of load almost always occurs. Bureau specifications and various industry standards use the terms "not detrimental" or "noninjurious" when placing limits on acceptable amounts of sparking. These terms are somewhat ambiguous and are difficult to enforce. The ASA Standards C50.5 (now ANSI) [13] attempts to define these terms by indicating that evidence of commutator burning or the need for abnormal maintenance (paraphrased) should be considered unacceptable.

The exciter main field is connected to shunt both the armature and the commutating field. The current passing through the main shunt field is usually controlled by a pilot exciter with a rheostat in this exciter configuration, to vary the flux to the exciter armature. The shunt field is composed of many turns with relatively low ampere capacity. This low current facilitates field flux control.

The pilot exciters for each of the separately driven main exciters for generating units G1 through G6 and for pumping units P1 through P6 (at Grand Coulee) serve to supply essentially fixed voltage to both the main exciter shunt field and to the field of the synchronous motor driving the main exciter.

Pilot exciters are usually "flat compounded" (relative strengths of series and shunt fields) to provide a relatively low voltage variation of perhaps 2 to 5 percent under various loads and temperatures.

Exciters manufactured to comply with the standards [13] were required to meet temperature rise limitations for Class A insulation (40 °C rise). However, it is possible to specify compliance with the standards of [14], which permits using Class A, B, F, or H insulation systems with their corresponding temperature rise limitations.

The commutator is made up of hard copper bars or plates that are insulated from the shaft and each other by mica sheets. Spring loaded brushes, mounted in brush holders, carry load current from the exciter armature to the external circuits. The brush material varies considerably, and experience has shown that changing from one brush material to another may improve operation. Atmospheric or environmental changes, or changes in load or maintenance conditions, may produce brush/commutator operation problems.

The bright copper surface of a freshly machined or "turned" commutator will soon develop a film or patina that will, if conditions are proper, provide a smooth surface for the brushes to ride on and will minimize brush and commutator wear and losses. This film may be changed or destroyed by a number of atmospheric or environmental changes. Corrosive fumes, high humidity, airborne dust or abrasive particles, or improper adjustment of commutating pole airgap are only some of the possible causes of brush/commutator problems.

Normal commutator/brush wear is to be expected; the brushes require interval replacement. Commutators require refurbishing to smooth ridges and grooves resulting from wear, and sufficient material must be provided to permit machining without loss of exciter capacity.

Losses in the separately driven exciter motor-generator set are not usually included in main generator efficiency calculations.

Shipment considerations for a Type 2 exciter are similar to those for a pumping unit of similar size. Since the exciter and its drive are mounted on a common base, the exciter can be shipped as a unit.

8.10.4.3 *Type 3: Exciter Direct-Connected to Main Generator Shaft.* -This type of exciter has a shaft orientation to match that of the main generating unit. Since most Bureau generators are of vertical-shaft construction, their exciters are also vertical shaft. The major difference between the Type 2 and 3 exciter, other than source of drive power, is that the Type 3 exciter has no bearings. Exciter airgap control is derived exclusively from the main generator shaft. It would be impractical to install bearings for the exciter, because they would operate in parallel with the main shaft bearings and would be subject to forces resulting from main shaft defections. The exciter's frame is bolted and keyed to the main generator frame; the pilot exciter's frame is similarly attached to the frame of the main exciter. The weight of the main and pilot exciter armatures must be borne by the thrust bearing of the main shaft.

The moment of inertia, of the main and pilot exciter armatures, adds little to that of the main generator rotor; usually it is not included in calculations of WR^2 for the main generator.

Main and pilot exciters are usually of open, self-ventilated construction. Exceptions to this are found in outdoor and semioutdoor plants where the exciters are housed within the main generator air housing; they are cooled by the main generator air cooling system.

The basic construction of a Type 3 exciter is essentially the same as previously described for a Type 2 exciter. The exciter armature is series connected through brushes and commutator to a commutating field winding. A shunt field winding is connected in parallel with the armature, commutator, brushes, and commutating winding.

An additional winding, "compensating winding," may be found in larger exciters or those having special considerations such as application of sudden large load changes. A compensating winding is simply an extension of the commutating winding beyond the interpole region. The compensating winding is placed in slots in the main shunt field pole face, and is series connected with the commutating field. Insulation of the compensating field winding differs from the commutating field because it is placed in slots rather than wound around a pole core. Using a compensating winding reduces the number of turns required for the commutating winding, which reduces leakage flux and pole saturation at high armature currents. A machine with a well designed compensating winding is less susceptible to voltage excursions resulting from rapid load changes, and may lend itself to applications requiring rapid main field demagnetization or field forcing.

The main exciters for generating units 1 and 2 at Glen Canyon Powerplant have compensating windings. Early planning for this plant contemplated using the first two units as synchronous condensers before reservoir head would be available to spin the turbines. The exciters for these two units were to be used as d-c motors, supplied from a motor-generator set, to accelerate the units to speed. After reaching speed, the exciters would be disconnected from the driving power source and then reconnected to the main generator field to supply excitation. The demands imposed on the exciters by their use as accelerating motors required the installation of the compensating windings.

Many machines use a special type of pilot exciter called a "rotating amplifier." Some industry trade names for this device are "Amplidyne," "Rototrol," and "Regulex." A rotating amplifier functions as a variable voltage source pilot exciter. The device is a separate, motor driven, special design d-c generator that is equipped with special fields that function to provide extremely high amplification of control signals and a fast time constant. Control signal power amplification of over 1,000,000 to 1 is possible with a rotating amplifier. Application of this device permits forcing the main exciter field to attain required high exciter response ratios. Disadvantages of rotating amplifiers include maintenance and noise problems; they have considerable total losses, and ventilation is a concern.

Solid-state pilot exciters are now being used in applications where rotating amplifiers were once necessary. Many plants are replacing rotating amplifiers with solid-state pilot exciters upon plant renovation. The solid-state systems offer improved performance over the rotating device, and do not present the brush/commutator, bearing, noise, heating, and other problems experienced with rotating amplifiers.

For efficiency calculation, Type 3 exciter losses are included in those of the main generator.

Special shipment considerations for a Type 3 exciter are required because the exciter has no bearings. Usually, the rotating armature is crated and shipped separately from the rest of the exciter. The same is true for conventional, main shaft-driven pilot exciters. Rotating amplifier, and solid-state pilot exciters are shipped as units separate from the main machine.

Special design and construction requirement are needed for each exciter. Therefore, it is necessary to purchase spare parts at the time of original purchase to avoid long delays for special design and construction of replacement parts. Failure of a major exciter component could result in extended main machine outage while replacement parts are obtained. The Bureau requires a spare exciter armature complete with shaft and commutator, a spare exciter shunt field coil, and a spare complete set of exciter brushes and brush holders. The same spares are required for pilot exciters. Spare parts for rotating amplifiers are generally limited to a complete set of brushes.

8.10.4.4 *Type 4: Brushless Exciter*.- The brushless exciter is direct connected to the shaft of the machine that it serves. Many machines using this configuration do not have separate shafts for generator and exciter; the exciter is simply mounted on the main shaft. Most of these exciters have been furnished with small, horizontal-shaft machines.

The construction of the brushless exciter is that of an a-c generator, with a rotating armature and a stationary field. This is a distinction from the main machine, where the field is the rotating member and the armature is stationary.

The a-c output of the rotating exciter armature is rectified by shaft mounted diodes, and then connected to the main machine field. Metering of field voltage and current is not practical.

The stationary field of the brushless exciter is supplied with controlled d-c power from the excitation control equipment.

Cooling for the brushless exciter is supplied by the main machine system. Most of the main machines using brushless exciters are self cooled; shaft-mounted fans of the main machine supply cooling air for the exciter.

Brushless exciters used with synchronous motors require a rotor-mounted field discharge resistor to discharge current produced by emf induced in the rotor during starting. Since a generator *may not* have any armature current during starting and stopping, a field discharge resistor *may not* be required. However, induced emf(s) are possible in the field circuit of a generator; emf may be of sufficient magnitude to damage the exciter diodes.

Technology advancements indicate that this configuration will be used increasingly in larger generators as time passes.

For efficiency calculations, Type 4 brushless exciter losses are included in those of the main generator.

8.10.4.5 ***Type 5: Static Exciter***.-This type of exciter consists of a power connection to the main machine terminals, voltage regulating circuity, two or three redundant SCR (silicon controlled rectifier) bridges, and a connection to the main generator field. Static exciters receive power for the generator field and their internal circuitry from a PPT (power potential transformer) that is usually connected directly to the generator terminals through a tap to the generator voltage bus or cable system.

Although a generator with a static exciter requires less vertical space in the powerplant than one with a rotating exciter, more floor space is required for the cubicle lineup. Usually, the PPT is located near the generator voltage bus in a separate cubicle or in one of the cubicles in the static exciter lineup. One or more cubicles are included for voltage regulating circuity including the automatic and manual voltage regulators, setpoint adjusters, limiters, protection devices, and firing circuits.

Some static exciters have one cubicle with two or three redundant SCR bridges; others have a separate cubicle for each bridge. The redundant bridges are used to ensure that excitation is available even if a set of SCRs fails. Some static exciters use control circuitry to sense failure of an SCR and transfer to a redundant bridge. Other exciters have all the bridges operating in parallel so that when an SCR fails, its fuse will open and it will be taken out of the circuit, while the other bridge makes up for the loss. In either case, each SCR bridge is rated for the full normal operation and field forcing capability required for the generator. When the bridges can be removed for service with the generator on-line, two bridges are sufficient. Otherwise, three bridges are usually required.

Forced air cooling is generally required to prevent overheating in the SCR cubicles. Redundant fans are used for increased reliability. Air flow sensing devices are used to determine failure of one set of fans, and to annunciate the condition and switch to the other fans. Each set of fans usually operates from a different power source to reinforce reliability.

The output of the SCR bridges is connected to the slip rings on the generator shaft through a d-c busway or cables. In most cases, a d-c field breaker and discharge resistor are included in the field circuit. The field breaker and discharge resistor are located in a cubicle in the static exciter lineup.

The slip rings have the same maintenance problems as with exciter types 1, 2, and 3; but the SCR bridges tend to be more reliable due to advancement in semiconductor technology, and the elimination of commutators and other moving parts. Losses of the static exciter are primarily in the PPT and rectifier bridges, with additional losses coming from the control components and fans, all of which are included with the losses of the main generator in efficiency calculations.

8.10.5 Summary

A synchronous machine excitation supply source is a vital part of the machine. The performance of the exciter not only controls the machine which it supplies excitation power, but also controls or influences the entire power system that the machine connects.

The exciters supplying the synchronous machine can be of many different configurations, and the performance can vary widely. Bureau practice has been to specify exciter type and overall exciter performance requirements and configuration rather than to identify the requirements and rating for various components.

Exciter design, construction, efficiency, reliability, and impact have been improved dramatically by the application of modern high power solid state technology.

8.11 EXCITATION CONTROL

8.11.1 Introduction

This section will cover the SCR (silicon control rectifier) based controls used for shunt static voltage regulators and exciters. (The acronym SCR was also used in section 8.5.7 for "short circuit ratio;" do not confuse these unrelated terms.)

The shunt static voltage regulator and static exciter are essentially the same except that the power amplifier SCRs for the static exciter are larger to accommodate the field current requirements of the main generator field, while the power amplifier of the shunt static voltage regulator only needs to supply the current required for the rotating exciter field, that amplifies the current for the main generator field.

8.11.2 Power Amplifier

The heart of the modern static exciter or voltage regulator is the power amplifier, which uses SCRs, to convert three-phase a-c to a controlled d-c. In most cases, six legs are used in the rectifier assembly to allow the d-c voltage to be controllable from a maximum positive value, which is used for "field forcing," to a negative value almost equal in magnitude, which is used for "negative field forcing."

The value of output voltage is controlled by firing pulses that switch the on SCRs. The SCRs turn themselves off when no current flows. Current cannot flow through the SCR in the negative direction. The firing angle is the phase shift between the firing pulses and the peak of the wave form. The SCRs are fired in the order 1, 6, 2, 4, 3, 5, as shown on figure 8-17. When SCR No. 6 is fired, with SCRs Nos. 1 and 5 already conducting, the higher voltage from phase A to phase C causes the current flow through SCR No. 5 to be passed through No. 6, thus turning off No. 5. Similarly, No. 2 turns off No. 1. When the firing pulse precedes the voltage peak, by just under 30 degrees, the maximum positive d-c voltage occurs (see fig. 8-18). By timing the firing pulse to trigger the SCR at 60 degrees after the volage peak (see fig. 8-19), the average d-c voltage is zero. By firing just under 150 degrees after the voltage peak (see fig. 8-20), the largest negative d-c voltage is obtained.

It should be noted that the inductive circuit of the generator or exciter field keeps the current flowing in the positive direction to allow the SCRs to conduct even through the voltage may be negative. Once the negative voltage reduces the field current to zero, the SCRs will no longer conduct current because they will switch off immediately without any current flowing. A firing angle producing a pulse more than 30 degrees before the voltage maximum,

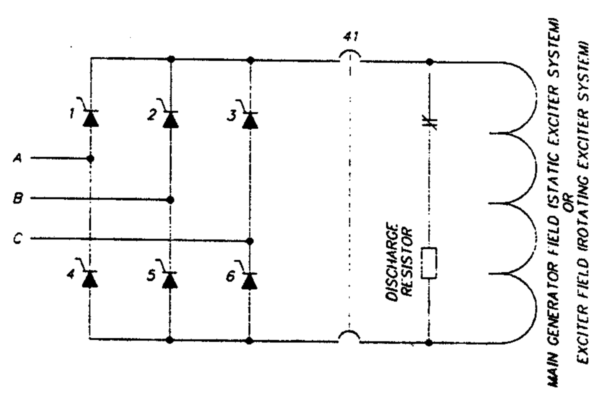


Figure 8-17. – Field circuit with a full-wave SCR bridge.

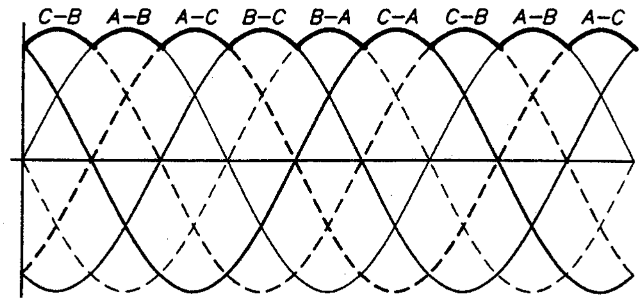


Figure 8-18. — Maximum output from a six-SCR bridge.

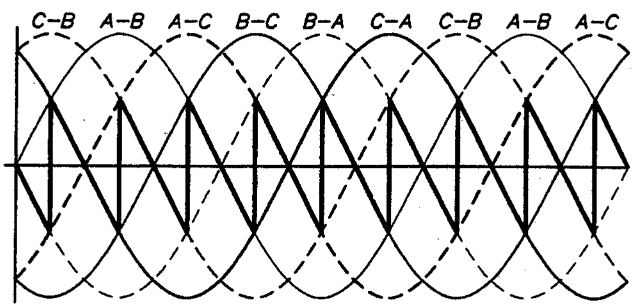


Figure 8-19. — Zero-average output from a six-SCR bridge.

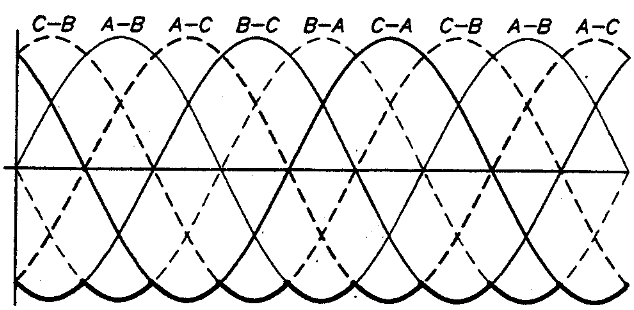


Figure 8-20. — Maximum negative output from a six-SCR bridge.

or 150 degrees after the maximum will result in misoperation of the circuit.

The Bureau requires that redundant power amplifiers be provided to maximize generator reliability. Two amplifiers may be supplied, provided each is capable of producing full positive and negative field forcing and the rectifiers from either one can be removed while the other is in operation, and the generator is on-line. Three full capacity amplifiers may be provided in lieu of having rectifiers that can be removed with the generator operating. Some manufacturers provide a system where only one amplifier operates at any given time; control is transferred to another amplifier when a failure is detected. Others provide firing pulses to all amplifiers, and connect them in parallel.

8.11.3 Voltage Regulator Elements

The voltage regulator or static exciter usually taps three-phase a-c power from the generator terminals. In some cases, the three-phase a.c. comes from the station service distribution panel. An exciter PPT (power potential transformer) is used to reduce the generator voltage to an appropriate level for the exciter or to isolate the exciter from the station service. Usually, the PPT has a fused disconnect switch on the primary side—along with an overcurrent relay in each phase. The secondary side of the PPT usually has a three-pole air-circuit breaker and a set of current transformers that are used in the generator differential protection. The load side of the circuit breaker is connected to the power amplifier, with potential transformers tapped-in to power the voltage regulator control components.

When the power source for the static exciter or voltage regulator comes from the generator terminals, power is not available to the power amplifier nor to regulator components until the generator voltage builds up to a certain point. To build up voltage, the field is "flashed" by connecting the field to the station batteries. Once the generator has developed sufficient voltage, the field flashing is terminated, and the controlled output of the power amplifier is connected to the field.

The automatic voltage regulator monitors the generator terminal voltage and adjusts its output to maintain the terminal voltage at a constant value. This regulator is also referred to as the a-c regulator because it regulates the generator terminal voltage, which is an a-c voltage.

A manual voltage regulator also is provided to regulate the generator field voltage on static exciter systems, or the exciter field current on rotating exciter systems. The output is adjusted as necessary to maintain a constant field current. This regulator is called a "manual regulator" because it maintains the generator flux at a constant level without regard to loading, but requires operator intervention to maintain terminal voltage. This regulator is also called a d-c regulator because it regulates the generator or exciter field, which is d.c.

Since control of the generator can be transferred from the automatic regulator to the manual regulator due to operator intervention or failure of some part of the automatic regulator, an autotracking device is provided to adjust the reference for the d-c regulator to produce an output for the d-c regulator that matches that of the a-c regulator. Therefore, should control transfer, sudden change in exciter output would not be experienced. On most systems this device only operates when the automatic voltage regulator is in control.

A regulator balance indication device, sometimes called a "transfer voltmeter," shows the difference between the output of the manual and automatic voltage regulators. This device is used by the operator to adjust the automatic voltage regulator reference to the point where a smooth transfer from manual to automatic control can occur.

The output of whichever voltage regulator is in control is fed into the firing circuit, which determines the appropriate firing angle to produce the desired output voltage from the power amplifier, and produces the pulses to fire the SCRs. One firing circuit can be used for all amplifiers or—for more reliable operation—each amplifier may have a dedicated firing circuit.

When two or more generators share step-up transformers, a reactive current compensator must be used to prevent VAR (volt-ampere reactive) flow between the generators. Otherwise, if the reference voltage for the automatic voltage regulator for one unit is not set exactly the same as the others, the regulator will try to raise the generator bus voltage while another regulator tries to maintain a lower voltage. The reactive current compensator monitors the line current from each generator, and reduces the regulated terminal voltage as current increases. This has the same effect as adding an impedance between the regulating point and the point where the generators are paralleled. Where each generator has its own power transformer, the transformer impedance produces this effect and a compensator usually is not necessary.

The reference points for the automatic voltage regulator and the manual voltage regulator are provided by an automatic voltage level adjuster (90P) and a manual voltage level adjuster (70P). Traditionally, these devices have been motor-operated potentiometers. Cam switches attached to the shaft connecting the motor to the potentiometer are used to operate indicating lights and a starting interlock. Because of the maintenance requirements of the mechanical devices used in the adjusters, newer adjusters use solid-state components in lieu of the motor and potentiometer.

To prevent generator pole slipping caused by insufficient field current, a MNEL (minimum excitation limiter) is used. This device monitors generator terminal conditions (voltage and current), and overrides the automatic voltage regulator to limit the decrease of field current to prevent the generator from operating below an operating curve that is higher than the under excited portion of the generator capability curve. An MXEL (maximum excitation limiter) monitors field current and overrides the automatic voltage regulator to prevent the increase of field current above a control curve that is slightly below the overexcited portion of the generator capability curve. In this region, the capability curve is primarily influenced by excessive field heating.

To prevent core heating of the unit transformer caused by low-frequency or high-voltage operation, a volts per hertz limiter is used. With such a limiter, a maximum voltage is automatically set—depending on the frequency—to prevent the generator from exceeding a preset volts per hertz ratio.

Many Bureau generators have a terminal voltage limiter that monitors generator terminal voltage. It acts directly into the firing circuits, by-passing the automatic and manual voltage regulators, to reduce the terminal voltage.

Protection devices are used on Bureau generators to prevent damage to the generator or other equipment during potentially damaging system conditions or regulator failures. When the generator terminal conditions fall below a curve that lies between the MNEL curve and the generator capability curve, the under excitation protection initiates a generator shutdown. When the field current exceeds a preset value, the OEP (over excitation protection) begins an inverse timing period—where the duration is based on the amount of over excitation. During this period, the autotracking feature is disabled and the manual voltage level adjuster is moved down to the rated voltage speed no-load position, unless it is already below that point, in which case it is held there. After the timing period and if the over excitation condition persists, control is transferred to the manual voltage regulator. If the condition still persists, the OEP initiates a generator shutdown. The volts per hertz protection operates at a point above the volts per hertz limiter and initiates a generator shutdown. To prevent excessive terminal voltage, a generator overvoltage protection device will initiate a generator shutdown if the terminal voltage exceeds a preset point. A loss of field relay will shut the generator down when the protection device determines, from armature voltage and current, that the field current source has been lost. A field ground detection relay will also shut down the generator if the field is grounded at any point. These protection devices will lock the generator out of service until an operator resets the relays.

8.11.4 Control Switches

A regulator control transfer switch is provided on the unit or main control board. This switch has two positions, MANUAL and AUTOMATIC. In some plants, an INDICATE position is also included and the AUTOMATIC position is labelled REGULATE. The MANUAL position selects the manual voltage regulator to control the firing circuit. The INDICATE position is a leftover position from older control systems and serves the same purpose as MANUAL. On older systems, the INDICATE position enabled the regulator balance meter. Most newer systems keep this meter in service at all times. The AUTOMATIC or REGULATE position places the automatic voltage regulator in control. Some systems have indicating lights above the switch to show which regulator has control. This is useful because certain conditions cause control to transfer automatically from the automatic to the manual voltage regulator while the switch remains in the automatic position.

The manual voltage level adjuster control switch (ANSI designation 70CS) and automatic voltage level adjuster control switch (ANSI designation 90CS) are used to change the position of the voltage level adjusters. Both of these have RAISE and LOWER positions with a spring return to center position. The operator uses the control switch, for whichever regulator has control, to adjust the regulator reference point. Before transferring control from the manual to the automatic voltage regulator, the automatic voltage level adjuster control switch must be used to adjust the regulator balance indication to achieve a smooth transfer.

Generally, the unit control transfer switch has LOCAL MANUAL, LOCAL AUTOMATIC, and REMOTE or SUPERVISORY positions. When this switch is in LOCAL MANUAL, the operator has control of the voltage regulator through the regulator control transfer switch and either the automatic or manual voltage adjuster control switch. With the switch in the LOCAL AUTOMATIC position, the plant computer or automatic plant controls have control of the voltage level adjusters and generator auxiliaries to automatically start and synchronize the units. Once the units are on-line, the operator has control of the voltage regulator through the voltage level adjuster control switches. The REMOTE (SUPERVISORY) position transfers control to a PMSC (programmable master supervisory control) system or to a remote location.

8.11.5 Power System Stabilizer

Large generators that are over 50 megawatts, and some other generators that can influence the stability of weak power systems, have a PSS (power system stabilizer) added to the voltage regulating equipment to prevent disastrous power swings. While the generator is on-line, the PSS monitors machine speed or internal frequency, and alters the voltage references as the speed fluctuates. The internal frequency is a representation of machine speed determined from the terminal frequency, voltage, and current. In some cases, the PSS determines an accelerating torque by comparing the power system conditions to the internal frequency. Using the accelerating torque allows the PSS to better maintain the system stability. The parameters of the PSS are coordinated with the power system to ensure stable performance.

8.11.6 Field Circuit Equipment

The d-c output from the power amplifier supplies power to the exciter field, or to the generator field when a full static exciter is used. To de-energize the field after a load rejection, the SCRs are fired to produce a negative field voltage until the terminal voltage reaches the rated level. This leaves the generator operating at rated voltage to allow it to be placed back on-line quickly, while minimizing the overvoltage caused by the generator overspeed. When a unit lockout occurs, where regulator power may not be available, the field must be short-circuited through a discharge resistor to provide a controlled de-energization. If the field was simply opened, the voltage produced by opening the inductive circuit of the field would cause field current to arc across the opening contacts, and could damage the field insulation. Short circuiting the field with no additional resistance results in a gradual de-excitation, which increases the generator overvoltage because of overspeed, and increases the duration of fault current if the lockout was caused by a generator fault.

To isolate the field, a d-c field discharge circuit breaker (ANSI designation 41 on fig. 8-17) is generally used. This device is a double-pole circuit breaker with a set of auxiliary contacts that place the resistor in the circuit immediately before the field is isolated from the power amplifier. The problem here is the unavailability of field discharge circuit breakers; only a few companies still make these devices. The alternative is to use a single-pole d-c circuit breaker, or the a-c circuit breaker on the PPT secondary to isolate the field. If a field discharge circuit breaker is not used, other means must be used to place the resistor in the field circuit. The most common method uses a "crowbar" circuit that consists of two SCRs connected in series with the resistor, with the combination permanently connected across the field. One SCR allows current flowing through the field in the positive direction to flow through the resistor. This SCR is fired immediately before the circuit breaker is opened. To add redundancy, an overvoltage on the field winding results in an automatic firing of the SCR. As a final safeguard, the SCRs are sized to breakover and conduct at a voltage below that where field insulation damage occurs.

8.12 VENTILATION AND SURFACE AIR COOLERS

8.12.1 Introduction

Four factors affect the ventilation of a machine: (1) total losses to be dissipated, (2) surface exposed for dissipating losses, (3) quantity of air moving past the dissipating surfaces, and (4) temperature of cooling air. The rate of heat dissipation is dependent on the temperature difference between the dissipating surface and the cooling air. To vary any factor can completely upset a stable, balanced condition. A practical value is that 1 kilowatt acting for 1 minute raises the temperature of 100 cubic feet (2.83 m^3) of air by about 64 °F (18 °C). Cooling surface efficiency can considerably change this general approximation.

Small hydrogenerators are self-cooled; they depend only on ventilating air to remove heat produced by machine losses. Movement of ventilating air is forced by shaft- or rotor-mounted fan blades. Heated air is exhausted to the air surrounding the machine; air intake is from the same surroundings. Ducting may be provided to reduce or eliminate recirculation of heated exhaust air. As machines increase in size, with associated increase in losses, ventilation by fresh air alone is not practical. Air-to-water heat exchangers, "surface air coolers," are necessary to adequately control machine temperature. A completely enclosed cooling air system is installed, which requires the input of fresh cool water and the output of heated wastewater. Machine friction, or bearing losses, are removed by separate oil-to-water heat exchangers. Exciter losses are also removed by cooling systems separate from the main generator cooling system. This is true for both rotating and static exciters, and for self-ventilated, force-ventilated, and water-cooled exciters. Main generator surface air-to-water heat exchangers may be used with various combinations of ventilation and/or coolers for the bearings and exciter.

Extra-large generators may be equipped with special cooling systems that supply cooling water directly to the armature winding, stator core, rotor, or various combinations of these. The 700-megawatt generators at Grand Coulee Third Powerplant are equipped with direct liquid cooling for the armature winding, and surface air coolers for cooling the rest of the stator and rotor. The bearing losses are removed by heat exchangers in the bearing reservoirs, and the exciters have a separate liquid cooling system. The special designs required for direct water cooling of armatures, stator cores, and rotor will not be discussed in this manual.

By using the completely enclosed main generator cooling air system, an important secondary benefit is the elimination of the entrance of air-borne particulate contamination.

Using electric motor-driven blowers to move the cooling air has been considered. This option offers the advantage of being able to adjust air flow to suit machine cooling demands. Conceivably, reduced windage losses at low values of machine loading would be possible. Disadvantages would include increased costs for the blower drive system (including power supply controls and ducting), design concerns regarding laminar air flow through parts of the machine at low air velocities, and dependency of the machine on the blower drive for proper operation. Presently, the Bureau of Reclamation has determined that disadvantages of this system outweigh the advantages; therefore, this system has not been implemented by the Bureau for hydrogenerators.

Rotor-mounted fan blades or scoops may be the only source of power required to move ventilating air through the machine; rotor spider arms and/ or rotor rim spacers may be used. Fan blades are discussed in section 8.4.

After leaving the fan blades and rim, the ventilating air moves past the poles and into the airgap. Some machine designers will use some of this air to cool the armature end-turns, jumpers, and ring buses. Other designs cool the end-turn areas with fresh or chilled air. Some machines are built to cool one end-turn area with fresh air and the other end-turn area with heated air leaving the armature. Regardless of the system used, end-turn cooling should be given special attention to avoid hot air recirculation, eddies, and other problems.

Armatures of small generators may be cooled entirely by air passing through the airgap and by air passing over the back of the core. Larger machines are made with spaces between core laminations that permit cooling air to pass radially through the core. This air also passes the armature winding and facilitates a more uniform cooling.

After leaving the core of small, self cooled machines, the heated air is exhausted to the atmosphere. Larger machines are equipped with air housings to enclose the machine and permit recirculation of the heated air. Surface air coolers are installed within the air housing to remove the heat from the ventilating air; ducts are provided to route the air through the housing and machine.

Generators may be classed according to the number and location of the surface air coolers; these classes may include single-cooler, two-cooler, or radial coolers. Usually, single cooler machines have an extension on one side of the air housing to enclose the cooler. Two-cooler machines generally have coolers located diametrically opposite from one another on the generator. The radial class may have any number of coolers within the air housing, usually equally spaced around the stator of the machine.

Single- and two-cooler machines will frequently be of the horizontal-tube configuration; generally, they will extend from the generator frame to the air housing, with air seals to prevent movement of air around the coolers. Air movement through the coolers is vertical—either upward or downward.

Radial coolers in larger machines are usually of the vertical-tube configuration; the coolers are mounted over openings in the generator frame wrapper plate. Air leaving the coolers enters the space between the cooler and the air housing, and then returns to the generator rotor.

8.12.2 Materials

The materials used for fans, ducts, and shrouds are discussed in various other sections of this chapter, and will not be repeated here. This section covers the materials for surface air cooler only.

The surface air coolers are assembled from tubes with attached radiating fins, which terminate at each end in a tube sheet. The tube sheets are mounted in water boxes, and the water boxes are piped to the main cooling water headers through valves.

The tubes are required to be 90-10 copper nickel, which has proven to be the best material available. The composition of 90-10 copper nickel is nominally 88.6 percent copper, 10 percent nickel, and 1.4 percent iron. Originally, the material was developed for seawater applications, but found its way into freshwater applications because of its superior performance. This material has excellent corrosion resistance, good biofouling resistance, immunity to stress corrosion cracking, and can withstand high water velocities without erosion better than most copper alloys. The alloy is specified as "copper alloy No. 706" according to ASTM designation B-111 [15].

Problems experienced with materials such as Admiralty metal, 70-30 copper nickel, arsenical copper, aluminum brass, aluminum bronze, and

Muntz metal include: dezincification, stress corrosion, impingement erosion, handling damage, biological fouling, and chemical pitting. Stainless steel had seen wide application in freshwater applications, and has a fairly good performance record. However, stainless steel has shown some susceptibility to chloride pitting and crevice attack. These problems have prompted the Bureau of Reclamation and many others to specify 90-10 copper nickel exclusively for the tubes and tube sheets.

Bureau Solicitations DS-7001, and later, have permitted using aluminum fins. This construction usually incorporates an aluminum tube, with integral fins, which is tightly fit over a 90-10 copper-nickel tube. The heat transfer characteristics—from the air through the aluminum fins and the outer aluminum tube to the inner copper tube and then to the water—is represented to be as good as that from the air through copper fins, solder, copper tube and then to water. Also, the manufacturers of the aluminum fin construction coolers state that the mechanical bond between the aluminum and copper is so tight that there is no possibility of water or other contaminant entering the interface between the inner and outer tubes. This factor eliminates the possibility of galvanic action between the two different tube materials. The outer aluminum tube is removed at the tube ends where the inner copper tube is rolled into the tube sheets. The exposed junction of copper and aluminum, where the aluminum tube has been removed, presents a potential corrosion area.

Water boxes and water box covers are required to be manufactured from nonferrous metal. Exceptions to this requirement have been approved when the boxes and covers are covered or painted with an acceptable waterproof material. Acceptable ferrous materials have been steelplate or cast iron covered with an epoxy material. The cooler frames are manufactured from heavy gauge galvanized steel sheet or steelplates.

8.12.3 Functions

The capability of a cooler to function is dependent upon the temperature difference between the warm air and the cool water entering the cooler, the heat conductivity of the surface air cooler tubes, and the relative exposure time of the air and water to the cooler tubes. These factors have criteria and limits which, in turn, place limits on the cooler design. Requirements for machines with multiple coolers include:

1. The generator must be capable to function at 100 percent of rated capacity with all water supply to one cooler shut off (air continuing to pass through cooler). This permits a machine with a faulty cooler to continue operation, at any load up to rated, until the machine can be shutdown and the cooler removed from service.

2. The machine may be possible to operate with a cooler completely removed; however, this operation changes airflow patterns and the impact is difficult to predict. Such operation is not covered by the specifications requirements. Means are provided to remove each cooler through the air housing so that disassembly of other machine components is not necessary.

3. The machine is required to be designed in a way so that an operator can pass between the cooler and the air housing.

4. Water couplings of a type to facilitate installation and removal of the cooler are required.

5. Lifting eyelets are required for installation and removal of the coolers.

6. The cooling water supply and discharge headers are not usually furnished by the generator supplier, although most suppliers have indicated a willingness to do so.

7. The coolers should have a maximum allowable working pressure of 100 lbf/in² (689 kPa), and be able to pass a hydrostatic pressure test of 150 lbf/in² (1034 kPa). While it is normal to actually operate at a much lower pressure, such as 30 to 40 lbf/in² (207 to 276 kPa), the higher requirements ensure good design and construction.

8. The cooling water supply temperature should not exceed 20 °C. This specifications limit is retained for all plants unless the expected temperatures exceed this temperature. Some plants with shallow reservoirs behind the dam—like those on the lower Colorado River—occasionally have water temperatures as high as 30 °C; the coolers there are specially designed to function normally at higher temperatures.

Large water-cooled pump motors which take cooling water from Granite Reef Aqueduct in Arizona are designed to use water temperatures higher than 30 °C. Typically, most plants with deeper reservoirs supply water in the 10 to 15 °C range; plants in northern portions of the country may supply water at as low as 4 °C. The rationale for retention of cooler design based on 20 °C water, even for plants with 4 °C water, is that additional cooler capacity is obtained. The additional capacity permits operation of the machine at a lower temperature, which increases machine life and permits continued machine operation with some of the cooler tubes plugged. Some reduction in I^2R losses may result from operation at lower temperatures.

9. The surface air cooler tubes are required to be straight, with copper or integral aluminum radiating fins continuously soldered or continuously mechanically bonded to the tubes. The straight-tube requirement facilitates installation and removal of tubes from the cooler. The tubes are made with a belled portion, usually at one end only, that is slightly larger in diameter than the outside of the radiating fins. This makes it possible to remove a tube and its fins through a hole in the tube sheet that has been sized to accept the belled portion. The belled end is alternately placed at either end of the cooler to enhance tube sheet space utilization. Tube removal is accomplished with the cooler removed from the machine; direction for removal is dependent on location of belled end. The straight-tube design facilitates tube cleaning, by rodding, without removing the tubes from the tube sheets. An apparent relaxation of the requirements, since 1973 when Solicitations DS-7001 was written, has been the acceptance of designs using nonremovable tubes—provided that the tubes can be cleaned inplace by rodding and that tubes are not connected in series. Some coolers are manufactured with tubes connected in series back and forth across the cooler. Several parallel paths of series connected tubes may exist in larger coolers. This design has not been accepted by the Bureau because of the concern that a failure in any tube of the series string would constitute a failure of the entire string, and because of the inability to clean or "rod" the tube strings.

10. The outer diameter of the tube is required to be 3/4 inch (19 mm), with a minimum wall thickness of 0.049 inch (1.24 mm). This requirement helps to ensure tube strength.

11. The water velocity in the tubes is required to be 5 ft/s (1.5 m/s) or less. Studies conducted by the Navy Department led the Bureau to implement this limit in the 1960s. The studies also indicated that water velocities of about 7 ft/s (2.1 m/s) could produce impingement or erosion in copper alloy tubes. The materials in use at that time were more susceptible to damage of this type than is 90-10 copper nickel, but the 5 ft/s limit has been retained for 90-10 tubes to completely avoid this type of damage. In addition, the water velocity can be increased in tubes remaining functional when failed tubes are plugged. The 5 ft/s velocity limit provides some margin before critical velocities are reached. This velocity limit does introduce another concern about laminar flow, which will be discussed in section 8.12.5.

12. As previously mentioned, the tubes terminate at tube sheets made of the same material as the tubes. These tube sheets are attached to water boxes at each end of the cooler.

13. Water boxes are equipped with the means to accommodate expansion and contraction of the tubes. Baffles are placed inside the boxes to channel the cooling water through the tubes in alternate directions for an unspecified number of passes through the cooler. Baffles permit connection of the cooling water supply/discharge piping at the same end of the cooler. The boxes have coverplates that can be removed to permit access to the tubes. An air vent, or air release valve, is provided on each cooler to ensure that the cooler is completely full of water during operation. Drain valves are provided to completely drain the coolers for servicing.

14. Allowable pressure loss through the cooler shall not exceed 5 lbf/in² or 10 lbf/in² (34.5 kPa or 68.9 kPa) in some isolated instances. This limit permits the designer of the water supply and discharge piping to select the proper size of pipe. If the pressure loss through the coolers is increased, the diameter of the supply and discharge piping must be increased to maintain total system pressure loss. Losses in piping as well as coolers must be considered; the designer selects an optimum value.

15. The quantity of cooling water available for all cooling systems in a machine is specified to

allow the design engineer to accomplish the work. Usually, estimated quantities are obtained from machine manufacturers before specifications are written.

16. Special tube supports are installed between the water boxes to provide proper separation and alignment of the tubes, and to minimize the effects of vibration. Aeolian (wind induced), 60 hertz, and machine rotational induced vibrations and their harmonics are all present in the machine at the cooler. Therefore, the tube support design requires a careful and complete analysis to ensure trouble-free operation.

17. Water quality data, including chemical analyses and data regarding silt or other waterborne particulate matter, should be made available to the machine manufacturer for use in cooler design. Cupro nickel (90–10) tubes can be expected to exceed 15-year life for most applications.

18. It is possible to equip surface air coolers with condensate drip pans, and with leak detectors to sound an alarm; however, these features have not been used by the Bureau on a customary basis.

19. Normal O&M (operation and maintenance) practice is to plug the ends of defective tubes in a cooler until overall cooler performance is significantly impaired. Normal specifications practice—regarding cooling water temperatures and operation with coolers out of service—produce an inherent excess of cooler capacity, and tube plugging will not appreciably impair operation until a considerable number of tubes are plugged. When the decision is made that cooler performance is no longer acceptable, the entire cooler is removed and retubed. Normal cleaning activity includes passing a rod through each tube, to remove scale and collected debris, with the coolers inplace in the machine or removed. The cooler construction and installation in the machine should be such as to facilitate these practices.

8.12.4 Instrumentation

Self-cooled generators usually are not equipped with devices to measure inlet cooling air or discharge air temperature. Direct measurements of machine component temperatures are used to determine machine conditions. Self-cooled generators installed inside of buildings, or in unusual surroundings, may be equipped with devices to detect high ambient air temperature. Unusual surroundings would include those where a possibility of recirculation of hot discharge air to the machine might occur. Generators with surface air coolers are equipped with the following instrumentation at each generator:

- A sensing device to determine temperature of air leaving each surface air cooler. The bulb of the device is located in a position that represents the average temperature of the air leaving the cooler. This position may be determined during the generator heat run tests when one cooler is instrumented with 20 devices located in grid fashion over its face. The location of a device that produces readings closest to the average of all the sensors is identified. The same relative position then may be selected for location of the permanent device at each cooler.
- Cooling water supply pressure for each bearing reservoir and for the surface air coolers.
- Cooling water supply temperature for each bearing reservoir and for the surface air coolers.
- Cooling water discharge temperature for each bearing reservoir and for the surface air coolers.

In addition to the devices located on the machine, remote indicating devices are used to determine cooling conditions. These remote devices require sensors at the machine to determine:

- Discharge air temperature from each cooler. Again, the permanent location of the sensor may be determined after the heat run to obtain average air temperature.
- Cooling water supply pressure for each bearing reservoir and for the surface air coolers.

Generators with direct cooling of stator core, armature winding, rotor, and various combinations of these with surface air coolers are treated as special conditions and routine requirements have not been established. However, it is reasonable to assume that all conventional instrumentation required for an air-cooled machine would also be required for a direct-cooled machine, in addition to temperature and pressure measurements for the direct cooling system. Water, or other liquid coolant, quality determination is required for machines having direct cooling of the armature winding because the coolant functions in direct contact with the armature copper and forms a path extending from full-line voltage to ground potential. The same concern for water quality would exist if a machine has direct cooling of the field winding.

The cooling water supply pressure devices are used to inhibit generator starting until water supply is established, and to alarm and shutdown the machine if cooling water supply is lost during operation. Cooling air temperatures and cooling water temperatures are measured and recorded, and are used for alarm purposes.

8.12.5 Operation

The primary purpose of the machine ventilation system is to remove the heat losses from the machine. This is accomplished by passing air over or through the various heat sources in the machine to pick up the heat; then the heated air is either exhausted to the atmosphere or channeled through the coolers. After passing through coolers, the chilled air is recycled to the machine. Heat transfer in the cooler is accomplished by passing cool water through tubes to remove heat from the air. Then, the heated water is discharged, usually into the tailrace of the plant. The cooling water supply usually is pumped from the plant tailrace. Most powerplants anticipate possible operation of the generators occasionally as synchronous condensers. The penstocks may be unwatered at such times, making cooling water unavailable from the penstock. Recirculation of heated cooler wastewater to the supply pump has not been a problem.

Air movement inside the machine is produced by action of generator rotor spider arms and/or fan blades mounted on the rotor rim. The air moves past the rim and field poles, by the armature and through the core, through ducts in the frame, to the coolers. Having passed through the coolers, the air is returned over and/or under the stator back to the rotor. The rotor fan blades of a machine that undergoes rotation reversals, such as a generator/motor, must be configured differently than the blades for a unidirectional machine. The bidirectional fan blades are not necessarily as efficient as unidirectional blades.

Ducting and shrouds are provided at various places in the machine to direct and control air movement. The rotor rim may be formed with spacers, and perhaps fan blades, placed intermittently between laminations. The stator core laminations are also separated at intervals by spacers to form ducts through the core. The ducts serve to move air through the middle parts of the machine—reducing temperature differentials and potential hot spots. The armature wedges are notched on one side in unidirectional machines, to match the location of each duct through the core. The wedge notches serve to improve airflow from the machine airgap into the stator core. Usually, the wedges are notched on both sides in reversible generator/motors. Shrouds may be installed to direct or control the flow of cooling air around the stator end-turn areas.

An overall air housing is installed to confine cooling air to the machine. The air housing may be fabricated entirely from steelplates and framework, or may consist of steelplates, framework, and concrete. Some generators have been equipped with controlled vents in the housing to permit using some of the machine heat losses for building heating. Automatic closing of vent covers is required to prevent the escape of CO_2 from the generator in the event of a CO_2 release. This system tends to reduce some benefits by increasing the possibility of entrance of airborne particulate contamination into the generator, but this system can be used effectively to reduce building heating costs. Another plant heating system routes the heated cooler waste water to heat exchangers in the building. This system of heated wastewater offers significant advantages over the heated exhaust air system—because of elimination of contamination and CO_2 release concerns. Heat is transferred to the air by the field poles, amortisseur, armature, core, ring bus, jumpers, and connectors. It is important to note that the cooling of components in the stator end-turn areas may occur after cooling air has left the coolers and before the air reaches the rotor.

Turbulent flow is required for both the cooling air and the cooling water to effect heat transfer. Coolers are dependent on turbulent flow of the cooling water in the cooler tubes, and of the cooling air past the fins and tubes. If the cooling water flow becomes laminar, very little heat transfer from the air through the tube wall to the water will occur. A review of thermodynamics and heat transfer show that—for water and a given tube surface roughness—the product of velocity and diameter becomes a basis for design in determining turbulent versus laminar flow. As the diameter of any particular cooler tube is constant, water velocity in the tube is the sole variable determining types of flow. Further review shows that a "transition zone" exists between the fully laminar flow zone and the fully turbulent flow zone for any given tube size. In this transition zone, either laminar or turbulent flow may occur; however, the tendency is for the type of flow to be that of the closest zone. Normally, coolers are manufactured to function in an area near the top of the transition zone, close to fully turbulent flow. Design for operation in the fully turbulent zone is probably not practical for most coolers.

Valves are provided in the pipe connections to the supply headers at each cooler water inlet and outlet. The purpose of these valves is to shut off the water completely during machine shutdown or cooler maintenance periods. Some machines are equipped with automatic controls that are designed to fully open the valves after machine start and warmup, and to fully close the valves at machine shutdown. These valves and controls are not to be confused with the automatic cooling water control systems discussed below; they are not intended to be used for throttling.

Some generators are equipped with an automatic cooling water control system that limits the temperature rise experienced by the machine. The system functions to vary the temperature of the cooling water entering the cooler while maintaining constant water velocity in the cooler. This is achieved by routing the heated discharge water through a diverting valve. The diverting valve is controlled to reroute some, all, or none of the heated water back to the cooling water supply pump. If heated water is routed back to the supply pump, the heated water is mixed with fresh water to produce a desired temperature of inlet water to the cooler. A proportional set-point controller operates to reduce the controlled inlet water temperature as machine temperatures increase. For example, an inlet temperature of 30 °C water may be selected for no-load operation and as machine loading is increased, to full load, the temperature of the cooling water would be reduced to 20 °C. This would then provide for an apparent machine temperature *rise* reduction of 10 °C, from machine no-load to full load. The selected set-point control temperatures may be varied to change the apparent temperature rise reduction.

The purpose of the automatic cooling water control system was to reduce the overall temperature change experienced by the machine armature winding. Industry-wide problems have been encountered with machines having class B, asphaltic-bonded insulation systems. The problems were primarily tape separation associated with operation at higher temperatures and girth cracking associated with temperature cycling in long core machines. The advent of epoxy and polyester-bonded insulation systems solved these problems more effectively than the automatic cooling water system. In addition, the new bonding systems promised many other benefits, and the asphaltic-bonding system was eliminated as an acceptable option in new machines and replacement armature windings. Therefore, automatic cooling water control systems no longer had a purpose and their requirement was deleted for machines having armature winding insulation restricted to epoxy and polyester bonding.

Other water control systems have been implemented in various isolated machines. Some of these systems have been installed on a test or experimental basis and some have been to solve problems peculiar to certain machines. One system involved inserting temperature sensors through the insulation in an end-turn, at the neutral end of the armature winding, to rest directly against the armature winding copper. The sensor was thus responsive only to armature loading, and was virtually insensitive to temperature changes produced by other machine losses. This permitted construction of a control system that would follow machine load and control cooling water accordingly.

Operators and test engineers sometimes have used the cooler inlet and outlet shutoff valves to throttle waterflow to the coolers, and thus attempt to regulate machine temperatures and/or save water. Although some success has been achieved, *caution* apropos to this practice is stressed.

Throttling will reduce the water velocity and increase the probability of laminar flow in the cooler tubes. As the transition zone between fully laminar and fully turbulent flow represents an unstable or unpredictable situation, flow may change suddenly from one type to the other. It is entirely conceivable that turbulent flow could continue for some time after valve adjustment, and then suddenly change for no apparent reason. This could cause an abrupt change in machine temperature rise with consequential negative results. Therefore, continuous operator attendance at the generator temperature monitoring instruments should be required whenever cooler waterflow is throttled, and the practice should be limited to test periods.

The automatic cooling water control systems mentioned above do not present the hazards discussed for throttling because they incorporate a design using constant water flow through the cooler.

Condensation will appear on the surface air cooler tubes whenever the dew point of the air entering the coolers approaches the temperature of the tubes. It is unlikely that the dew point will approach the tube temperature when the generator is operating at normal loading. However, for a light generator load, condensation can occur upon: cold water temperature, high humidity, or any combinations of these. The most critical concern for potential harm resulting from condensation is directed to the cooler itself. Condensation can be responsible for corrosion (galvanic or other) that can lead to cooler failure.

Various opinions exist in the industry as to potential damaging effects that condensation might have on other machine components. Concerns have been minimal for machines having epoxy or polyester bonded armature windings. Some organizations having hydromachines located in high humidity locations have installed drip pans under the coolers, and collection systems to route the condensation accumulations from the machine. Currently, the Bureau has not implemented any such system.

Most of the foregoing discussion has been directed to the generator surface air coolers. Most of the comments are also applicable to other coolers in the machine—including bearing oil coolers and static exciter coolers; however, these coolers are much smaller in size and usually can be handled more easily than the large surface air coolers. Also, the cost of replacing an entire bearing cooler rather than repairing it becomes practical in some instances. The bearing cooler operates in an oil medium rather than air, therefore, it likely may have somewhat different heat transfer design considerations. As a result, requirements related to repair, such as straight-tube design and removable water box covers, may be either relaxed or eliminated for bearing and static exciter coolers.

8.12.6 Summary

A generator's rating is based partly on the temperature that the generator will reach when fully loaded. A ventilation system is required to remove the heat produced by machine losses. Ambient air alone cannot be used to remove the heat in larger machines; supplemental cooling in the form of air-to-water heat exchangers must be used.

Many factors affect the generator ventilation and cooling system. Subtle changes in the system can have dramatic results in system performance.

Experience gained by the Bureau through operation of many hydroelectric powerplants has been used to develop procurement specifications that closely restrict acceptable cooling system design.

When replacing asphaltic-bonded insulation systems in older hydrogenerators, consideration should be given to removal of automatic cooling water systems if the machines are so equipped. The automatic cooling water control systems are probably of no value for machines with polyester or epoxy resin bonded insulation; continued use of the automatic system presents only a maintenance problem.

8.13 BRAKES AND JACKS

8.13.1 Brakes

Hydrogenerators and generator–motors are equipped with a braking system to decelerate a rotating unit and to resist torque produced by turbine wicket gate leakage. Vertical-shaft machines use an airbrake system with a piston-cylinder-brakeshoe assembly mounted on the machine's lower-bearing bracket. The brakeshoes operate against a brake ring mounted on the machine rotor. Horizontal-shaft machines usually use a rotor-caliper system similar to the "disc-brake" system used on automobiles. Dynamic braking may be useful for decelerating a rotating unit, but offers little attraction as a restraining system for a machine at rest.

The hydrogenerator brake system design must recognize the:

- Magnitude of the rotating mass to be stopped
- Estimated amount of wicket gate leakage

- Overall stopping time limitations
- Different direction of rotation possible during braking for generator-motors
- Time duration of brake application

Turbine information is supplied to the generator manufacturer in addition to the Government's requirements—including air pressure and application timing.

Several different procedures have been used for brake application timing:

1. Intermittent application from a specified speed such as 50 percent of rated speed until rotation slows to 25 percent and then continuously applied to standstill.

2. Continuous application from a specified speed such as 50 or 30 percent of rated speed to standstill without prior intermittent application.

3. Requirements for the manufacturer to provide brakes capable of decelerating the machine to a standstill within a specified time such as 7-1/2 minutes and then for the manufacturer to determine the speed at which brakes are to be applied to comply with the time specified.

The amount of turbine's wicket gate leakage may be stated as a percentage of rated torque, or may be stated as sufficient to overcome machine friction and windage, and to drive the machine at some speed—such as 50 percent of rated.

The air pressure limits are of concern because the lower limit will determine the minimum braking effort available to satisfactorily stop the machine; the maximum limit will determine the amount of lifting or vertical movement of the rotating parts caused by brake application. The brakes are designed for a normal air pressure of 100 lbf/in^2 (689 kPa), and should be capable of adequate operation with air pressure variations from about 75 to 125 lbf/in^2 (517 to 862 kPa). Bureau specifications have not been overly restrictive regarding required brake performance.

The brake ring is fastened beneath the rotor of vertical-shaft machines to the spider arms. The brake ring is made up of segmented arcs to facilitate renewal without the necessity of major machine disassembly. The segmental construction also permits the manufacturer to leave gaps at the ends of the segments, which will help compensate for the rapid thermal expansion of the segments that occurs during braking. The segment mounting provisions must permit expansion to occur without causing buckling of the segments. Usually, the ring is located radially as close to the rotor rim as possible to permit the force exerted by the brakes to operate directly under the greatest single mass in the machine (the rotor rim) and to minimize vertical stress on the rotor spider arms. The configuration of some machines may prevent location of the brakes below the rim, while still supporting the brakes on the lower-bearing bracket. For example, the 700-megawatt machines at Grand Coulee Third Powerplant have a relatively small diameter turbine pit opening below the generator. This opening is spanned by the lower-bearing bracket that supports both the thrust bearing and the lower-guide bearing, but the bracket does not extend radially outward far enough to reach under the rotor rim. The brakes are located as far out on the bracket arms as possible, and the brake ring is mounted directly on the rotor spider—well inside the rotor rim. This arrangement required the machine designer to provide an increased braking surface (more brakeshoes with greater shoe area) than would have been required if the brakes could have been located under the rim. This is true because of the moment arm from the rim mass inward to the brake. However, placing the brakes on the bracket arm eliminated any need for a separate brake mounting and anchoring system—capable of transmitting the braking torque to the foundation—for each brake assembly.

Nonasbestos brakeshoe material is now available for new machinery; it is being used to replace brakeshoes in older machines.

Horizontal-shaft generators may not be equipped with bearings capable of supporting an appreciable amount of axial thrust; therefore, a braking system that does not depend on axial force is required. A rotor-caliper system meets this requirement. A drum brake arrangement could probably be made to meet the requirement, but it might be somewhat clumsy to install and would probably be much more difficult to service than the rotor-caliper system. The rotor-caliper system provides shoes or pads operating against a shaft-mounted rotating disk, or rotor. The pads are held in a caliper system that squeezes the pads against the rotor during braking.

Dynamic braking depends on dissipating energy generated by the generator armature to accomplish deceleration. The dissipation of energy generated may be accomplished by connecting a load, such as a resistor bank, to the armature terminals and then exciting the generator field. At Mt. Elbert Pumped-Storage Powerplant, Colorado, the static starting system can be used to provide dynamic braking by dissipating energy back into the power system. Dynamic braking will impose unusual and possibly severe stresses on the generator; the generator must be electrically and mechanically designed to withstand these stresses. Also, dynamic braking cannot provide any restraining effort to hold the machine at standstill during shutdown periods; a more conventional brake system must be used to supplement it. For these reasons, dynamic braking has not received widespread application.

8.13.2 Jacks

Vertical-shaft generators and generator-motors are equipped with hydraulically operated jacks that may be combined with the brake assembly or may be completely separate. If combined, the jacks operate against the brake ring to lift the rotating elements. If separate, the jacks operate against the brake ring or separate pads placed under the machine rotor. The function of the jack system is to raise the machine rotating parts a sufficient distance to permit adjustment or removal of thrust bearing components and to relieve pressure on the thrust bearing during shutdown periods. The jack system also permits separation of the generator-turbine shaft coupling during disassembly. The jacks may be used to assist in formation of a fluid film in the thrust bearing during starting.

Mechanical blocks are provided to hold the jacks in their raised position, thus eliminating the need to maintain hydraulic pressure when the machine is to be shutdown for an extended time. The mechanical blocks may be a simple device to wedge under the jacks, or separate screw jacks may be furnished. If screw jacks are used, care should be taken to ensure that the load imposed does not cause damage or deformation to components such as the brake ring.

8.13.3 Combined Brake and Jack Systems

Combining the brakes with the jacks provides an attractive option because the restraining action of the brake is inherently available to resist torque produced by wicket gate leakage. Combining both functions into one assembly offers maximum economy of materials and space usage, but it may create some problems. For instance, location of the jacks may not be ideal with relation to the load. Some engineers have expressed the opinion that the jacks should be located as close to the shaft as possible. This location provides a loading, with resulting stresses, that most closely approximate that imposed on the rotor spider during operation. However, this is not the best location of the for brakes. Others have stated that the jacks should be located under the rotor rim where the greatest weight exists. This might be the best location for the best braking, but as indicated in section 8.13.1, location of the brake ring under the rotor rim is not always possible. As a result, the ideal location for the jacks may be compromised in the combined brake/jack arrangement.

Another brake and jack problem arises when the same cylinder must operate with compressed air during braking and with hydraulic oil during jacking. Air bubbles may exist in the cylinders while jacking, which may produce irregular jacking action, and an oil mist may remain in the cylinders and connecting piping after jacking. This oil mist can collect and drain through connecting piping into the air receiver/compressor systems and cause damage. Filters and separators can be installed to prevent or diminish these problems, but they complicate the system and increase costs. A system using a dual piston/cylinder arrangement has been used; it effectively separates the oil and air systems while retaining the advantages of the combined brake/jack system. However, the dual piston/cylinder arrangement also complicates the system and increases costs.

Separate jacks, operating against the brake ring surface offers the functional advantages of the combined system and avoids the problem of oil-air cross contamination. Costs of this system may be greater, but the system may be somewhat less complicated. The compromise in the location of the jacks—because of the brakes—still exists.

Separate jacks, operating against pads under the rotor, can be located to best support the load with existing circumstances of machine configuration, that is, location of rim, supporting brackets, or concrete foundation. These jacks and pads may not be capable of restraining rotation against turbine's gate leakage; measures, such as dewatering the turbine must be taken to ensure that the rotating force does not occur while the machine is on the jacks. Another problem arises with this design if individual pads are located on each rotor spider arm. The machine rotor will not come to rest with the arms and pads precisely aligned with the jacks each time it stops. If the pads and jacks are not aligned, operator intervention to move the rotor into alignment with the jacks becomes necessary before jacking can be accomplished. This operation can be time consuming and laborious; therefore, separate jacks, without a continuous jacking ring on the rotor, may not be an acceptable option.

8.13.4 Instrumentation and Accessories

Brakes are equipped with limit switches that are used to prevent machine startup when the brakes are in the engaged position. These limit switches may be used to indicate brake application during deceleration, and to indicate if any individual brake is binding or otherwise misoperating.

Limit switches are provided to indicate the position of the jacks, and to limit the amount of rotor lift produced by the jacks. A minimum amount of lift is required to separate the shaft coupling and to service the thrust bearing; a maximum limit is established by permissible upward movement of the turbine rotating parts. A normal travel limit is less than 3/4 inch (19 mm).

A motor-operated pump is used to supply hydraulic oil to the jacks. In some plants, a hand operated pump is used for the supply pressure.

Each brake is equipped with springs or other positive means to return the brake piston to its lowered position after air pressure release. Some method of adjusting the return force on each brake piston is required.

8.13.5 Operation

Operation of the brakes generates a large amount of heat and dust that are dissipated into the surrounding air. Discoloration of brake components is a common occurrence, and warping or deformation happens occasionally. Deformation can diminish or destroy the effectiveness of a brake assembly and can cause consequential damage to other parts of the generator. Dust products resulting from brake application can permeate the entire generator. Usually, brake dust is the largest source of contaminants in the machine. Problems associated with dust as related to the new nonasbestos brakeshoe materials have not been fully identified at this time. Accumulations of dust on various heat-producing components have a deleterious impact on their heat transfer abilities; dust clogs cooling air passages to further degrade machine cooling. Some opinions have been expressed that dust accumulations on high-voltage armature windings create a semiconductive coating that enhances corona suppression—this may be wishful thinking. Customary Bureau practice is to clean the machine at certain intervals and to remove dust accumulations to the greatest extent practical.

8.13.6 Summary

Brakes are required to bring a generating unit rotating mass to rest and to hold this mass at standstill during shutdown periods. Jacks are required for vertical shaft machines as an aid during maintenance and starting, and to relieve pressure on other machine components during periods of shutdown. If jacks are planned as an aid, during generator startup, such operations plans should be made known to the machine designer/manufacturer and the operation should be made a part of the specifications. Regretably, it is possible to design an otherwise satisfactory jacking system that will not be capable of performing satisfactorily during generator startup.

8.14 SOLEPLATES AND ANCHORS

8.14.1 Introduction

Soleplates and anchor bolts, or foundation bolts, complete the vital link between the stationary parts of a generator and the plant foundation. Despite the vital nature of this function, virtually no literature exists that covers the design or construction considerations for these components.

The soleplates and anchor bolts *must:*

- Hold the generator in a precise location in space
- Support the entire weight of the generator and rotating parts of the turbine

- Support the unbalanced hydraulic thrust of the turbine

In addition, tangential loading caused by machine torque and all abnormal forces, such as those produced by short circuits or out-of-step synchronizing, *must* be transmitted from the generator to the plant foundation. Cyclical forces, such as vibration, and those forces resulting from load changes *must not* affect the positioning of the soleplates.

In addition to the forces listed above, significant thermal and magnetic forces continually act on the stator; these forces may not be uniform around the machine. The magnetic forces associated with maximum unbalanced magnetic pull can exert tremendous upset forces at the generator foundation. The soleplates and foundation bolts must function to maintain stator circularity, elevation, and centering while any or all of these forces are present.

Anchoring and load supporting devices for special case machine features such as upper-bearing brackets that transmit loads directly to the concrete foundation and stator positioning beams will not be addressed in this section.

A rotor erection pit with a plate or pedestal may be required to facilitate rotor erection during construction, and subsequent rotor removal for maintenance purposes.

Many machine component parts including generator air housing, static exciter, excitation control cabinets, piping, ducting, conduits, cables, bus, boxes, and miscellaneous cabinets and devices require mounting and anchoring provisions. The loads imposed by these components are not of the same dynamic nature as those imposed by the generator proper.

A slight shifting of the generator foundation may occur as the reservoir behind a newly constructed hydroelectric dam is filled. This shifting may cause the generator to move out of plumb if the generator is installed before the reservoir is filled. Manufacturer's machine designers can compensate for this out-of-plumb operation, and they may even consider such movement as a normal condition. However, the machine manufacturer should be made aware of the possibility of such a movement—including an estimate of the magnitude and direction, if available—should machine installation scheduling become a problem.

8.14.2 Stator

The soleplates and foundation bolts supporting the stator of machines that have the thrust bearing located below the rotor must transmit all machine torque (or tangential loading) and must support the weight of the stator, upper-bearing bracket, and all other loads on the stator. In addition to torque associated with normal machine loading, torque associated with short circuit forces and out-of-step synchronizing must be resisted by the soleplates and foundation bolts.

In addition to the loads above, the weight of the rotating parts of the generator and turbine and the unbalanced hydraulic thrust must be supported by the stator soleplates and foundation bolts in conventional suspended machines with the thrust bearing located above the rotor.

Bureau specifications are written to place a maximum value of vertical and tangential loading that may be imposed on the foundation concrete by the soleplates. The manufacturer must then determine: location, number, and size of soleplates required to comply with the specifications limits, and also design the soleplates to conform to machine requirements.

Occasionally, Bureau practice has been to furnish and install the anchor bolts in locations determined by the machine supplier. Current practice is to require the manufacturer to supply the anchor bolts, and for the construction contractor to install them.

The machine configuration, including the way that the manufacturer chooses to circulate cooling air within the machine, may require the stator frame to be raised above the concrete foundation. In this case, the manufacturer may choose to use soleplate extensions between the soleplates and the stator frame or a larger one piece soleplate may be used to raise the stator above the concrete.

Keys or dowels are required between the stator frame and soleplate to transmit tangential loading. Also, keys or adequate vertical bearing surfaces on the soleplate are required to transmit machine tangential loading to the concrete foundation.

Stator diameter excursion caused by thermal and magnetic forces may be of such magnitude in extra-large diameter stators that a solid connection of the stator to the foundation concrete is not practical. In such a case, manufacturers have successfully implemented designs that use a sliding radial key system between the stator frame and stator soleplates. The radial keys resist tangential forces while still permitting radial movement of the stator.

8.14.3 Lower-Bearing Bracket

The lower-bearing bracket of most hydrogenerators is mounted separately from the stator. The foundation bolts and soleplates for the lower-bearing bracket in conventional suspended machines (thrust bearing above rotor) must resist all radial loading transmitted from the bearing and must be capable of supporting the vertical loads imposed during jacking of all rotating parts of the generator and turbine. A frequently overlooked load is the tangential load transmitted by the bracket while braking the rotating parts of the generator and turbine to standstill. This load is produced by the combined WR^2 of the turbine and generator, and by turbine gate leakage.

The foundation bolts and soleplates for the lower-bearing bracket in machines with the thrust bearing located below the rotor, must support the vertical loads imposed by the rotating parts of the generator and turbine during operation in addition to the loads imposed by suspended machines.

8.14.4 Rotor Erection Pit

The rotors of larger generators frequently are erected at the job site due to shipping limitations. To reduce erection time, an area in the plant is set aside to permit rotor assembly outside of the generator.

A foundation plate or pedestal, with provisions to match the generator shaft coupling and coupling bolt holes, is required to support the generator rotor during erection. The shaft is temporarily bolted to the plate during rotor erection. The plate or pedestal may be furnished by the Bureau, or by the generator manufacturer to meet floor loading limitations set by the Bureau. If furnished by the manufacturer, the plate or pedestal becomes the property of the Bureau for future plant use.

Considerable overturning load may occur during rotor construction; additional supports may be required under the rotor spider arms or rim. Usually, these supports are portable and are not anchored permanently to the concrete.

8.14.5 Machine Components

As indicated above, loads imposed on the foundation by the generator air housing, various ladders and stairways, handrails, gratings, static exciter, excitation control cabinets, piping, ducting, conduits, cables, bus, boxes, and miscellaneous cabinets and devices is not of the same magnitude or dynamic nature as the loads imposed by the stator and bearing brackets. Therefore, conventional structural steel bases with embedded anchors or expansion bolts are used. These mounting provisions will not be discussed here.

8.14.6 Construction Installation

The foundation bolts for the stator must be placed in the concrete foundation long before stator erection begins. Therefore, it is necessary to know placement dimensions to ensure accuracy of placement of the bolts. Usually, these dimensions are part of the initial data received from the machine manufacturer.

One or more steel templates may be used for setting the foundation bolts and soleplates. The templates may be furnished by the Bureau with dimensions and tolerances furnished by the machine supplier. A steel template for setting the anchor bolts and soleplates is *not* small nor is it inexpensive; generally, a steel structure is used that will locate all of the soleplates simultaneously. A template like that shown on figure 8-21 requires a structure of about the same diameter as the stator frame plate and the lower-bearing bracket, and is frequently assembled at the jobsite. The large and cumbersome nature of these templates has caused the Bureau to implement a practice of not requiring them unless there are to be more than two identical generating units in a plant. The template offers considerable value by ensuring an accurate and expedited placement of the bolts and soleplates. If a template is not used, it is necessary to locate each foundation bolt using surveying instruments, and it is necessary to use temporary devices to hold the bolts in position while concrete is being placed around them.

A typical design for foundation bolts is to use a relatively long bolt with the head of the bolt placed downward. A plate or washer placed at the bolt

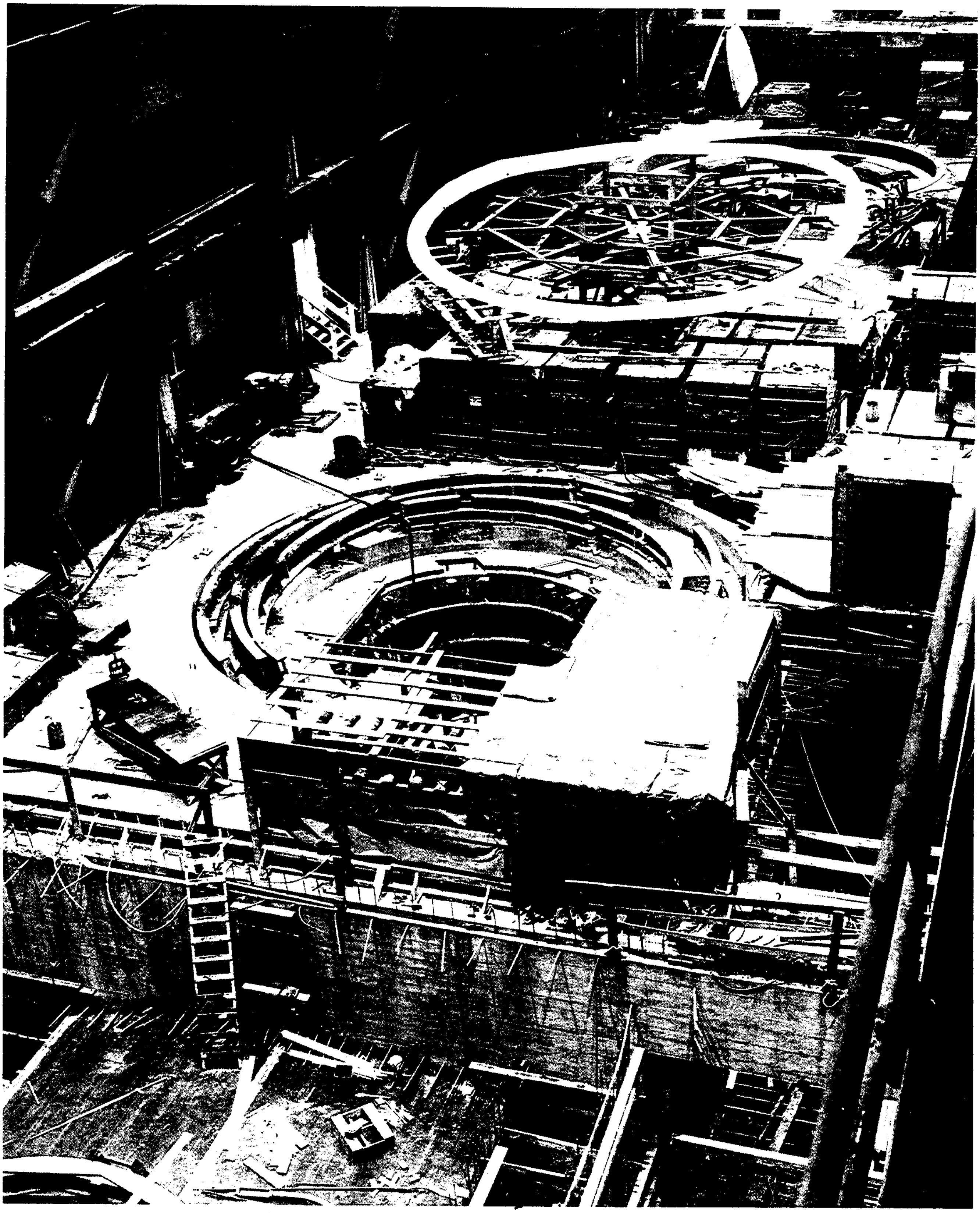


Figure 8-21. — Steel template (encircled) for setting stator soleplates.

head is used to achieve adequate bolt loading distribution to the concrete. The bolt body is located within a sleeve, which will permit a small amount of bolt bending motion within the sleeve after concrete has been placed around it. Soleplates, or soleplate extensions, are placed over the foundation bolts and located as accurately as possible. Nuts secure the foundation bolts to fix the location of the soleplates.

Following erection of the stator on the soleplates, the soleplates are adjusted to achieve final correct level and elevation for the stator. Final centering of the stator may require some movement of the soleplates on the foundation. The soleplates may be equipped with oversize foundation bolt holes or slots. Movement may be accommodated by the small amount of foundation bolt bending movement within the sleeves surrounding the bolt body. After final stator leveling and centering, the anchor bolt nuts are torqued and tack welded, dowels are installed between stator frame and soleplates, and the soleplates and foundation bolts are grouted in place.

The lower-bearing bracket soleplates and anchors are leveled, centered, and permanently fixed in position after the stator has been permanently located.

8.14.7 Summary

Generator soleplates and anchor bolts provide the vital link to transmit generator and turbine physical loading to the foundation. Tests are not performed to demonstrate the adequacy of the soleplates and anchors, but any evidence of failure must be given immediate attention. A failure in the mounting system must be treated as a failure of the entire machine.

8.15 FIRE DETECTION AND PROTECTION

8.15.1 Introduction

The concentration of large amounts of energy within the relatively small volume of a generator, and the possibility that this energy can be suddenly discharged through an unintentional path, creates a concern for potential fire hazard within the machine.

A significant fuel load exists within the machines. This fuel can be identified as insulation binders, blocking, ties, lubricants, wiring insulation, paints and varnishes, plastics, fiberglass sheeting, electrical "potting" compounds, and other materials. Some thermosetting resins used for armature insulation binder have been described as "flame retardant," "fire resistant," or as a material that will not support a flame after removal of the ignition source. However, Bureau experience has proved that the high temperature arcs—associated with an armature failure—can readily ignite these materials. Furthermore, the energy released by combustion of the resins is capable of sustaining further combustion. Application of "flame retardant" paint or coverings has not been found to be a solution for these high intensity fires.

To limit the damage produced by a failure within a generator, it is necessary to:

- Limit the intensity (if possible) and duration of the ignition source (fault)
- Limit the fuel load (if possible)
- Limit the amount of oxygen for support of combustion
- Limit the confinement area

To use a fire suppressant material to extinguish an electrical arc is not practical. It is possible to limit the energy in the arc using fast acting sensors, relays, rapid field forcing, circuit breakers, high-impedance grounding systems, reactors, and system design. However, a fault produced arc will persist until the energy producing the arc is removed. Combustion produced by the arc can be controlled once the arc itself has been extinguished.

The fuel load represented by the armature winding insulation is probably the largest single fuel source in any particular generator. The quantity of material used for armature insulation cannot be controlled by fire considerations alone. The same is true for many other materials used in the machine. The presence of the materials is required for machine functional reasons; they cannot be summarily removed to eliminate fire hazard; however, good judgement in using the materials can significantly reduce the fire risk.

The air housing covering large machines for control of ventilating air presents an ideal opportunity to install a built-in automatic fire suppression system. Small machines having open or self-cooled ventilation systems do not lend themselves readily to automatic systems; manual fire suppression systems must be used. Manual fire suppression systems for smaller open machines may include portable CO_2, water spray, or foam. Automatic fire suppression systems for large machines include: water deluge, Halon 1301, and CO_2; Bureau systems have all been of the CO_2 type.

Water deluge systems depend on release of large volumes of water into the moving rotor of the generator. The rotor movement sprays the water throughout the machine, and reduces temperatures to extinguish the fire. The initial cost of a water deluge system is lower than that for other systems; water may not be particularly injurious to resin-bonded armature insulation systems. However, water spray will enter other parts of the machine, such as the field pole windings, pole bodies, and armature core, where damage can result. The dielectric strength of the field windings will be decreased by water penetration, necessitating a thorough dryout following each water release. Although the presence of water between laminations in the pole bodies and armature core may not have any immediate repercussions, water can produce long term corrosion and loss of interlaminar insulation with associated problems. Removing all water in the pole bodies and core by dryout can be a time consuming procedure. Water drainage, with potential pollutants, is a concern with water deluge fire suppression systems.

Halon 1301 has been studied for possible use as a generator fire suppressant. This system offers three advantages over CO_2:

1. A conentration of about 5-percent Halon 1301 should be ample for fire suppression, as compared to about 30 percent concentration for CO_2. While the cost per pound of Halon 1301 is considerably higher than CO_2, the much lower required concentration requirement for Halon 1301 could produce an overall cost savings.

2. Halon 1301, at 5-percent concentration, presents little hazard to personnel.

3. Release of Halon 1301 into the machine does not produce the thermal shock problem associated with the release of CO_2.

Fire control experts have advised the Bureau that Halon 1301 decomposes into corrosive halogen acids when heated to temperatures exceeding 1112 °F (600 °C). Arc temperatures can be several thousand degrees Fahrenheit; it is possible for arcing faults to persist after release of the fire suppressant. In addition to being corrosive, the decomposition products of Halon 1301 and their resultant by-products can be conductive. Therefore, in addition to careful containment to avoid hazards and environmental contamination following an arcing failure, an extensive cleanup of the machine would be absolutely necessary.

Systems using CO_2 have proved to be effective in control of generator fires. The CO_2 displaces oxygen to extinguish the fire, and therefore needs to be maintained at a concentration of 30 to 50 percent by volume. This represents a large quantity of CO_2 necessary to flood an entire generator. Removing CO_2 after discharge is another problem due to lowered oxygen levels with associated hazards to personnel. The CO_2 is considered to be nonpoisonous, but it is odorless and colorless and can kill by suffocation. The CO_2 is heavier than air, and tends to collect in low and poorly ventilated locations; therefore, careful purging of the machine and plant is required following CO_2 release.

In addition to being hazardous, a thermal shock hazard to the machine accompanies a CO_2 release. The CO_2 enters the machine as part gas and part solid (snow) at a temperature of about -120 °F (-85 °C). Generally, the CO_2 nozzles are located by the machine manufacturer to avoid directly striking the armature windings with the stream of CO_2. The high velocity of the stream, combined with its cold temperature, can be destructive to the insulation. Assuming that a machine has been operating at a rated temperature of 248 °F (120 °C), sudden exposure of the coil surface to high velocity CO_2 at -120 °F can produce significant thermomechanical movement with potential cracking. The low temperature of the CO_2 gas can have a significant effect in lowering the temperature of the burning fuel to help extinguish the fire.

Considerations of the advantages and disadvantages of the three schemes (water deluge, Halon 1301, and CO_2) have caused the Bureau to continue exclusive use of CO_2 for generator automatic fire suppression systems. Automatic CO_2 systems are frequently supplemented with manual systems of water, foam, and portable CO_2.

The user of this manual is encouraged to refer to the Bureau's report: *CO_2 Fire Protection Study for Hydrogenerators* [16]. The *Bureau's Design Standard No. 4* [8] discusses control systems of the CO_2 fire protection system, but does not discuss the sensors and control system that determines the presence of fire in the generator.

Currently, Bureau standards for fire detection and CO_2 discharge control have been not developed, and industry-wide control consensus does not exist. A survey was conducted during 1980 by CIGRE on the fire protection of hydrogenerators [17].

The NFPA (National Fire Protection Association) standard No. 12 [18], and ANSI/IEEE standard 492 [19] both address CO_2 fire extinguishing equipment. Bureau specifications are written to require initial CO_2 gas concentration in accordance with [18].

8.15.2 Fire Detection

To suppress a machine fire, initially, it is necessary to sense or determine that either an actual fire exists or that conditions that can produce a fire exist. In addition to manual release devices, automatic fire detection sensors include, but are not limited to, the following:

- Unit differential relays
- Split-phase differential relays
- Thermal links
- Ionization detectors
- Smoke detectors
- Stator ground relays
- Infrared detectors (heat sensors)
- Ultraviolet detectors (arc sensors)
- Optical detectors (flame or flicker detectors)
- Heat sensing wire resistor systems
- Pressurized tubing systems
- RTDs (resistance—temperature detectors)
- RF (radio-frequency) detectors
- Rate-of-rise thermal detectors

Differential relaying and split-phase differential relaying on machines so equipped are regarded as the generator's first line of fire defense. Operation of a differential relay should always produce an automatic release of CO_2. However, differential relaying cannot be made sensitive enough to detect all electrical faults that can produce fires, and fire ignition sources other than electrical faults detectable by differential relays exist. Therefore, additional sensors or combinations of sensors are implemented to achieve a scheme of alarm and trip for the CO_2.

The problem facing the design engineer is to develop a scheme that will alarm when conditions are such that a fire is possible and trip when a fire occurs, while avoiding nuisance alarms and trips. Nuisance alarms quickly destroy an operator's confidence in the system, with the potential result of operator indifference when real alarm conditions occur. Nuisance trips add to this indifference in the cost of CO_2, machine investigation, cleanup, and generator outage time.

Many sensors listed above detect conditions within an area close to the sensor's location, while others monitor average conditions existing in a large space (volume). It is not practical to install sufficient local or spot detectors to monitor conditions throughout the machine. Also, it has not been practical to calibrate large volume monitors to sufficient sensitivity to permit detection of small or hidden location faults. Therefore, common practice is to locate sensors close to areas determined to be high risk, or of high fault probability, and to supplement those sensors with devices capable of monitoring average conditions in a large space. Operation of two or more sensors within the same time frame can be an even greater assurance that an actual fault exists. Control systems which delay alarm or trip resulting from operation of a sensor until a second sensor (either the same or different type) also operates have proved to be effective. These delay systems dramatically reduce nuisance alarms, but unfortunately, they must increase the time delay before starting fire suppression—with a consequent increase in damage.

Some sensors previously listed are of the "early warning" type, which are in contrast with the "thermal" detection type that react to temperature change resulting from a fire. Various combinations of early warning and thermal detectors have shown promise.

8.15.3 Fire Protection

As noted, all Bureau hydrogenerator fire protection systems have all been of the CO_2 type, with two different systems being used. The most frequent system used is the high-pressure cylinder type. Where a large volume of CO_2 is required, such as for the generators in Grand Coulee Third Powerplant, a low pressure system with a refrigeration plant is used.

Both the high- and low-pressure systems depend on a system of piping and valves to route the CO_2 to the faulted generator. The low-pressure system differs from the high-pressure system in that only one storage source for CO_2 exists. Two sources, initial release bank of cylinders and delayed release bank, are required for the high-pressure system.

Separate piping systems, headers, and nozzles within the generator are required for the initial and for the delayed release of the high-pressure CO_2. Low-pressure systems require only one piping system of headers and nozzles within the generator for the initial and delayed releases.

The initial release of CO_2 within the generator is designed to achieve the required concentration of 30 percent, by volume, as quickly as possible. The delayed release is designed to compensate for air housing leakage, and to maintain the 30-percent concentration for 30 minutes after the initial release.

The control system for the generator disconnects the machine from the power system, closes the turbine wicket gates, and initiates rapid generator field forcing when the CO_2 is released. However, rotor rotation will continue for some time after shutdown is initiated, and the rotor motion will distribute the CO_2 throughout the machine.

Specifications are written to require the air housing to be sufficiently air-tight to retain the CO_2 concentration at 30 percent or higher, by volume, for at least 30 minutes after the initial release. This concentration is considered adequate for fire suppression purposes without the additional delayed release. However, the possibility of open doors or hatches, loose covers, and leaking gaskets always exists. The delayed release of CO_2 ensures that an adequate supply of fire suppressant continues to exist.

A sudden release of a large quantity of CO_2 gas into a well sealed air housing will cause an increase in the atmospheric pressure within the air housing. This sudden increase in pressure can cause the air housing to distort, and if the gas is permitted to enter the bearing oil reservoirs—it can distort the oil surfaces sufficiently to expose the bearings—with possible consequent bearing damage.

Pressure relief doors or other pressure equalizing features are installed in the air housing to prevent damage resulting from CO_2 release. The pressure relief doors are designed to open when the pressure inside the air housing exceeds the outside air pressure by about 0.2 lbf/in^2 (1.4 kPa). The pressure relief doors reclose when the pressure differential has decreased to about 0.1 lbf/in^2 (0.7 kPa) to reduce the loss of CO_2 to the outside atmosphere.

Bureau specifications are written to require a bearing assembly and housing design that will prevent bearing damage resulting from unequal pressures in the event that the air housing pressure relief devices fail to operate. The CO_2 headers are required by the specifications to be located above the generator rotor. The nozzle locations on the headers are selected by the machine manufacturer to best suit the machine design and configuration.

Usually, the CO_2 system is furnished by a supplier different from the generator supplier; the CO_2 supplier will furnish the nozzles for installation by the generator contractor.

The nozzle location frequently selected is in the area of the armature upper end-turns. This location delivers the CO_2 to an area having a number of fault occurrences; the natural air flow in the machine can quickly deliver the CO_2 to downwind fault locations. Another frequently selected location has been on the upper-bearing bracket arms immediately over the fans on the rotor or over the pole pieces.

8.15.4 Tests

Two field tests are performed to ensure the integrity of the CO_2 fire protection system. One test is performed during generator commissioning to demonstrate the ability of the air housing to maintain the CO_2 concentration. This test is performed on only one generator in multimachine plants; it tests the design of the fire protection system as opposed to a verifying that *each* machine's system performs as intended. The test is performed concurrently with the full-load rejection test. Test results will indicate the operation of:

- Air housing pressure relief devices
- Bearing pressure equalization features
- CO_2 concentration achieved

- Time duration that CO_2 concentration is maintained after initial release

A second test is performed to demonstrate that the fire detecting system design will function as intended. This test is performed on only one generator in multimachine plants, and CO_2 is not released during the test. During this test, various procedures may be implemented to simulate actual fire conditions, including: use of smoke bombs, local heaters, and other methods to test the operation of the detectors and sensors.

8.15.5 Summary

Virtually any material used to manufacture a hydrogenerator can be oxidized especially, if the material is exposed to high temperatures. Rapid oxidation (fire) can cause significant damage in a generator, and the cost of machine repair or replacement; the cost of lost revenue justifies the installation of fire detection and suppression equipment. Losses suffered by the Bureau from generator fires have led to the practice of installing an automatic, built-in CO_2 fire protection system in all new generators having an air housing.

8.16 INDICATION, INSTRUMENTATION, PROTECTION, AND CONTROL

8.16.1 Introduction

The amount of indication, instrumentation, protection, and control equipment installed in any given generator is somewhat related to the size (capacity) and importance of the generator and the plant in which the generator is installed. As generator capacity increases, the complexity of the system that monitors, controls, and protects the machine increases. Also, as generator capacity increases, the complexity of the machine itself and its component parts increases. An apparent step function in the amount of monitoring, control, and protection features occurs when machine size increases to that where an air housing is required. Far fewer features will be found for open, self-ventilated machines.

Major factors that determine the amount and type of monitoring, control, and protection features are the plant's physical size, number of generating units in the plant, and whether the generating unit will be controlled from a remote location. A small, single unit, supervisory controlled plant might be equipped with "conventional" indication and control equipment with transducers for converting monitored signals mounted in a unit control board. A large plant with several generators might have transducers for condition monitoring installed in the machines themselves. The methods used for collection and transmission of data to places external to the generator will not be discussed here.

The features listed in the following section 8.16.2 were intended to include most of the features that might be found on large generators. Features for special cases such as those required for a direct liquid cooled armature winding are not covered. All large machines may not be equipped with all of the features listed, or they might be equipped with some not listed; a small machine may not have any of the features. The listing intends to inform the reader of the type, scope, and importance of the features and the components they address.

The components—and the monitoring, control, and protection features for the component—are listed in the same order that they appear in previous sections of this chapter. If a feature is described as being mounted on an apparatus and "remote," the intention of the "remote" notation is that the data conveyed by the feature is transmitted to a location remote from the generator. If noted as "remote only," the intention is that the data derived from the device is not necessarily made available at the apparatus.

8.16.2 Components

8.16.2.1 *Shaft, Coupling, and Coupling Bolts*

(a) *Indication*:

- Shaft defection monitor.-This device monitors shaft runout, and is connected to sound an alarm and shutdown the unit in the event of sustained and excessive shaft deflection. The device is located at a point where the manufacturer believes that the most serious deflection might occur. A control panel for the monitor usually will be located on the unit control board.
- Creep detector.-This device is used to detect shaft movement during shutdown periods. The device usually is located at the generator-turbine coupling.

(b) *Instrumentation*.-None.

(c) *Protection*:

- Shaft grounding bush.-This device is mounted below the rotor to provide a continuous ground on the shaft.
- Vibration detector.

(d) *Control*.-None.

8.16.2.2 Bearings and Lubrication

(a) *Indication*:

- Thrust bearing metal temperature.—As many as four RTDs.
- Upper- and lower-guide bearing metal temperature.—RTD.
- Thrust bearing oil temperature.-Thermometer on thrust bearing oil reservoir.
- Upper-guide bearing oil temperature.-Thermometer on upper-guide bearingreservoir.
- Lower-guide bearing oil temperature.-Thermometer on lower-guide bearing reservoir.
- Thrust bearing, upper-guide bearing, and lower-guide bearing cooling water return temperature.-Thermometer in each bearing water outlet piping.
- Bearing cooling water supply temperature.-Thermometer located in bearing water supply piping.
- Bearing oil level sight gauges for each oil reservoir.-Care should be taken to ensure that these gauges are visible from the oil supply and drain valve locations.
- Thrust bearing, upper-guide bearing, and lower-guide bearing cooling water supply pressure detectors located at connections to bearing coolers.-For remote indication only.
- Thrust bearing high pressure lubrication system oil pressure.-Optional, mounted on apparatus.
- Test blocks for measuring bearing insulation resistance.
- Sampling valves.-One on each bearing oil reservoir.

(b) *Instrumentation*.- Bearings other than self-equalizing, spring plate, or coil spring types are equipped with strain gauges and a strain meter for use during initial adjustments of the bearing (primarily adjustable shoe-type bearings).

(c) *Protection*:

- Thrust bearing high-pressure lubrication pump motor combination starter, with thermal overloads in all three phases and an unfused disconnect switch or circuit breaker.
- Thrust bearing high-pressure lubrication system check valves at each bearing shoe and in the high-pressure supply line. These devices prevent normal operating oil-film pressure from being lost through the high-pressure lubrication system when the high-pressure system is not in service.
- Thrust bearing high-pressure lubrication system filters or screens to prevent debris from being forced between bearing surfaces with the lubricating oil.
- Bearing cooling water supply pressure.-Two devices, one to operate on decreasing pressure and one to operate on pressure failure—for remote alarm and shutdown.
- Bearing cooling water supply.-Two devices, one to indicate pressure available and one to indicate flow—for remote starting interlock.
- Thrust bearing, upper-guide bearing, and lower-guide bearing oil temperature.-Two devices in each bearing reservoir, one for alarm and one for indication—remote only.
- Thrust bearing, upper-guide bearing, and lower-guide bearing oil level.-Two devices in each bearing reservoir, one for alarm and one for indication—remote only.
- Thrust bearing metal temperature.-One or more devices for alarm—remote only.
- Upper-guide bearing and lower-guide bearing metal temperature.-One device on each bearing, for alarm—remote only.
- Drip collector tray under high-pressure lubrication pump, if pump is located inside generator housing.

(d) *Control*:

- Bearing reservoir oil fill and drain valves—one for each reservoir.
- Bearing cooling water supply valves.-Manual shutoff and automatic control valves—one each all bearing coolers.

8.16.2.3 Bearing Brackets

(a) *Indication*.-None.

(b) *Instrumentation*.-None.

(c) *Protection*.-None.

(d) *Control*.-None.

8.16.2.4 *Spider and Rim*

(a) *Indication.*-None.

(b) *Instrumentation.*-None.

(c) *Protection.*-None.

(d) *Control.*-None.

8.16.2.5 *Field Poles, Field, Amortisseur, and Collector Rings*

(a) *Indication.*-Collector ring brushes for field voltage indication.

(b) *Instrumentation.*-In excitation control equipment.

(c) *Protection.*-By excitation control and plant control equipment.

(d) *Control.*-By excitation control equipment.

8.16.2.6 *Stator Frame*

(a) *Indication.*- Movement or deflection indicators (installed on a test basis).

(b) *Instrumentation.*-None.

(c) *Protection.*-None.

(d) *Control.*-None.

8.16.2.7 *Stator Core*

(a) *Indication*:

- Core tooth and base temperature (installed on a test or temporary basis).
- Airgap variation.-Currents determined by current transformers located in armature winding parallel paths are compared to indicate airgap irregularities. Systems only installed on extra-large generators and on an "as needed" basis.
- Inspection openings through stator wrapper plate and frame.

(b) *Instrumentation.*-None.

(c) *Protection.*-High impedance neutral grounding system.

(d) *Control.*-None.

8.16.2.8 ***Armature Winding.***-Most armature winding condition monitoring, protection, and control is accomplished using data derived from current transformers, potential transformers, excitation supply and control equipment, and other machine component sources. In addition, the following devices are used for monitoring, protection, and control *at the winding*:

(a) *Indication*:

- Armature winding temperature by RTD—for remote only.
- "Figure 8" ties around windings to indicate slot filler movement.
- Gauging holes in wedges to permit measurement of under wedge spring compression, as an indication of coil tightness in the slots.

(b) *Instrumentation.*-A gauge with instructions for its use—for measuring under-wedge spring compression.

(c) *Protection*:

- Rotating machine surge arresters and capacitors at terminals.
- A large and complex array of equipment—remote from generator.

(d) *Control.*-A large and complex array of equipment—remote from generator.

8.16.2.9 *Air Housing*

(a) *Indication.*-Each door and access hatch equipped with interlock switches to indicate door position—for remote only.

(b) *Instrumentation.*-None.

(c) *Protection.*-None.

(d) *Control.*-None.

8.16.2.10 ***Excitation Supply.***-Many of the features listed below are not found on all types of exciters. The exciter type number refers to the exciter types discussed in section 8.10 of this chapter. Most of the features will be found under the Type 5 exciter in section 8.10.3.1, and many additional features will be found in section 8.11.

(a) *Indication*:

- Field current shunt and transducer.-Local indication on apparatus for Type 5, and remote indication for Types 1, 2, 3, and 4.
- Lights to indicate the individual rectifier failure—Type 5 only.
- Auxiliary contacts for indication of static exciter cooling fan operation—Type 5 only.
- Static exciter cooling air flow from each fan—Type 5 only.
- Thyristor cabinet high temperature alarm—Type 5 only.
- Excitation supply transformer temperature—Type 5 only.
- Excitation supply transformer current transformers.-Two CTs in each phase of the low voltage windings—Type 5 only.
- Field voltage isolation transducer—Type 5 only.

(b) *Instrumentation*.-Field current ammeter.-On exciter and remote—for Type 5 only. No field ammeter on exciter for other exciter types.

(c) *Protection*:

- Thyristor cabinet high temperature shutdown—Type 5 only.
- Excitation supply transformer temperature detector—Type 5 only.
- Excitation supply transformer overcurrent relay—Type 5 only.
- Excitation supply transformer over and under pressure sensing device—Type 5 only.
- Excitation supply transformer gang operated current limiting fuse disconnect switch—Type 5 only.
- Excitation supply air circuit breaker—Type 5 only.
- Generator main field discharge resistor and breaker—Types 1, 5, and occasionally 4. No breaker for Types 2 and 3.
- Exciter field discharge resistor and breaker—Types 2 and 3.
- Voltage spike protection—Type 5 only.

(d) *Control*.-Excitation control equipment is specifically covered under paragraph 8.16.2.13, which addresses Excitation Control (sec. 8.11). The control devices listed below are found on the exciter itself:

- Field flashing circuit breaker—Type 5 only.
- Switch to control rapid demagnetization feature—Type 5 only.
- Main field rheostat—Type 1 only.
- Exciter field rheostat—Types 2 and 3.

8.16.2.11 Ventilation and Surface Air Coolers

(a) *Indication*:

- Cooling discharge air temperature at each surface air cooler (transducer for remote indication).
- RTD for temperature measurement of cooling air discharge from each surface air cooler—for remote indication.
- Air cooler water supply header pressure—for remote indication only.
- Cooling water supply temperature—thermometer in supply header.
- Cooling water discharge temperature—thermometers in discharge piping from each surface air cooler.

(b) *Instrumentation*.-None.

(c) *Protection*:

- High temperature alarm device on each surface air cooler.-Two electrically separate contacts—for remote alarm.
- Surface air cooler water supply header loss of pressure.-Two electrically separate contacts—for remote alarm.
- Surface air cooler water supply header flow failure.-Two electrically separate contacts—for remote alarm.
- Air release valves at each surface air cooler.
- Drip pans under each cooler with leak detectors.

(d) *Control*:

- Surface air cooler water supply header pressure.-Two electrically separate contacts—for starting interlock.
- Surface air cooler water supply header flow.-Two electrically separate contacts—for starting interlock.
- Water supply and discharge valves at each cooler.
- Motor-operated supply and discharge header valves. To inhibit cooler water flow during machine start and warmup period.

8.16.2.12 *Brakes and Jacks*

(a) *Indication*:

- Limit switch with two electrically separate contacts on each brake to indicate brake engagement.
- Brake air pressure gauge.
- Jacking oil pressure gauge.
- Jack maximum raised position indicating light.
- Jack oil reservoir sight gauge.

(b) *Instrumentation*.-None.

(c) *Protection*:

- Jacking oil pump motor combination starter with three thermal overloads and unfused disconnect switch or circuit breaker.
- Limit switches to prevent generator startup with brakes in engaged position.
- Jack limit switches to prevent excessive lift.
- Springs on each brake to ensure return to disengaged position upon release of air pressure.

(d) *Control*:

- Jacking oil pump with motor, starter, and controls.
- Brake air pressure valves and controls from governor.
- Automatic brake application control system.

8.16.2.13 *Excitation Control*.-See section 8.11 for a description of all indication, instrumentation, protection, and control.

8.16.2.14 *Soleplates and Anchors*

(a) *Indication*.-None.

(b) *Instrumentation*.-None.

(c) *Protection*.-None.

(d) *Control*.-Lubrication fittings on extra-large machines equipped with sliding radial key system soleplates.

8.16.2.15 *Fire Detection and Protection*

(a) *Indication*:

- Armature current differential relaying system.
- Split-phase differential relaying system.
- Thermal links.
- Smoke detectors.
- Ionization detectors.
- Ground detector relays.
- Infrared heat sensors.
- Ultraviolet arc sensors.
- Flame or flicker sensors.
- Heat-sensing wire systems.
- Pressurized tubing systems
- RTD temperature systems.
- Radio frequency arcing detectors.
- Rate-of-rise thermal detector systems.

(b) *Instrumentation*.-None.

Note: Some detector systems may be equipped with special instrumentation.

(c) *Protection*.-Various combinations of sensor indication to reduce nuisance alarm and CO_2 release.

(d) *Control*:

- Automatic alarm and CO_2 release systems—based on detection system employed.
- Manual CO_2 release controls.

8.16.2.16 *Heaters and Lighting*

(a) *Indication*.-Indicating lights on heater starter to indicate heater operation.

(b) *Instrumentation*.-None.

(c) *Protection*.-Combination magnetic starter with thermal overload devices, and circuit breaker or disconnect switch.

(d) *Control*:

- Heater Hand-Off-Auto control.
- Generator internal-external temperature differential control device.
- Lighting control switches.

8.17 CURRENT TRANSFORMERS

The rated current output of the smallest hydrogenerators is higher than the practical limit for use of shunts. As a result, all hydrogenerators use CTs (current transformers) for metering and relaying. A full discussion of instrument transformer considerations is beyond the scope of this manual.

Engineers responsible for the design of the plant protection and instrumentation system determine the CT type, ratio, metering accuracy at various burdens, and relaying accuracy classification requirements, and all other characteristic, performance, and testing requirements for the CTs.

The CTs are required to be in accordance with ANSI C57.13 [20] and may be either: bushing or wound type, multiratio, indoor, or dry type, with single or double secondary windings. The insulation class of the CTs is chosen to permit high potential dielectric testing of the armature winding with the CTs assembled in the winding. This is true for CTs located in both the main and neutral leads of the generator.

The CTs are used for metering, differential protection of armature winding, split-phase armature winding, static excitation, excitation control, and differential protection in power system external to generator.

The CT secondaries are almost exclusively rated for 5 amperes, regardless of primary rating. As a result, the sensitivity of the relaying supplied by the CT decreases as primary current rating increases. That is, the relaying connected to a 30,000:5 CT will be only one-sixth as sensitive as the same relaying supplied by a 5000:5 CT. This consideration becomes more critical when designing a protection system for detecting turn-to-turn faults of a high capacity, multiturn armature winding or for detecting low current faults in any armature winding. A system has been developed whereby CTs are installed in leads from individual parallels of larger machine armatures, and differential relaying is connected. This scheme has proved successful in not only detecting armature failures, but also in detecting excessive rotor eccentricity or airgap variation.

The leads from the CT secondary windings are extended to the generator main terminal box for those CTs located in the main generator. The CTs in static excitation cubicles may have their leads terminated in the cubicles rather than extending the leads to a relatively remote terminal box in the generator.

It is essential to short circuit unloaded CT's secondary windings to prevent dielectric failure when primary current is flowing. Therefore, all CT leads are terminated on short-circuiting type terminal blocks.

The CTs for small self-cooled generators usually are located in the main leads outside the machine. Usually, generators having an air housing will have sufficient space between the stator frame and the air housing to allow location of CTs within the space. The ambient air temperature inside the air housing is assumed to be limited to 40 °C; this limit is specified for the CTs. For CTs located elsewhere such as in switchgear or excitation cubicles, they may be exposed to different ambient temperatures and may require a temperature rating different from those located in a generator air housing.

8.18 PIPING

8.18.1 Introduction

Hydrogenerators are equipped with varying amounts of piping, depending primarily on the size of the machine. Small, self-cooled (open ventilation) generators may be without piping, or only a minimal amount for bearing lubrication lines. As machine size increases, piping systems for bearing lubrication, cooling water, compressed air for braking systems, and for CO_2 fire protection systems become necessary.

Most of the piping inside the generator is supplied by the machine manufacturer. The Bureau has frequently required fabrication and installation of piping for the surface air cooler water supply and discharge main headers to be by contractors other than the generator supplier. Piping furnished with the generator is extended to points of termination on the generator as determined by the Bureau. A requirement for all piping within the generator to be designed and furnished as a part of the generator offers significant reduction in required coordination. Conflicts arising in ventilating air flow restrictions, machine assembly/disassembly junctions, size and type of piping required, and other concerns are reduced or eliminated if the machine manufacturer supplies all components within the generator.

The ANSI Code for Pressure Piping [21] requires using seamless steel pipe or tubing where a possibility of failure due to vibration may occur. Bureau specifications require using seamless steel pipe or tubing only for bearing lubrication oil piping. Water piping, regardless of location, is required to be of nonferrous metal or stainless steel; air piping material is not controlled by the specifications.

Partial or complete disassembly and reassembly of generator components occur during normal generator maintenance. Removal of components, such as surface air coolers, brakes and jacks, and bearing oil coolers, requires using flanged couplings or unions in connections to piping systems serving the various components. In addition to piping connections to component parts, which may be removed, generator suppliers may install unions or flanges in piping at various locations to facilitate machine field erection.

Pumps for thrust-bearing high-pressure lubrication systems are sometimes located outside the generator; all piping between these pumps and the bearings is supplied with the generator. Other specific items for any given machine, such as external bearing oil coolers or armature inner cooling water, may be furnished in their entirety—including piping by the generator supplier.

Connections between generator internal piping and external plant piping are made with insulating couplings. The basis for the use of insulating couplings is a result of concerns that possible differences in piping material, such as internal copper connected to external iron, would lead to galvanic action and erosion at the joint. Generator manufacturers are known to favor copper piping because of the ease of shaping and making connections; embedded piping is rigid steel.

8.18.2 Lubricating Oil Piping

Dirt or other debris can enter and remain in lubricating oil piping systems during initial construction or during maintenance periods. To prevent such foreign material from entering bearing reservoirs, flushing connections between the oil supply and drain piping are provided. These connections permit an operator to flush all supply lines with oil before filling the bearing oil reservoirs.

Sampling valves are provided on each bearing oil reservoir. These valves should be located at the bottom of the reservoir for sampling purposes; they will reveal the presence of water or debris in the oil.

Reservoir drain valves and piping are provided for each bearing reservoir. Current specifications require these items to be sized and sloped so as to drain each reservoir in less than 45 minutes when the oil is at a temperature of 40 °C.

The liquid level in the bearing reservoirs may rise above the correct level, either due to improper filling or to a leak in the cooler of a water-cooled bearing. Overflow drains and piping are provided to safely route any such excess oil out of the generator.

Oil at high pressure is required for thrust bearing high-pressure lubrication and for the hydraulic lifting jack systems. The piping for these systems is special, and must be specifically designed for the applications.

8.18.3 Cooling Water Piping

As previously mentioned, the Bureau has required contractors, other than the generator supplier, to furnish the water piping for the surface air coolers inside the generator. The basis for this division of responsibility is that the design of the cooling water supply and discharge headers remains with the Bureau. The pressure loss through the surface air coolers is limited by the specifications: the overall pressure loss through the piping system can be controlled by the piping system design. Conflicts about the machine do arise, and careful coordination between piping design and generator design is required to resolve these conflicts. Various machine suppliers have indicated a willingness to supply the surface air cooler water piping to meet Bureau requirements. This procedure appears to satisfy both the Bureau's needs to control overall piping design and the machine designer's need to properly locate components within the machine.

Air can become trapped in the top of surface air coolers; vents are required to evacuate the air and permit complete filling of the cooler with water. Specifications require the piping from these vents to be furnished by contractors other than the generator supplier.

All water piping furnished by the generator supplier is required to have an insulating covering to retard condensation from forming on the piping.

8.18.4 Air Piping

As discussed in section 8.13, air brakes may be used to decelerate the rotor during shutdown; contamination of the air system with oil may occur if a combination brake/jack is furnished. Therefore, special attention must be given to the air piping system design. Filters, separators, and proper piping layout are required. Air piping for other braking systems are more conventional in nature.

8.18.5 Carbon Dioxide Piping

Bureau specifications for the CO_2 piping are placed in the portion of the specifications for the fire protection system. The piping for the CO_2 ring headers must comply with the latest standards of the National Fire Protection Association [18]. In addition, piping is required to be hot-dipped galvanized steel pipe or nonferrous tubing with tapered pipe threads on all pipe and fittings.

8.18.6 Summary

Hydrogenerators may have an extensive system of oil, air, water, and CO_2 piping, depending on machine size and importance. The types, classes, and configuration of the piping systems have usually been left to the discretion of the generator supplier. Only a few limits, requirements, or restrictions are placed on the piping systems in generator purchase specifications. However, piping systems perform important functions in the supply and discharge of fluids and gases required for generator operation. A failures in any of the systems can cause extensive generator outages and expensive cleanup or repair. Therefore, a high level of quality in the piping systems is mandatory.

8.19 TERMINAL BOXES, CONDUITS, BUS, WIRING, AND GROUNDING

8.19.1 Terminal Boxes

Hydrogenerators are equipped with terminal boxes, accessible from outside the machine, for continuation of internal wiring to places external to the machine. The number of boxes is dependent on the relative size of the machine. Small generators may have one box for termination of the main lead power cables, another box for termination of low voltage auxiliary power and control secondary leads, and possibly another box for termination of field leads.

As machine capacity and size increase, the termination of main lead cables or bus on terminal boards or studs becomes impractical, and a main lead terminal box is no longer necessary. Similarly, main field leads may be brought directly to collector ring terminals without a terminal box on larger machines.

Machines having a speed-signal device are equipped with a separate terminal box that is reserved for connection of speed-signal leads only. The critical need to protect the speed-signal device from short circuits or unintentional contact justifies the complete isolation of these circuits.

Machines equipped with insulation on one or more bearings are equipped with a separate terminal box for termination of leads from the bearing insulation layers. Again, the necessity to avoid bridging these terminals (shorting the bearing insulation) justifies a separate terminal box. The leads from the bearing insulation layers are not continued beyond the terminal box. Access to the terminals is only for test measurement of bearing insulation.

Terminal boxes are manufactured and installed in a way to be accessible from outside of the machine. Small, self-cooled-machine terminal boxes may have bolted covers; larger machines may have terminal boxes with hinged doors that are not equipped with handles to discourage casual opening. Terminal boxes for machines installed in concrete "barrels" may be excepted from the "accessible from outside the machine" criteria stated above. Terminal boxes for such a machine might be located on a concrete wall inside the air housing.

Maintenance of the air seal for the air housing found with larger machines is of considerable importance; attention must be given to terminal box design and construction to maintain the integrity of the seal. This is of particular concern for machines equipped with a CO_2 fire protection system. The loss of CO_2 through terminal boxes and the CO_2 exposure to personnel who might be working in the terminal box is not acceptable. Therefore, terminal box seals are made between the box and the internal parts of the generator rather than at the terminal box covers or doors so that the CO_2 does not intentionally enter the terminal boxes. If a terminal box is located internally on a large generator, a CO_2 safety clearance must be obtained before working in the terminal box.

Separate terminal boxes, or provisions for terminating circuits leaving the equipment, may be provided for static exciter power supply transformers, static exciter supply circuit breakers, static exciter cubicles, excitation control cubicles, and separately driven (Type 2) exciters.

Barriers with warning nameplates are installed in the terminal boxes to separate 480 volts and higher voltage circuits from lower voltage circuits. To develop consistency between installations, Bureau specifications require the 480-volt and higher voltage circuits to be located on the right-hand side of a terminal box when viewed when facing the front of the box. Special care is taken to ensure that leads from the insulated brushholders—used for measuring field voltage—are terminated in the high-voltage barriered portion of the terminal box when exciter ceiling voltage exceeds 480 volts. Bureau specifications require the terminal boxes to be installed in accordance with ANSI/NFPA No. 70 standards [22].

Terminal blocks in the terminal boxes are required to have voltage ratings equivalent to the insulation of the conductors terminated on the blocks, and capable to withstand the high potential test voltage level of the equipment served by the terminal block. These blocks are required to provide a barrier between adjacent terminals, be of one-piece construction, and have a suitable cover with a removable marking strip. Various types of terminal blocks are installed in each terminal box or cubicle, such as

- the "shorting type" for current transformer leads,
- the "solder type" for RTD leads, grounding bus screw type for grounding shielded cable shields and spare conductors, and
- other types suitable for the conductors they terminate.

Most terminal blocks, other than those found in small generator terminal boxes, are originally filled to about 75 percent capacity, which leaves 25 percent of the terminals as spares for future use or for terminating spare conductors. This extra capacity may not be required for small machines because the potential need is limited.

8.19.2 Conduits

Generally, wiring within small generators is not vulnerable to physical abuse or damage; internal conduit is not necessary to protect the circuits. As machine size increases and access to the internal parts becomes possible and necessary, the potential for damage to circuits requires the use of conduit. All conduit is required to be rigid metal according to standards. The standard reference has been changed at various times to agree with the governing entity at the time the specifications are written. Some circuits, such as RTD leads, are not easily installed in conduit; these circuits are required to be armored for protection.

Care must be taken to ensure that machine disassembly and assembly activities are possible without major interference from conduit runs across machine component junctions. This may require installation of junction boxes. Conduit is used to connect all static excitation components. All conduits must be cleaned before installing cables to ensure that debris or obstruction is not in the conduit.

8.19.3 Bus

Small generators usually do not require the use of bus beyond the main lead terminals. Generally, larger machines are equipped with bus to extend main lead power to a neutral wye connection and to a point, such as the barrier, where the leads leave the air housing. This bus is usually copper with field-applied insulation. Barriers are provided to shield this bus from the accessible areas in the air housing.

Beyond the air housing, bus may be used to carry generator output to switchgear and/or step up power transformers. Taps on this bus may be required to obtain static excitation power. If a machine is equipped with a static exciter, the bus taps may be furnished with the generator. The bus taps are required to match the construction class (cable, nonsegregated phase, segregated phase, or isolated phase) of the main power bus.

Bus may be used to supply main field power from the exciter. The class and rating of this main field bus must be selected to suit the requirements of the particular job.

8.19.4 Wiring

All generator internal wiring (other than main, neutral, and field leads) usually is required to be insulated for 600 volts, and is required to be No. 12 AWG or larger. Exceptions to this are the speed-signal device leads that are required to be No. 10 AWG or larger, and alarm and RTD leads that may be No. 16 AWG or larger. All conductors are required to be stranded, tinned copper.

The RTD leads are required to be armored and to have either AVA or SIS insulation according to with NFPA No. 70 standards [22]. The leads are three conductor that permit paralleling two of the three conductors to determine conductor circuit resistance, which can then be deducted by measuring instruments, leaving only the resistance of the detector for temperature determination.

All static exciter and excitation control cubicle wiring is required to conform to NEMA Standard SG5 [23], and is restricted to insulation types AVA, AVB, TA, SIS, or TBS.

Power cables insulated for 600 volts and multiconductor control cable are restricted to type XHHW insulation. These cables are shielded; the shielding is grounded at each end. At least one conductor in each multiconductor cable is left unused (nonactive) and is grounded at each end. Any additional unused or spare conductors in cables are grounded at both ends. Bureau practice is to avoid combining a-c and d-c circuits in the same multiconductor cable to reduce mutual effects. Bureau practice avoids combining current transformer and potential transformer leads in the same multiconductor cable. Transducer leads are required to be shielded.

8.19.5 Grounding

A complete grounding system that is functional at all times is essential for successful operation of a hydrogenerator; the primary protection of the machine is dependent on a properly designed grounding system. The numerous stray magnetic fields create induced emf(s) and leakage currents that can present safety threats to personnel if the machine is not thoroughly grounded.

Small generators may not be equipped with an armature neutral grounding system; however, strong dependence is placed on a good generator frame grounding connection. Larger generators are equipped with an armature neutral grounding system; usually, the system is of the high-impedance type, which will limit damage (iron burning) of the armature core in the event of a ground fault failure in the armature winding. A single lead insulated for at least generator line-to-neutral voltage, but more often for full line-to-line voltage, is extended through a nonmagnetic conduit or duct to a single-phase distribution transformer. The initial unidirectional inrush current associated with a fault demands the use of nonmagnetic conduit to ensure development of full voltage across the transformer.

The distribution transformer has a primary voltage rating that is about 1.5 times the generator line-to-line voltage. This rating limits transformer magnetizing inrush current in the event of an armature ground fault. The distribution transformer has a secondary voltage rating of 240/120 volts; the center of the winding (120 volt connection) is grounded. The kilovolt-ampere capacity of the transformer is determined primarily by the armature winding capacitance, surge shaping capacitors, and any other capacitance contributing devices permanently connected to the generator armature, divided by an overload factor. This overload factor is based on a time or duty factor. Older plants were designed with long or continuous duty factors; however, these designs required large kilovolt-ampere ratings for the transformer, large kilowatt ratings, and physically large resistors. Present Bureau practice is to design for a 1-minute neutral grounding time rating. The kilowatt rating of the resistor is selected to match the capacitive kilovolt-amperes developed through the transformer during fault conditions, and the resistor duty rating matches that of the transformer.

Clamp type ground lugs are provided for making connections to the plant grounding system. As noted above, small generators may have only one connection at the stator frame. However, components separated from the machine, such as static excitation components, must be grounded. Larger machines require a more complex system, and each component not solidly connected by a metallic device must be individually grounded. Lower-bearing brackets of a vertical-shaft machine fall into this category, and dependence cannot be placed on grounding through the stator frame.

Static excitation components also are individually grounded even though there may be metallic connections through conduit and various housings. Excitation supply transformers are supplied with grounding lugs. At least two ground connections, located approximately at diametrically opposite positions, are provided on lower-bearing brackets and stator frames.

Air housing deck cover plates particularly, for those machines having concrete air housings must be given special attention to ensure adequate grounding at all times. Maintenance procedures may require removal of some, but not all plates. The plates may not be bolted or permanently connected to the deck support framework, and various types of air seals may be used to electrically insulate the plates.

Handrails, hatches, stairways, and ladders may not be electrically bonded to the generator frame; special grounding for these components may be necessary.

Some current transformers require secondary ground connections near the transformer. The housings of main lead extension bus require grounding; special design considerations based on the type of bus used may be required. A grounding bus, with screw connectors, is required for grounding conductor shields and spare conductors in the main terminal board. A ground brush usually is fitted on the lower-bearing bracket to provide shaft and rotor grounding. The sizes of all grounding lugs are selected to accommodate the cables they connect.

8.20 HEATERS AND LIGHTING

8.20.1 Heaters

Most hydrogenerators are equipped with electrical space heaters to prevent formation of condensation during shutdown periods. Most of these heaters are connected 460 volts and 3 phase, although lower, single phase power has been used for small machines. Excitation system cabinets may be equipped with heaters; these heaters may be 115 volts, single phase.

The generator space heaters may be located between the air housing and stator frame, or under the rotor or stator in the lower-bearing bracket area of larger generators. The heaters are equipped with suitable guards to prevent burns due to inadvertent contact. Several heaters are located around the machine to improve heat distribution, and equal spacing between the heaters is strived for efficacy. Heaters are located in the most convenient place possible under the stator in smaller machines. The kilowatt capacity of the heaters is determined by the generator supplier to suit the particular machine.

A combination magnetic starter-disconnect switch or circuit breaker is furnished with the generator to control heater operation. The starter is located so that it is accessible from outside the generator. A control system is installed to permit Hand-Off-Auto control of the heaters. This automatic control consists of a differential temperature device that detects generator internal and external temperatures to determine if the heaters should be energized. Heater operation is blocked when the generator is running.

8.20.2 Lighting

Larger machines, having provisions for access inside the air housing, are equipped with lighting and convenience outlets inside the air housing. Additional lighting and convenience outlets may be provided at the collector rings, main terminal box of the generator, lower-bearing bracket area, and in static exciter cabinets. Air housing lighting is controlled by three-way switches located near each door in the air housing. Other lighting usually is controlled by a single switch.

The air housing lighting may be furnished by a contractor other than the generator supplier if a concrete air housing is used; this would permit embeddment of conduit and boxes for the lighting system by the concrete contractor.

Separate circuits are used to supply the lights and convenience outlets so that interruption of power to one circuit will not necessarily affect the other circuit. Convenience outlets are required to be of the GFCI (ground fault circuit interrupting) type.

8.21 LOADING CONDITIONS AND UNIT STRESSES

Generator manufacturers have shown a general unwillingness to divulge stress level versus material strength for the various materials used in their designs; also, material availability, material quality, quality control, and industry practice has varied over time. Usually, industry standards do not prescribe materials nor stress levels for various applications. Therefore, Bureau of Reclamation specifications place limits on the stresses that may be imposed on various parts of a generator under normal, abnormal, and temporary loading conditions.

- Normal conditions are considered to include the loading resulting from 100 percent of rated load at rated speed, load rejection overspeed, and short-circuit loading at the machine terminals. Many generators have been constructed to standards that permit continuous loading to 115 percent of rated load; this requires the machine to have the structural and mechanical capability to carry the extra loading continuously. Thus, 115 percent of rated load at rated speed becomes the "normal load" for material stress considerations.

- Abnormal loading is considered to be primarily the stress imposed by runaway conditions. Loads imposed by rotor jacks on jackpads or brake rings are also considered to be abnormal.
- Hydraulic turbines operating at heads higher than they are rated are frequently capable of producing more power than what the coupled generator is rated. If the generator is required to produce overload power under such circumstances, the condition is considered to be temporary loading condition.

Bureau specifications state stress limits in terms of: yield point, yield strength, and ultimate strength of the material. Ductile metals, such as low-carbon steel, that may be used for many parts of a generator have a well-defined yield point. Other metals, such as high-strength steel and many nonferrous metals, do not have a yield point. Technically, the yield point is defined as ". . . the lowest stress of a stress-strain diagram for a given material at which a marked increase in strain occurs without increase in load." Yield strength is a term used to describe materials that do not have a yield point. Yield strength is defined as ". . . the maximum unit stress that can be developed in a material without causing more than a permissible set or 'offset'." Both yield point and yield strength are measures of the maximum useful strength of a material; materials stressed to either of these limits will undergo plastic deformation. Therefore, specifications limits are imposed that prohibit stressing materials to those limits under any machine loading condition.

General industry practice frequently limits the yield strength to 0.2 percent offset. Bureau specifications follow this practice except for all rotating parts of the generator, where the yield strength limits are reduced to 0.02 percent offset. The yield point stress, for all rotating parts of the generator, is limited to two-thirds under runaway conditions. Strain is customarily stated in terms of inches of elongation per inch of test specimen length, or inches per inch. Therefore, an offset of 0.2 percent would be a permanent stretch of 0.002 inches for each inch (0.051 mm/mm) of test specimen length.

The ultimate strength, sometimes called tensile strength or compressive strength, of a material is defined as ". . . the maximum unit stress that can be developed in a material." Ductile materials will reach a maximum stress and then undergo plastic deformation (necking down and elongation) at decreasing levels of stress before eventually breaking. Brittle materials, usually those with no yield point, will reach maximum unit stress at the breaking point.

The yield point, yield strength, and ultimate strength of any given material is not necessarily the same in tension, compression, and shear. As a rule, the yield in shear is significantly less than either the yield in tension or compression for any given material.

Present Bureau specifications are written to limit the maximum stress under normal loading conditions to one-third of the yield point or to one-fourth of the ultimate strength of the various materials. Limits of maximum stress under abnormal loading conditions are two-thirds of the yield point. Unit stresses under temporary loading conditions, up to the maximum output of the turbine, are not permitted to exceed one-half the yield point.

Earlier specifications for generators limited normal loading stresses to one-third of the yield point or one-fifth of the ultimate strength. Better quality control of materials by the industry apparently permitted raising the limits of ultimate strength stress.

Special limits are imposed on generator shaft coupling bolt material. These limits require that coupling bolts have a yield point not less than 1.2 times the yield point of the shaft flange material. Specifications require the bolts to be prestressed to a value equal to 80 percent of the yield point of the shaft flange material. Limits of stress at maximum bolt tension (total tension including prestress) are not imposed by the specifications.

An exception to the above limits for generator components is made for bolts in general. This exception permits any bolt, other than a coupling bolt, to be prestressed to not more than two-thirds the yield strength of the bolt material, without limits placed on the total load (prestress plus any tension load) that the bolt may have.

Bureau specifications requirements for coupling bolts—and bolts in general—are currently being reviewed. Future specifications requirements and limitations particularly, those for bolt prestress and maximum load, may change as a result of this review.

Vibration (alternating stresses) or shock can stress a material beyond its proportional or elastic limits with occasional devastating effects. For example, a fastener loaded in tension and stressed beyond its elastic limit will undergo some plastic elongation (loosening), thus reducing its fastening function. If vibration continues, the resultant hammering could lead to total failure.

For many years Bureau specifications contained a restriction that prohibited using bolts or rivets loaded in tension on the generator rotor. The rationale for this restriction was based on the concern that bolts loaded in tension would tend to loosen; looseness of rotor components can lead to catastrophic failure. This restriction no longer exists in current specifications language, but the concern continues. Good engineering practice, for large machines, avoided using bolts-in-tension on generator rotors. However, the possibility that a design using tension-loaded bolts on a generator rotor could be proposed. Situations involving small generators might be where such a proposal could be encountered. The economic tradeoffs of initial cost versus potential failure would have to be considered carefully in such a situation.

Threads on bolts, nuts, studs, and screws are required to conform to ANSI Standards [24], except for small components that are determined to be replaceable as a unit by the Government's Contracting Officer. Manufacturer's standard threads, if different from ANSI Standards, may be used for such small integrally replaceable components. However, threads of fasteners used to connect any such components to other parts of the machine are required to meet the ANSI Standards.

Many machine components are fabricated from a welded steelplate; welding can create many problems if not properly performed and treated. Tempering or annealing can occur nonuniformly at a weld, and warping caused by uneven stress is a possibility. Stress relieving is necessary to ensure proper performance of the component. For these reasons, factory assembly, welding, and stress relieving is preferred. Still, some field welding may be necessary, but should be kept to a minimum because stress relief of field welds is not usually possible.

Dowels can only be loaded in shear. Dowels are frequently used to transmit loads (such as through shaft couplings), to precisely locate mating component parts, ensure correct reassembly to original positions, and to restrict movement in one direction while permitting limited movement in another direction. Generally, dowels are installed by field drilling between mating machined surfaces, and inserting interference fit dowels—at the interface. Locking devices are frequently installed to prevent dowel movement, except when the movement is intentional.

Keys must meet the overall specifications limits for unit stress. Usually, keys are driven into premachined grooves or keyways to transmit the load from one mating surface to another. Sometimes, the material from which the keys are made is different than the material in which the keyway grooves are machined. As a result, the stress–strain characteristics of the key may be considerably different than the keyway. Shear keys are an example of situations using different materials for key and keyway.

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CHAPTER 9

CLEANING AND PAINTING

9.1 GENERAL

The Bureau of Reclamation has developed considerable experience in cleaning and painting systems to be used throughout water projects. This expertise has led the Bureau to develop detailed standard specifications requirements and specifications restraints for the cleaning and painting systems for general use in its facilities. Procurement solicitations for hydrogenerators are written to include many of the requirements and restraints developed for water project use.

Unfortunately, many generator components must be painted using systems that are unique for use in high voltage rotating electrical machinery environment; Bureau standard paint systems are not suited for this use. In fact, application of Bureau standard paint systems would be deleterious to some generator components. To complicate matters further, many of the special systems required for electrical machinery are proprietary with the various machine manufacturers. Different manufacturers use entirely different paint systems to achieve the same purpose. For these reasons, generator procurement solicitations specifications are written to require Bureau standard paint systems to nonsensitive parts of the generator, and to require the contractor's systems to be applied where required to meet various functional purposes.

A recurrent problem has been writing the specifications narrative necessary to clearly define "nonsensitive" generator parts. Some misguided attempts to apply Bureau standard paint systems to sensitive generator areas have occurred.

Some specifications require application of Bureau standard paint systems to generator parts "visible or accessible," after assembly, with inference that the viewing position is *external* to the generator. Unfortunately, many internal areas of large generators are "visible *and* accessible" from places *inside* the generator after assembly. Many of these internal areas should properly receive Bureau standard paint systems.

Other specifications have attempted to identify those generator components that should receive Bureau standard paint, or manufacturer's paint system, on a part-by-part basis. Unfortunately, many generator components are not readily identified by a generic or industry-wide accepted name or term. Consequently, a machine component furnished and described by a contractor may or may not be identified by the same term in the specifications. Disagreements between the contractor and the Bureau can result regarding which paint system should be applied.

Yet, another problem occurs in stating requirements for paint systems to be applied to accessories and devices which are finished with a subcontractor's or supplier's paint system when received by the generator manufacturer. Items such as relay and contactor cases, small motors, pumps, various detectors, instruments, switch covers, transformers, and other devices would be in this category. Although the device may not be in the "sensitive" category, repainting it with a Bureau standard system may not be practical. However, if such devices are to be mounted in a location visible to the public from outside the machine, painting for aesthetic purpose to blend with surroundings having Bureau paint systems may be necessary. In the case, where Bureau standard paint must be applied to a device painted with a manufacturer's standard paint, it may be necessary to remove the manufacturer's paint and then clean and repaint the device with a Bureau standard system. Another possible solution may exist if a Bureau standard system can be applied over the manufacturer's paint.

For purposes here, a distinction is made between paint coatings which are applied for various machine functional purposes (sec. 9.2) and paint coatings required for all other purposes (sec. 9.3). Preparation of surfaces, cleaners and cleaning, paint composition, and application are responsibilities vested with the contractor under section 9.2. Preparation, cleaning, and painting systems under section 9.3 are required to meet Bureau standards.

9.2 FUNCTIONAL REQUIREMENTS

Requirements for functional painting are discussed in more detail in chapter 8. The following would be included here:

The paint for the main field pole winding is required to function as an insulation—to prevent bridging of the insulation interleaving coils. Generally, field coil conductors are made from bare copper and solid insulation is used to separate conductors in the coils—leaving the bare edges of the copper coils exposed to cooling air. Airborne debris can be deposited on the pole windings, particularly in the area where the poles attach to the rim. This debris can bridge the insulation between coils and cause short circuits between adjacent coils. Paint applied to the field winding is intended to prevent bridging. The paint has the negative effect of inhibiting heat transfer from the field coils to the cooling air; care must be taken to avoid excess paint thickness. Paint having the proper electrical insulating and heat conductivity properties is selected by the contractor (manufacturer). The color or pigmenting of the paint is left entirely at the contractor's discretion, but the color selection is frequently black.

Armature windings are painted with a semiconductive paint on that part of the coils which will be installed in the armature core slots; a grading paint is applied to the coils over a short section of each coil on each end of the slot semiconductive paint. The semiconductive paint and grading paint form a part of the winding corona protection system.

The armature end turns, coil jumpers, and ring buses usually are painted with a synthetic enamel.

The armature winding slots formed in the core may be painted with a semiconducting compound, to function as a part of the machine corona protection system. Application of this paint is at the manufacturer's option, and usually is not required by specifications. The paint is applied by brush, in the slot portion only, before the armature winding coils are installed in the slots. Spray application of this paint should be discouraged due to possible problems resulting from overspray accumulations in areas outside of the slot.

Following complete installation of the armature winding in the core, an overall finish paint of buff or light blue colored enamel is applied to all exposed portions of the coils, wedges, core, jumpers, and ring bus. The purpose of this finish paint is to serve as a visual aid in the detection of corona activity, fretting corrosion of laminations, movement, or accumulation of contamination. Care must be taken to prevent accumulations of paint in the slot wedge spring gauging holes. Such accumulations could obstruct accurate determination of underwedge spring compression. If paint should accidentally clog a hole, subsequent attempts to clean the hole would be of questionable value. Therefore, before paint application, masking of the holes is required.

The paint system is selected by the contractor to ensure proper heat conductivity properties, and to ensure compatibility with the corona protection and core plate systems (core plate is discussed later here).

Occasionlly, the interior surfaces of bearing oil reservoirs have been required by specifications to have a coating of white, oil resistant paint. The purpose of this paint is to serve as an inspection aid to determine presence of debris accumulations in the reservoir. Lubricating oils are transparent, but a bare metal surface of the reservoir interior obscure the presence of metallic fragments. A painted white surface helps reveal the presence of such fragments. Interior painting of bearing oil reservoirs has not been consistently required for all Bureau generators. When it has been required, some reservoirs have been painted with Bureau standard paint systems, and other reservoirs have been painted with a contractor's paint system. The possibility of contaminating the lubricating oil exists. Therefore, if a paint coating is required, the choice of paint system should be made by the contractor to avoid problems of divided responsibility.

Temperature sensitive paints may be applied to various parts of the machine such as pole caps, amortisseur winding, pole faces, core, and other places where temperature detecting instrumentation is not practical. These paints change color after reaching certain temperatures, and subsequent examination may reveal hot spots or operating temperatures that cannot be readily determined by other methods.

Laminations used to form an armature core are covered with a paint or varnish that functions to insulate a lamination from those adjacent to it. Insulation is necessary to reduce eddy currents. The laminations are required to have the insulating varnish applied to both sides. The insulating varnish is called "core plate;" usually it is an inorganic phosphate type of material.

For most new stator cores, laminations are punched from sheet material that may already have a protective coating applied. Punching action will produce burrs requiring dressing. The punching action and any subsequent deburring of the sheet material will damage any existing protective coating. Therefore, many manufacturers will apply core plate after punching and deburring.

It may not be practical for a manufacturer to purchase expensive dies for punching a relatively small number of laminations. In this case, the manufacturer may choose either to saw cut the laminations or to laser cut them. Saw cutting may produce more burring and tearing (of the lamination edges) than punching. Laser cutting may produce laminations without burrs. For small low voltage machines, laminations may not require deburring at all.

For these reasons, Bureau specifications have not included deburring or post-punching application of core plate as a requirement. The rationale is that generator performance requirements that limit core temperature rise and core losses will be the controlling factor of the manufacturer's decisions regarding lamination preparation requirements.

Laminations used to form generator field poles may require using an insulating varnish—depending on the manner in which the laminations are made. As noted in section 8.5.3, laminations made from cold rolled magnetic sheet material may require application of core plate. In this case, the manufacturer usually will choose a core plate material similar to that discussed earlier. The application of the core plate to both sides of field pole laminations may not be required.

It is possible to require the manufacturer to apply paint to areas of the machine such as the outer periphery of the core. The purpose of the paint coating would be to reveal future debris or contaminates or to indicate undesired core movement by way of paint cracking. Such painting requirements have not been routinely required as their value has not been documented.

9.3 PAINT FOR OTHER THAN MACHINE FUNCTIONAL PURPOSES

Generally, all ferrous surfaces of all generator parts, other than those in section 9.2, are required to be painted to Bureau standards. The standards require paint materials to be approved by the Bureau, and require that preparation and application comply with specifications. The Bureau standards permit exceptions for certain listed parts and accessories which may be finished with a manufacturers standard paint. Listed exceptions might include enclosures or cases of standard manufacture—commercially available accessories—switches, relay and contactor cases, small motors, instruments, transformers, and various excitation cubicles are examples. Still, the Bureau may apply an aesthetic paint to some items. The finish color paint may be made a requirement of the generator procurement solicitation or it may be applied under a subcontract.

Care must be exercised in contract enforcement of the previous general statements. For example, collector rings may be made of steel, but are not a listed exception item. Any paint applied to surfaces of collector rings is intolerable. The same is true for bearing journals. Similarly, paint applied to the wearing surface of steel brake rings is neither required nor permitted. Paint application to the surface of any heat radiating surface requires special consideration, and likely at the manufacturer's discretion. In general, paint applied to machined surfaces would probably be unacceptable—depending upon the function of the machined component. Therefore, the general statements covering, cleaning, and painting in generator procurement solicitations must be judiciously achieved.

Surface air cooler water boxes are required by specifications to be manufactured from nonferrous metal; exceptions to this requirement occur. Some generator contractors have been permitted to furnish boxes made of steel plate or cast iron—covered with an epoxy paint. The epoxy paint system, proposed by the contractor, for this use requires Bureau approval; approval is given if the contractor's system complys with Bureau standard paint system requirements.

CHAPTER 10

FACTORY ASSEMBLY AND FIELD ERECTION

10.1 GENERAL

The highly complex custom design and construction of a hydrogenerator requires the use of specialized equipment and skilled crafts. Small generators may be completely assembled and tested at a factory, but as physical and electrical sizes of generators become larger, shipping of completely assembled generators becomes increasingly impractical. For shipment, disassembling factory assembled generators is nonetheless practical within a range of sizes for small generators.

For large generators, components are shipped to the jobsite where they are assembled for the first time. Large generators require considerable specialized assembly skills and precision machine work during both factory manufacture and field erection. Successful generator operation is highly dependent upon the completeness and quality of both the factory manufacture and field erection activities. Hence, field erection is considered to be a vital extension of the generator manufacturing process.

A small generator may be factory assembled and mounted on a base for shipment. After receipt at the jobsite, the generator and its base are anchored into position and the required connections made. Separate bases for small generators may be manufactured and shipped before the generators, to allow anchoring and embedment of the base.

Large generators require manufacture, fabrication, and shipment of many components which later must be assembled and erected at the jobsite. More than one factory may be involved in preparing components. The sequence of factory work and field erection must be coordinated by implementing an efficient schedule.

Experience has indicated that the relative costs to the contractor for factory personnel, as compared to field personnel, varies not only from one contractor to another, but from one country to another. Shipping costs are a major part of a contractor's expenses. The cost of shipping large, massive equipment can be disproportionately greater than the cost if the same equipment was dissembled. This is particularly true for ocean transportation.

A contractor's costs for field erection personnel can be noticeably lower than for factory personnel to accomplish the same task. Also, foreign bid differentials may not be applied to the component in the bid for domestic labor, thus providing added incentive for foreign bidders to "unbalance" their bid by maximizing field erection.

Commonly, field erection personnel possess less skill, experience, and familiarity with the manufacturer's product than the factory personnel. Usually, equipment and facilities available at the jobsite are not comparable with those at a factory. Consequently, the quality of finished work performed at the jobsite can be significantly less than that performed in a factory. However, a contractor may achieve significant cost advantage by performing all work possible in the field. The Bureau's concern for installing high quality machinery is compromised when low quality field erection is allowed. Therefore, both factory and field inspection is necessary for quality assurance. A specifications requirement that the contractor accomplish all manufacturing and assembly possible at the factory, and for quality control that components be shipped in assemblies as large as shipping limitations permit. This specifications requirement must be subjective; strict enforcement is inherently difficult.

The reasons that counter maximizing factory assembly is when shipping damage happens or other unforeseen issues cause a large, complex, factory assembled component to be rejected after it's arrival at the jobsite. Damage is more likely to occur to a large assembly than to individual components during shipment. Repair or replacement of a large assembly can be time consuming and expensive. The delay required to return a damaged assembly to a factory, time to accomplish repairs, and to return of the assembly to the jobsite may be unacceptable.

In considering all these factors, the Bureau prefers shipping of the largest factory assembly possible. In lieu of largest assembly, a requirement that field erection of some components, such as stacking of stator cores, may take place when special considerations are apparent.

10.2 FACTORY ASSEMBLY

Hydrogenerator shafts are always factory machined; only a minor amount of finish work is required during field erection. Rotor spider-hub bolt hole reaming is an example of field erection machine work required by manufacturers. A discussion on factory manufacture and alignment of generator shafts is in chapter 8.1.

If separate procurement solicitations are prepared for a generator and its turbine, the Bureau must decide which contractor will align the two shafts. Usually, turbine procurement precedes generator procurement; this results in a turbine contract award, and frequently, turbine manufacture commences even before issuance of generator procurement solicitations. Thence, a decision is made requiring the turbine shaft to be shipped to the generator manufacturer for alignment. The basis for the decision might be that the turbine shaft is finished before the generator shaft. Domestic manufacture of the turbine shaft combined with foreign manufacture of the generator shaft may result in the opposite sequence. Another option is to require shipping of both shafts to an alignment shop in the United States or Canada for alignment.

If procurement of both generator and turbine is included in one solicitation, a Bureau decision for alignment responsibility is not necessary. However, the fewer the number of necessary shipping and handling events, before arrival of the shafts at the jobsite, is usually the best procedure.

Generator bearing runners are always factory machined and aligned with their associated shafts. Antifriction metal used for plain bearing surfaces may be fitted or "scraped" at the factory for small machines. Final "scraping" may be done at the jobsite for large machines requiring field assembly.

Generator rotor spiders and rims may be completely assembled to the shaft in the factory, balanced, and shipped as an assembled component for small generators. Frequently, shipping restrictions prevent factory assembly of the spider and rim to the shaft. Some shafts have been shipped with a spider hub, or even a complete spider attached. Most large generators require complete stacking of the rotor rim at the jobsite (see sec. 8.4).

Field poles must be installed at the jobsite if the rotor rim is field stacked. The individual pole pieces, amortisseur, and field windings are factory assembled.

Stator frames are fabricated at the factory for large generators, temporarily assembled, and necessary machine work performed. The frames may be manufactured in segments of a cylinder to allow disassembly for shipping. The stator core may be stacked in the factory, and a partial armature winding installed in the core segments. Thus, the assembled stator's segments would be relatively complete before shipment, requiring only bolting the segments together and installing and connecting make-up armature coils in the core split joints at the jobsite. Experience has proved that the joints where stator segments are connected can produce problems. Uneven stresses may produce movement of the core at the joints, that ultimately can lead to failures in either the core and coils or both. Therefore, specifications for some large new generators and for stator core replacements in existing machines require core stacking and armature winding installation at the jobsite. Usually, stator frames or frame segments are the largest single generator pieces—as prepared for shipment.

Armature windings are always factory manufactured. Installation of the manufactured coils into the stator core may take place in the factory, in the field, or some coils in the factory and some in the field. Similarly, connection of the coils may be done in the factory, field, or both.

Rotating exciters usually are completely assembled at the factory. Special machinery is used to perform rotational tests of direct connected exciters at the factory because the exciters are without bearings of their own. Following testing, the exciter rotors are removed and shipped separately from the exciter stators.

Static exciters and excitation controllers are completely assembled and most tests are performed at the factory. Complete testing may not be possible without a connected generator field for loading. Often, a static exciter may be manufactured at a factory other than the one for the generator.

Surface air coolers may be purchased from a supplier by generator contractor, or the generator manufacturer may fabricate coolers at the generator factory. Regardless of location, the coolers are completely assembled and tested at the factory. Coolers for large machines are shipped individually packaged—separate from the machine. It would be extraordinary to ship coolers mounted on the generator.

Many small accessories, such as motors, contactors, switches, relays, and pumps are completely manufactured, tested, and shipped separately from the generator.

10.3 FIELD ERECTION

Generator field erection of large generators must occur simultaneously with many other activities during powerplant construction; also, collaborative efforts with others in construction is necessary. Each job has prototype uniqueness. Therefore, an attempt to outline a valid schedule for all types of construction would be futile. Nonetheless, the following generalities may be considered for large generators.

Foundation anchor bolts and sleeves must be embedded in the foundation. Therefore, early manufacture and shipment of these items, and any necessary templates, must be made before foundation concrete can be placed.

Station service electrical power, compressed air, and service water must be available before generator erection begins.

The powerplant crane and necessary handling and storage facilities must be available for use when the first large generator components are received at a jobsite.

Turbine erection must be complete to the stage where the opening above the turbine (below the generator) may be closed to allow the generator contractor exclusive use of the generator foundation, before stator erection may begin. Off-foundation stator erection is a possibility, if powerplant floor space is available and if the crane has capacity to move a complete stator. If so, the generator contractor's exclusive use of the generator foundation may not be necessary until final generator assembly begins.

A rotor erection pit and pedestal or both must be ready to accept a generator shaft to begin rotor erection. Generally, rotor erection and stator erection require nearly equal time; usually the erection of stator and rotor progress simultaneously. A few early plans for generators have envisioned rotor erection in-place in the stator. These plans have in mind a desire to reduce required crane capacity for handling a completely assembled rotor. A completely assembled generator rotor is almost always the heaviest component the powerplant crane must lift. The need to lessen the generator's outage time for its rotor work—during operation and maintenance—has effected a decision to install full capacity cranes which are capable of handling a completely assembled rotor.

A generator rotor must be provided with sufficient clearance to pass by other units in a multiple unit plant, and to place the rotor into the generator's stator. Although an air housing may not be in place, while erecting a generator, subsequent rotor removal and reinstallation during maintenance will probably require clearance over a completely assembled air housing.

Preliminary stator centering and leveling should begin before the rotor is placed into the stator.

The generator lower-bearing bracket must be in place on its foundation before rotor placement into the stator. The rotor weight must be borne by the bracket during final assembly.

Procurement specifications must assign responsibility to a particular contractor, for work required to connect the couplings of the turbine and generator, if separate procurement is made.

A significant amount of final assembly of the generator occurs after rotor placement. Installation of upper-bearing bracket, bearings, final centering and leveling of the stator, coolers, collector rings, air housing, exciter, and all accessories—including connections—must be made.

Major plant equipment such as bus, switchgear, step-up transformers, switchyard equipment, control equipment, station service, turbines, governors, gates and valves, and all other required equipment installations must be complete and operational before commissioning testing begins.

The powerplant's water storage reservoir must develop minimum hydraulic head.

Generator commissioning tests (see ch. 12) must be completed before the power on-line date.

10.4 OVERALL SCHEDULING

Overall scheduling, from the time of contract award for furnishing a generator to power on-line date, will require different periods based upon generator size and on market conditions at the time of contracting. Generally, contract times increase as generator kV•A capacity increases.

Generators requiring special design or are of particularly difficult construction require longer design, manufacture, and installation time. A measure of difficulty used by the industry is if the MV•A/(r/min) (i.e., ratio of megavolt-ampere capacity to rated synchronous speed) exceeds about 10 (see sec. 8.57). Machines having an MV•A/(r/min) of 10 or above are considered to be extremely difficult; they require considerably longer time to complete.

Complexities and confusion that exist during erection of a multiunit plant may extend contract completion times. Inclement weather conditions, particularly for outdoor or semioutdoor plants may require longer erection times. Jobsite remoteness can cause extended erection time. Installation of machines that have been factory assembled and tested will require significantly less time than those requiring field erection.

Regardless of machine configuration, prudence is required by checking with potential suppliers before finalizing a schedule; constraints may result which might otherwise be unrecognized.

A typical schedule following award of contract might be:

30 days after award	Receipt of key drawing and data list (large generators only)
120 days after award	Receipt of key drawings and data (large generators only)
240 days after award	Receipt of all approval drawings and data (small generators may require significantly less time)
At least 30 days before placement of foundation concrete	Receipt of anchor bolts, sleeves, templates, and rotor erection pedestal. Receipt of manufacturer's erection procedures.
6 months before power on-line (beginning of erection activities, more time may be required for extra-large or unusual generators)	Powerplant crane available. Station service electrical power, water, and compressed air available. Generator foundation available for generator contractor's exclusive use. Rotor erection pedestal and area available to generator contractor.
30 days before power on-line	Commissioning test procedure and schedule submitted and approved.
	Connection of generator and turbine couplings completed.
	All instrument calibrations available.
	All protective and control equipment complete and operational.
	All bearing oil reservoirs filled.
	Cooling water available.
	Penstocks, penstock controls, and penstock water available.
	Turbine, governor, and auxiliaries available.
	All electrical power transmission equipment complete and operational.

	All features necessary to begin bearing runs, balancing, and commissioning tests complete and ready.
Power "on-line"	Commissioning tests complete.
90 days before acceptance tests	Proposed test procedure and test schedule submitted by contractor.
30 days after acceptance tests	Test reports submitted.
Before final payment	As built drawings and data, instruction books available at jobsite.

Many other interim dates are important, although not mentioned in the above list. Receipt of safety information, final drawings, and factory test data are examples of items not listed. The overall time period required, from award of contract to power on-line, is not specifically covered due to possible extreme variations. Any one of, or all of, the time periods noted could vary over a fairly wide schedule.

CHAPTER 11

MAINTENANCE ACCESSORIES AND TOOLS

11.1 GENERAL

The term "maintenance accessories" should be interpreted to refer to devices used for handling, erecting, adjusting, or performing *maintenance* work on a generator. Devices which perform some function related to generator *operation* are not addressed in this chapter.

Generator procurement solicitations are written to require the contractor to furnish all lifting attachments and accessories required to attach the generator or its component parts to crane lifting hooks at the powerplant. Also, the contractor is required to furnish all wrenches, tools, and other devices required to assemble or disassemble the generator. Usually, the tools and accessories would be all those the contractor uses during generator erection.

Small generators that are shipped from the factory fully assembled or with only minor disassembly would require few special tools for field erection. Erection might be somewhat more than placement of the machine on its foundation and completing a few connections to the turbine shaft, and to power and control leads. Nonetheless, maintenance activities may require special tools for bearing removal and adjustments that would not necessarily be performed during field erection. Therefore, special attention may be required to ensure that all tools and accessories required for disassembly, maintenance, and reassembly are furnished with small machines.

As noted, tools and accessories used by a contractor during field erection of larger generators are furnished by the generator contractor to the Bureau. Tool and accessory requirements must be customized for each generator. It is not reasonable to list the Bureau's requirements when writing procurement solicitation requirements. That is, the solicitations are written to require the contractor to furnish:

- An itemized list of all tools
- A drawing of lifting attachments and devices
- A drawing of rigging arrangements
- In addition, some solicitations have required a drawing showing tool board arrangements.

The Bureau may require additional tools and accessories if a need is perceived. The tools are required to be new and unused prior to the contractor's use for erection. Some erection equipment used by contractors during field erection have been considered nonessential to Bureau maintenance needs, and have not become Bureau property after erection has been completed. Such equipment has included rotor and stator core lamination stacking machines, some special jacks and jack stands, hydraulic presses, and various instruments and gauges. Accessories used by the contractor during field commissioning and acceptance testing are not usually delivered to the Bureau. Contractors may use special accessories for curing or seasoning various components, and for determining status or condition, that do not become Bureau property.

11.2 TYPICAL ACCESSORY LISTING

As indicated above, tool and accessory lists are prepared by the contractor and submitted to the Bureau for each job. The Bureau will review the list and, if necessary, add items to meet anticipated maintenance needs. An all-encompassing listing is impossible, but some items appear recurrently. Such items include:

- A shaft lifting collar or device
- A rotor lifting beam
- A rotor erection pedestal

- Rotor rim or spider supports for supporting a rotor when on the erection pedestal
- Various wire rope slings and chains
- Various eye bolts, hooks, and backing-out studs
- Various shackles, thimbles, and other wire rope devices
- Various open end and box end wrenches
- Various spanners wrenches
- A set of socket wrenches
- Key driving devices
- Armature wedge driving devices
- A set of rotor balancing weights

11.3 SPECIAL NEEDS

Special tools and accessories necessary to adjust, remove, and replace wearing components such as brakes, bearings, brushes, and seals should be identified and furnished as necessary for each job. Some wearing components, such as contact points, may require only conventional tools for maintenance activities. Conventional tools such as screwdrivers, adjustable wrenches, files, or other readily available tools usually are not included with contractor furnished devices.

Generator shaft to turbine shaft coupling bolts and nuts may be furnished by either the generator contractor or the turbine contractor. Whichever contractor furnishes the nuts and bolts should also furnish tools and accessories required to remove and reinstall the bolts and nuts.

Recent developments in armature winding installation have included under wedge springs as an option. Some wedges in each armature slot have holes that permit insertion of a pin gauge through the wedge to measure actual spring compression. The contractor is required to furnish a gauge for future maintenance use if under-wedge springs are used.

Some contractors have used a push bar for insertion of armature coils into the stator slots. These push bars, and other devices required for their use, are made especially to match the configuration of the coils for a particular machine. The coils can be installed without using push bars, but the push bars significantly improve installation success. In several cases, if the contractor has used them, the Bureau has obtained the push bars for future maintenance work.

Thrust bearings—of the adjustable shoe type—must be adjusted by using a strain gauge to attain equal loading on all shoes. The Bureau has required the contractor to furnish a strain gauge if this type of thrust bearing is furnished.

Special devices may be required to calibrate various systems such as for fire detection; a contractor may be required to furnish necessary devices and instructions for their use.

CHAPTER 12

TESTS AND INSPECTION

12.1 GENERAL

Procurement solicitations are written specifically to state the required tests and reports of test results. The solicitation will state if approval of the test procedure to be performed is required by the Bureau.

Tests are conducted for a variety of reasons:

- Determination of material composition
- Fabrication quality
- Component function
- Conformance to requirements
- Demonstration that warranties have been fulfilled
- Record purposes

In most cases, when a test is identified in a solicitation, the contractor will be required to furnish the following:

- An outline of the test procedure
- Applicable testing standards
- Testing equipment to be used—including ratings
- Expected test results, limits of tests values and, occasionally, expected failure rates
- Calibration certificates of test instruments
- Electrical power and other requirements of the test equipment

NOTE.-Power is especially important for jobsite testing.

- A schedule for test performance
- Sample calculations and formulae for interpretation of test results
- Test results

In most instances, tests must be witnessed by a Government inspector. In some cases, Bureau approval of the limits or results may be required. Contractor certification of test results may be required.

Generator testing is categorized into five general time domains:

1. Factory
2. Field erection
3. Field commissioning
4. Field acceptance
5. Maintenance

Maintenance testing is addressed in other Bureau documents and will not be addressed here.

Turbine acceptance testing is usually delayed until after the generator acceptance tests have been completed. The information available as a result of generator acceptance tests permit the generator to be used as a calibrated load for the turbine tests.

12.2 FACTORY TESTS

Small generators that can be completely assembled and tested in the factory may be subjected to acceptance testing in the factory. Field testing of small machines may be limited to only those tests necessary to demonstrate that damage has not occurred during shipment and installation, and to demonstrate proper installation and operational readiness.

Factory testing of larger machines may be limited to materials and fabricated components. Full functional testing of some assembled components is required, as discussed below. Reports of materials testing may not be required by the Bureau. The Bureau has experienced a trend into requiring an increasing number of submittals of these materials test reports; response within the industry has revealed that some of these are considered proprietary by manufacturers. Such reports may be difficult to obtain.

Reports of tests performed on materials and components or subassemblies performed by the contractor's suppliers may not be required by the Bureau. Test reports of some components, such as instrument transformers, RTDs, and other calibrated devices are required.

Welding qualification tests, and reports of the results thereof, are at the Bureau's option. Another option is applied to nondestructive testing of principal generator parts and reports thereof. Nondestructive testing procedures are required to be submitted to the Bureau for approval.

Among the factory tests—for which reports of results are required—are the following:

1. Dielectric test of each field coil.

2. Dielectric test of each armature coil.

3. Strand insulation test (each strand of each armature coil).

4. Induced dielectric test of multiple turn armature coils (turn insulation test).

5. Power factor tip-up test of each armature coil.

6. Hydrostatic pressure test of each surface air cooler, bearing cooler, and heat exchanger.

7. Excitation system dielectric, component function, and performance tests.

8. Excitation control system dielectric, component function, and performance tests.

9. Resistance temperature detector tests.

10. Various paint tests.

11. Instrument transformer tests.

12. Various detector, instrument, and indicator calibration tests.

13. Tests of bus structures.

14. Test of special equipment, subassemblies, or components that are completely fabricated and become functional—before shipment to the field.

12.3 FIELD ERECTION TESTING

Many tests may be performed by the contractor during generator erection. These tests may be required to assure the contractor of proper assembly or condition. Some tests are made at regular intervals, such as at the end of each day or work shift, to limit the amount of remedial work necessary in event of test failure. Hipot tests of wiring and armature coil dielectric tests would be examples of such tests. Reports of such tests are optional. For example, wiring hipot test reports are not normally required (unless a history of failure to pass develops), and reports of shift armature coil dielectric tests are usually required to be formally submitted to the Bureau.

Equipment and subassembly tests for items such as motors, pumps, valves, lights, heating, switches, relays, contractors, circuit breakers, and piping are performed by the contractor; many of these tests are witnessed by a Bureau inspector. Although, the inspector may file records of the tests and results, formal submittal by the contractor of reports is usually not required. If the inspector becomes aware of frequent or recurrent failure to pass tests, action to discover the reasons underlying the failures may become necessary. Review of designs, construction, installation, test procedure, and test results may need to be formalized to ensure an acceptable installation.

Most generator solicitations are written to require reports of dielectric tests performed on coils installed in armature slots during each shift. It should be noted here that these tests are performed at reduced levels, and do not eliminate the need for the dielectric tests performed on the completed winding at the time of commissioning.

12.4 COMMISSIONING TESTS

After a generator has been completely erected in its final location, a series of operational or commissioning tests are performed to demonstrate that the generator is capable to operate and produce power. The tests are performed on each generator if several generators are included in one procurement solicitation. The contractor should submit a proposed procedure and schedule for these tests, so that the Bureau can arrange for witness inspection and participation. Frequently, these tests involve several different contractors. For example, contractors for supplying turbines, governors, switchgear, transformers, and construction could be involved in addition to the generator supplier. Bureau approval of the procedure and schedule usually is not made a solicitation requirement, but Bureau coordination of the tests is almost mandatory.

Commissioning tests might include, but would not be limited to the following:

- Dielectric tests of armature and field windings
- Resistance measurement of armature and field windings
- Excitation and excitation control system tests
- Bearing run
- Balancing
- Load rejection
- Fire protection system
- Preliminary heat runs
- Brake performance
- Overspeed

The excitation and excitation control system tests above usually are performed as a joint effort between contractor and Bureau personnel. Actually, the contractor is responsible for the whole test; but Bureau personnel perform alignment of the power system stabilizer, if the generating unit is so equipped. The basis for alignment by Bureau personnel is that proper setting must include both hydraulic and electric power transmission system considerations.

The above load rejection tests should not produce generator overspeed up to runaway speed, but some inelastic expansion of the rim may still occur and rebalancing may be necessary. Overspeed tests may be delayed until acceptance testing for some generators, although some engineers hold to the opinion that the best time for overspeed tests is during commissioning.

The fire protection system tests listed may be only a partial test to demonstrate proper assembly and function of the system. Later tests during acceptance testing (sec. 12.5) may be performed to demonstrate adequacy of the fire *detection* system in addition to the fire *protection* system.

12.5 ACCEPTANCE TESTS

Acceptance tests are required to be performed by the contractor to demonstrate that the machine meets the requirements of the procurement solicitation, and that the contractor's warranties have been met. The tests also create a record of generator characteristics which exist when the generator is first installed.

Most generator acceptance testing is delayed for a period of time—perhaps 1 year—after the generator is first placed in service. This period of early operation is used by the contractor to observe generator behavior and performance and to make any necessary adjustments. The operation permits bearings to "break in" or seat. Usually, friction losses will decline and reach a stable value during the break-in period.

The contractor is required to furnish all labor, materials, and equipment required for the tests, except for items specifically identified in the procurement solicitation. Typical of items identified as being furnished by the Government would be:

- Labor for disconnecting and reconnecting turbine and generator shaft couplings
- Use of crane and other plant facilities
- Alternating and direct current station service power
- Compressed air from station system
- Domestic and service water
- Use of turbine, governor, and operating facilities
- Direct current high potential test set
- Alternating current high potential test set
- Use of a second generator at either the powerplant or elsewhere for loss tests
- Station instruments and instrument transformers
- Use of plant control and switching equipment

The contractor is required to submit a test procedure for Bureau approval. The procedure must include all tests identified in the procurement solicitation. Typical tests would be:

- Balanced and residual component telephone influence factor
- Deviation of wave form
- Line charging capacity
- Synchronous condenser capacity
- Determination of efficiency
- Determination of WR^2
- Characteristic curve tests—including open circuit saturation, full load saturation, zero power factor saturation, and synchronous impedance
- Heat runs or temperature rise tests
- Ozone tests
- Transient reactance

- Subtransient reactance
- Time constants
- Negative sequence reactance
- Saliency ratio
- Excitation system and excitation control system tests not performed during commissioning tests or at the factory
- Fire detection and protection system tests not performed during commissioning tests
- Overspeed tests—if not performed during commissioning testing

All tests are required to be performed according to IEEE Std. 115-83 [1], IEEE Std. 421A-1978 [2], and other standards (e.g., American National Standards Institute) where applicable.

The contractor is also required to submit for approval a detailed schedule for performance of the tests. Submittal of this material will allow the Bureau to arrange for outages, equipment, personnel, and notification of power and water system authorities.

Some acceptance tests are performed on each machine installed under a procurement solicitation, and other tests are performed on only one selected machine if several identical machines are involved. Dielectric tests of armature and field, and resistance tests of armature and field are usually performed during commissioning tests (sec. 12.4) and are performed on each machine. Also, complete excitation system and excitation control system tests (sec. 12.5) are required on each machine.

The Bureau of Reclamation has developed standards for generator acceptance testing [3]. At one time, generator contractors were required to test machines in accordance with these standards. Because present practice requires the contractor to test according to national standards, the Bureau standard is given to the contractor to use as a guide. The Bureau standard presents much more detailed information than the national standards; an attempt is made to maintain the Bureau standard to agree with the national standards. Therefore, the Bureau standard can be of considerable value to a contractor during preparation and submittal of their own test procedure.

Bureau practice has been to furnish generator contractors with typical test schedules, as well as the design standard mentioned above. Again, contractors have found these typical schedules to be of considerable value. However, differences in availability of staff and equipment at different times can produce significant changes from the typical test schedules supplied to contractors.

Typical or tentative test schedules furnished to contractors for Glen Canyon and Blue Mesa Powerplants are shown in appendixes.

The field test procedure suggested for acceptance tests at Blue Mesa Powerplant is also shown in the appendix.

12.6 INSPECTION

Procurement solicitations are written to require that the contractor must provide and maintain an inspection system acceptable to the Bureau. The contractor is required to maintain records of inspections and must make the records available to the Bureau upon request.

The Bureau retains the right to inspect and test any or all parts of the generator at any time during manufacture or installation—and at any place. The Bureau maintains a staff of (or has access to) trained inspectors for factory inspection. Bureau field forces are responsible for inspection during generator field erection and testing. Bureau generator designers may participate in inspections both at a contractor's factory and during field erection and testing. The Bureau generator designer may participate in inspections after the generator has been turned over to operation and maintenance.

12.7 BIBLIOGRAPHY

[1] *Guide: Test Procedures for Synchronous Machines*, IEEE Std. 115-83, Institute of Electrical and Electronics Engineers, Inc., New York NY

[2] *Guide for Identification, Testing, and Evaluation of the Dynamic Performance of Excitation Control Systems*, IEEE Std. 421A-1978, Institute of Electrical and Electronics Engineers, Inc., New York NY.

[3] *Design Standards No. 12*, "Field Generator Tests," United States Department of the Interior, Bureau of Reclamation, ch. 2, 25 pp., Denver CO, 1968.

CHAPTER 13

OPERATION AND MAINTENANCE

13.1 GENERAL

The principal document developed during the design phase for use by operation and maintenance (O&M) personnel is the manufacturer's instruction book. The book is required to be furnished by the generator manufacturer. All the "Final Drawings and Data" furnished by the contractor, as discussed under chapter 5.8, are also prepared for use by operation and maintenance personnel.

Bureau of Reclamation hydrogenerator designers also prepare a *Design Summary*, that outlines the concepts used in preparing the generator procurement solicitation. This document may include a section listing "Operating Criteria" that the designer may want to convey to O&M personnel. The *Design Summary* will usually include a section covering "Construction Considerations" that may be of value to O&M personnel.

In theory, a generator designer's involvement in a job is essentially complete when the generator is turned over to operation and maintenance. However, the generator designer's detailed knowledge of machine design, construction, performance requirements, and expected behavior under various circumstances will frequently be relied upon by O&M personnel during the post-turnover period. The designer's knowledge has been called upon during diagnosis and forensics of a failure, and to facilitate generator repair and return it to service. Failure investigation is apropos to manufacturers' warranties.

A generator designer's knowledge has proved to be especially valuable during generator armature rewind and generator uprate improvements. These two undertakings usually require a generator designer to become involved for procurement solicitations preparation.

In summary, generator designers become involved at the inception of a hydroelectric project and remain involved throughout the project's life.

SPECIFICATIONS AND STANDARDS ASSOCIATIONS AND INSTITUTES

Various specifications and standards referred herein or may be applicable to equipment discussed here, but not specifically referred to in the manual, may be obtained from the following sources.

Bureau of Reclamation Specifications—Bureau of Reclamation, Attention: D-3520, PO Box 25007, Denver CO 80225-0007.

Military Specifications and Standards—Naval Publications and Forms Center, 5801 Tabor Ave, Philadelphia PA 19120.

Maritime Administration Specifications, Dept of Transporation, Division of Naval Architecture, Rm 2126, MAR-724, 400 Seventh St SW, Washington DC 20590, 2020-366-5836.

AASHTO—American Association of State Highways and Transportation Officials, 444 North Capital St NW, Suite 225, Washington DC 20001, 202-624-5800, Fax: 202-624-5806.

ACI—American Concrete Institute, 22400 W Seven-Mile Rd, Detroit MI 48219, 313-532-2600, Fax: 313-538-0655.

AISC—American Institute of Steel Construction, One E Wacker Dr, Suite 3100, Chicago IL 60611-2001, 312-670-2400, Fax: 313-670-5403.

AISI—American Iron and Steel Institute, 1133 15th St NW, Washington DC 20005-2710, 202-452-7100, Fax: 202-463-6573.

ANSI—American National Standards Institute, 11 W 42d St, New York NY 10036-8002, 212-642-4900, Fax: 212-302-1286.

ASME—American Society of Mechanical Engineers, 345 E 47th St, New York NY 10017-2385, 212-705-7722, Fax: 212-705-7674.

ASTM—American Society for Testing and Materials, 1916 Race St, Philadelphia PA 19103-1108, 215-299-5400, Fax: 215-977-9679.

AWS—American Welding Society, 550 N LeJeune Rd, Miami FL 33126-5699, 305-443-9359, Fax: 305-443-7559.

AWWA—American Water Works Assn, 6666 W Quincy Ave, Denver CO 80235-3098, 303-794-7711, Fax: 303-794-7310.

GA—Gypsum Assn, 810 First St NE, Suite, Washington DC 20002-4268, 202-289-5440, Fax: 202-289-3707.

GSA—The GSA Index of Federal Specifications, Standards, and Commercial Item Descriptions may be purchased from the Superintendent of Documents, U.S. Government Printing Office, Washington DC 20407, 202-708-7140, Fax: 202-863-2834.

IEEE—Institute of Electrical and Electronics Engineers, Inc., 345 E 47th St, New York NY 10017-2366, 212-705-7900, Fax: 212-752-4929, or 445 Hoes Lane, Piscataway NJ 08855-1331, 908-562-3800, Fax: 908-981-9667.

ICEA—Insulated Cable Engineers Assn, Inc., PO Box 440, South Yarmouth MA 02664, 508-394-4424.

JIC—Joint Industrial Council (Standards), 7901 Westpark Dr, McLean VA 22102-4269, 703-893-2900.

MBMA—Metal Building Manufacturer's Assn, 1230 Keith Bldg, Cleveland OH 44115, 216-241-7333.

NACE—National Assn of Corrosion Engineers, 1440 S Creek Dr, Houston TX 77084-4999, 713-492-0535, Fax: 713-492-8254.

NEC—National Fire Protection Assn, National Electrical Code, Batterymarch Pk, PO Box 9101, Quincy MA 02269-9101, 617-770-3000, Fax: 617-770-0700.

National Electrical Manufacturers Assn, 2101 L St NW, Suite 300, Washington DC 20037-1580, 202-457-8400, Fax: 202-457-8468

NEMA—National Electrical Manufacturer's Representatives Assn, 200 Business Park Dr, Suite 301, Armonk NY 10504, 914-273-6780, Fax: 914-273-6785.

SAE—Society of Automotive Engineers, 400 Commonwealth Dr, Warrendale PA 15096-0001, 412-776-4841, Fax: 412-776-5760.

UL—Underwriters' Laboratories, 333 Pfingsten Rd, Northbrook IL 60062-2096, 708-272-8800, Fax: 708-272-8129.

IHS/VSI — Information Handling Service/ Visual Search Microfilm File®, 15 Iverness Way East, PO Box 1154, Englewood CO 80150, 303-790-0600, 1-800-5252-7052, Fax: 1-800-447-3352.

*WPRS—Water and Power Resources Service, order from:

Bureau of Reclamation, Attention: D-922, PO Box 25007, Denver CO 80225-0007.

The request should identify the solicitation number and the specification requested by date, title, and number, as cited in the solicitation.

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* This reference is for various manuals and standard specifications printed, reprinted, or published while the Bureau of Reclamation was officially named Water and Power Resources Service. All references to Water and Power Resources Service or any derivative thereof, herein, shall be considered synonymous with the Bureau of Reclamation.

APPENDIX A

GLEN CANYON POWERPLANT

Generator Acceptance Tests
Tentative Test Schedule
October 1967

The words "Test Generator" refer to the generator receiving the complete tests. The words "Second Generator" refer to the associated paralleled unit.

Figure numbers refer to the drawings in the test procedure.

Estimated outage times apply only to the equipment which will operate with the test unit when the test requires it.

Estimated outage times represent the time required for testing, and are exclusive of time required for clearances and switching.

SCHEDULE FOR TEST GENERATOR

First Day

1. Discuss test schedule and procedure.
2. Unpack and set up test equipment.
3. Install test instrument transformers.
4. Clean rotor, if desired by the contractor.

Second Day

5. Test j.(1). — Open Circuit Saturation.
6. Install short circuit for synchronous impedance test.
7. Test j.(2). — Synchronous Impedance.
8. Remove short circuit connections. Open generator neutral grounding circuit.
9. Test b. — Corona test.
10. Restore generator connections to normal.

Third Day

11. Transfer station service to alternate source.

12. Install instrumentation for heat run test.

13. Test j.(3). — Full load saturation, zero power factor lagging.

14. Test g. — Line charging capacity.

NOTE.-Items 13 and 14 will require use of two additional units operating at no load and separated from the system. Total outage time estimated as 5 hours.

15. Restore all generators to normal service, and load test unit to approximately rated kV•A.

Fourth Day

16. Test k. — Heat runs.

Fifth Day

17. Uncouple turbine and generator. Install temporary connections, instrument transformers, and instrumentation for efficiency and WR^2 test.

Sixth Day

18. Test h. — Efficiency.

19. Test i. — Determination of WR^2.

NOTE.-Items 18 and 19 will require use of second generator and the 320-kW motor generator set for approximately 16 hours.

20. Restore second generator to normal service.

Seventh Day

21. Recouple turbine and generator. Remove efficiency instrumentation and temporary connections. Connect instrumentation for tests requiring oscillograph.

Eighth and Ninth Days

22. Test o. — Voltage regulator tests.

23. Test n. — Excitation system voltage response ratio.

24. Test e. — Deviation factor of wave form.

NOTE.-Item 22 will require use of two additional units for approximately 12 hours' time.

25. Restore two additional units to normal service.

Tenth Day

26. Open generator bus and install short-circuit connections for short-circuit test and determination of synchronous machine quantities.

27. Test m. — Synchronous machine quantities.

28. Test l. — Short-circuit test.

NOTE.-Items 27 and 28 will require that the second generator be out of service for approximately 12 hours for safety reasons.

29. Remove short-circuit connections.

Eleventh Day

30. Test d. — Telephone influence factor.

31. Test p. — Measurement of main exciter field rheostat travel time.

32. Test f. — Overspeed test.

Twelfth Day

33. Test q. — CO_2 test.

TESTS ON OTHER GENERATORS

Thirteenth Day

34. Test j.(1). — Open Circuit Saturation.

35. Test b. — Corona test.

36. Test o.(2). — Voltage regulator performance under load rejection.

Fourteenth through Nineteenth Days

Repeat items 34, 35, and 36 for all other generators.

APPENDIX B
BLUE MESA POWERPLANT

Generator Acceptance Tests
Tentative Test Schedule
July 1968

SCHEDULE FOR TEST GENERATOR UNIT 1

First Day

1. Discuss test schedule and procedure
2. Unpack and set up test equipment
3. Allow unit to cool for 18 hours without running

Second Day

4. Test c. — Stator and rotor resistances
5. Test b. — Corona test

Third Day

6. Test j.(1). — Open circuit saturation
7. Test j.(2) — Synchronous Impedance

Fourth Day

8. Test d. — Telephone influence factor
9. Test g. — Line-charging capacity

Fifth Day

10. Test k. — Heat runs at 100 percent load and 115 percent load.

Sixth Day

11. Uncouple turbine

Seventh Day

12. Test h. — Efficiency test

Eighth Day

13. Test i. — Determination of WR^2
14. Test j.(3) — Full load saturation, zero power factor lagging

Ninth Day

15. Couple turbine

Tenth Day

16. Test e. — Deviation factor of wave form
17. Tests m.(1), (2), and (4). — Transient reactance and short-circuit time-constant tests
18. Test m.(5)(b). — Rated voltage value of negative sequence reactance

Eleventh Day

19. Test l. — Short-circuit test
20. Test m.(3). — Open-circuit time constant
21. Test m.(5)(a) — Rated current value of negative sequence reactance

Twelfth Day

22. Test n. — Excitation system voltage response ratio
23. Test o. — Voltage regulator tests

Thirteenth Day

24. Test o. — Voltage regulator tests (continued)
25. Test o.(2) — Load rejection tests on Unit 2

Fourteenth Day

26. Test p. — Measurement of main exciter field rheostat travel time
27. Test f. — Overspeed test

Fifteenth Day

28. Test q. — CO_2 test

SCHEDULE FOR GENERATOR UNIT 2

Sixteenth Day

29. Test c. — Stator and rotor resistances
30. Test b. — Corona test

Seventeenth Day

31. Test j.(1) — Open-circuit saturation
32. Test o.(6) and (7) — Voltage regulator tests of overexcitation and underexcitation limiters

APPENDIX C

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLORADO RIVER STORAGE PROJECT
GUNNISON DIVISION
BLUE MESA POWERPLANT

Field Test Procedure for Generator

The following procedure covers the field tests to be made on the 33,333-kva, 3-phase, 11,500-volt, 90 percent power factor, 60-cycle, 200-rpm alternating-current generators furnished under specifications DS-6097 for the powerplant. The tests listed below shall be made on each machine:

a. Dielectric tests

b. Corona test

c. Resistances of armature and field windings

j. (1) Open-circuit saturation

o. (2) Voltage regulator performance under load rejection

(6) Test of overexcitation limiter

(7) Test of underexcitation limiter

The remaining tests shall be made on one machine only.

Field Test Procedure for Generator

The contractor shall make the following tests on the generator:

a. Dielectric tests

b. Corona test

c. Resistance of armature and field windings

d. Telephone-influence-factor determination

e. Deviation factor of wave form determination

f. Overspeed test

g. Line-charging capacity test

h. Efficiency test

i. Determination of WR^2

j. Tests to determine the following machine characteristics and curves:

(1) Open-circuit saturation (no load)

(2) Direct-axis synchronous impedance (short-circuit saturation)

(3) Full-load saturation, zero power factor lagging (rated current, zero percent power factor lagging saturation)

k. Heat runs

l. Short-circuit test

m. Tests to determine following synchronous machine quantities:

(1) Direct-axis rated-current transient reactance and direct-axis rated-voltage transient reactance

(2) Direct-axis rated-current subtransient reactance and direct-axis rated-voltage subtransient reactance.

(3) Direct-axis, transient open-circuit time constant

(4) Direct-axis, rated-current and rated-voltage, transient short-circuit time constant

(5) Rated current and rated voltage values of negative sequence reactance

(6) Determination of the ratio of the rated voltage value of quadrature axis subtransient reactance to the rated voltage value of direct axis subtransient reactance

n. Excitation system voltage response ratio

o. Voltage regulator and excitation system tests:

(1) Voltage regulator performance under steady load conditions

(2) Load rejection

(3) Voltage regulator performance under overspeed conditions

(4) Range of regulator control

(5) Operation with negative field current

(6) Test of overexcitation limiter

(7) Underexcitation limiter

(8) Interruption of power supply

p. Measurement of main exciter field rheostat travel time

q. CO_2 test

The above tests shall be made in accordance with the latest standards of the American Institute of Electrical Engineers where applicable, (IEEE No. 115, March 1965). The test procedures outlined below are intended to show a method of conducting these tests. Other methods under the above standards may be used for the tests to be performed by the contractor when satisfactory to both the manufacturer and contracting officer. The contractor may furnish and use any instruments and instrument transformers suitable for his tests.

The contractor shall furnish all instruments, equipment, materials, labor, and tools for conducting his tests, except as provided in paragraph B-9 of the specifications. The contractor may use any suitable miscellaneous Government-owned construction equipment available at the Project provided he assumes full liability for its use.

Attention is directed to Subparagraph B-9bb. of the invitation, which excludes the use of Government-furnished instruments and instrument transformers for conducting the short circuit and deceleration tests. The contractor shall provide calibrated current and potential transformers for these tests and calibrated low-ratio current transformers for the WR^2 test. The use of the permanently installed current and potential transformers for all other tests will be permitted provided the contractor assumes full responsibility for their accuracy and liability for their use. The calibration of all instruments used for the tests shall be determined by standardization tests made both before and after the generator tests.

At the option of the contractor, the neutral connection of the potential transformers may be directly connected to the generator neutral ground connection.

a. Dielectric Tests

(1) Alternating-current dielectric test of armature and field windings

It is probable that dielectric tests will have been made before operation of the units. If so, these tests need not be repeated. If not, the armature and field windings shall be given dielectric tests in accordance with the provisions of the specifications.

b. Corona Test

The corona starting and extinction voltages shall be determined by observation in the dark and by observation of the pattern on a cathode ray oscilloscope suitably coupled to a detecting circuit, together with calibrating equipment for determining the corona pulse sensitivity. The voltage applied to the stator windings of the unit under test shall be increased in suitable steps from 0 to 125 percent of normal operating voltage. The corona starting and extinction voltages, if occurring within this range, shall be recorded from oscilloscope observations and by observers stationed in the generator rotor. The magnitude of ionization as indicated by pulse height on the oscilloscope pattern shall also be recorded. Any presence of ozone shall be noted.

Suggested connections for the corona detection apparatus are shown on figure 1, which are based on Figure 3 of "Tentative Method for Corona Measurement" ASTM D-1868-61T. The generator bus, surge protective equipment, and potential transformers must be disconnected from the generator terminals during the test. The detection apparatus shall have a response which will clearly display a pulse having a rise time from zero to crest of 1.0 microseconds.

A diagram of the circuit adopted for the tests, including the values of circuit components and overall sensitivity, shall be included with the test report. The apparent corona intensity versus applied voltage (as defined in Paragraph 7.03(1) of AIEE No. 62) shall also be included. The apparent corona intensity is calculated as follows:

$q = KH$, in micromicrocoulombs (picocoulombs)

where

K = Calibration factor, and
H = Corona pulse height in inches or divisions.

The calibration factor K is the apparent charge per unit indicator reading (inches or divisions) and is calculated as follows:

$K = \frac{C V_0}{H_0}$ in micro-microcoulombs (picocoulombs) per division

where:

C = Capacitance of calibrating capacitor, in picocoulombs

V_0 = Square wave or pulse voltage (total rise peak-to-peak), and

H_0 = Indicator reading in inches or divisions

c. Resistance of armature and field windings.-The resistance measurements shall be made by direct comparison with a suitable double bridge at a temperature approximately equal to room temperature. The requirement for temperature approximately equal to room temperature will be waived if the machine is allowed to stand idle for at least 18 hours, thereby allowing the temperature to become uniform throughout the windings. Accurate readings of the temperature of the windings at the time of test must be recorded. The temperature of the field coils shall be determined by not less than six thermometers attached to the windings, and the temperature of the armature by measuring the resistance of all embedded temperature detectors.

In lieu of the double bridge, the resistance measurement may be made by the ammeter-voltmeter method, using not more than 50 percent of rate coil current. Suggested connections and instruments for the ammeter-voltmeter are shown on Figure 2.

d. Telephone influence factor determination.-The balanced telephone-influence factor and the residual-component telephone-influence factor shall be measured using a telephone influence factor (TIF) meter. The procedure shall be in accordance with paragraph 2.35 of the Standards. The meter shall incorporate an impedance network having the characteristic of the 1935 weighting factors.

e. Deviation Factor of Wave Form Determination

This test shall be made with an oscillograph and shall be made with the unit operating at no-load, rated voltage, and rated speed. The voltage waves between each pair of line terminals and from one phase to neutral shall be obtained at the terminals of the unit. If practical, this test should be made in conjunction with the open circuit saturation test.

The deviation factor of the wave is the ratio of the maximum difference between corresponding ordinates of the wave and of the equivalent sine wave to the maximum ordinate of the equivalent sine wave when the waves are superimposed in such a way as to make this maximum difference as small as possible. Suggested connections and instruments are shown on Figure 4. The neutral grounding equipment may be disconnected for this test at the option of the contractor.

f. Overspeed Test

To demonstrate the ability of the generator to successfully withstand the mechanical stresses incident to the maximum runaway speed (not to exceed 400 rpm) which can be attained by the combined unit at the hydrostatic head available at the time that the other generator tests are made, the unit under test shall be operated at no-load, unexcited with the turbine gates wide open. Brushes may be lifted at the option of the contractor.

Starting with the generator operating at approximately rated speed, the turbine gates shall be gradually opened to the wide open position. As soon as the speed becomes constant (or 400 rpm is reached), as determined by the Government's representative, the gates should be immediately closed. The speed shall be measured by a tachometer. Preliminary runs at lower speeds may be made if mutually agreed upon by the generator contractor and the Government's representative.

The following data shall be recorded:

(1) RPM by test tachometer.

(2) RPM by governor and control board tachometers.

(3) Reservoir and tailwater elevations.

(4) Bearing temperatures at start and finish of test.

g. Line Charging Capacity Test

The unit under test shall be driven by its turbine at no-load, rated speed, zero excitation, and rated voltage with the excitation under manual control. Generator kV•A shall be recorded. A portion of the reactive kV•A required may be obtained by overexciting another generator when operating in parallel with the unit under test. The additional reactive kva required may be obtained from unloaded transmission lines or from another synchronous generator.

Alternate.-If sufficient reactive kV•A cannot be made available from other units and lines to obtain the zero excitation condition on the unit under test, the test shall proceed as follows:

> With maximum obtainable reactive kva and other conditions as above, read generator kV•A, field current, and field voltage. Reduce reactive kva to one-half and repeat readings. From this information the line charging capacity may be predicted.

Suggested connections and instruments are shown on Figure 5.

h. Efficiency Test

The efficiency of the unit shall be computed from the expression:

$$\text{Percent efficiency} = 100 - \frac{\text{losses} \times 100}{\text{output} + \text{losses}}$$

The various losses are as follows:

- Friction and windage loss
- Core loss
- Stray-load loss
- Field I^2R loss at 75 °C
- Armature I^2R loss at 75 °C
- Main exciter losses, including rheostat losses

The friction and windage loss, core loss, and stray-load loss shall be measured by the retardation method. The friction and windage loss and core loss shall also be measured by input. The field I^2R loss at 75 °C shall be computed from the results of the field resistance test using a field current for each load as computed from the test saturation curves. Armature I^2R at 75 °C shall be computed from results of the armature resistance test. Suggested connections and instruments for the efficiency test are shown on Figure 6. The unit under test shall be uncoupled from the turbine when making the four following tests:

(1) Friction and windage loss by retardation.-The main exciter field of the unit under test shall be connected to the station battery through a test rheostat. Excitation of the unit under test shall be controlled by means of the test rheostat. Excitation of the driving unit shall be provided by the direct connected main exciter. The voltage regulator control switch for the driving unit shall be placed in the "Manual" position and excitation control provided by means of the main exciter field rheostat. The oil pressure lifts shall be on. With both generator circuit breakers closed, and the test unit's generator field disconnect switch closed, and its exciter field circuit breaker open, bring the driving unit up to approximately one-half normal speed by means of its turbine. Adjust the driving unit field excitation to produce approximately rated generator stator current. The test unit acting as an induction motor will then start and gradually accelerate. Close the test unit exciter field circuit breaker. When the test unit speed approaches that of the driving unit, adjust the test unit rheostat to obtain sufficient field current for the units to pull into synchronism. The speed of the driving unit shall then be increased to rated speed by means of its turbine. The generator field voltage of both units shall be adjusted to provide a field current approximately equal to that required for rated no-load voltage at rated speed.

The speed of both units shall then be increased to approximately 20 percent above normal. The test unit generator circuit breaker shall be opened, disconnecting the driving unit from the test unit, the motor-operated rheostat or test rheostat shall be adjusted to the resistance all in position, the exciter field breaker opened, the generator field switch opened after the field current has decayed to residual value, and the time-speed recorder or chronograph placed in service. The speed and the time or rate of deceleration shall be recorded until the speed of the unit is not more than 80 percent of normal. The friction and windage losses of the test unit an any speed can be obtained by substituting these values in the expression:

$$\mathrm{kW} = \frac{WR^2 \times N \times A}{1.082 \times 10^6\,(T_2 - T_1)}$$

or

$$\mathrm{kW} = \frac{77}{10^{10}} \times WR^2 \times N \times \frac{dN}{dt}$$

where:

- kW = loss in kilowatts
- WR^2 = flywheel effect of rotating parts in pound-foot^2 (by input)
- N = speed in rpm at which loss is to be determined
- A = any convenient number of rpm
- T_1 = time in seconds when speed is N+A
- T_2 = time in seconds when speed is N-A
- $\frac{dN}{dt}$ = rate of deceleration in rpm per minute

If desired the friction and windage losses of the exciter may be taken from the factory test data and subtracted from the total losses above to give the friction and windage losses of the generator only.

(2) Friction and windage and core loss by retardation.-This test shall be conducted in a manner similar to Test (1) above. The test and the driving units shall be brought to approximately 120 percent rated speed as in Test (1). The field current of the test unit shall be adjusted to give rated voltage at rated speed. The value of field current shall be taken from the curve drawn for the Open-circuit Saturation Test. The time-speed recorder or chronograph shall be placed in service. The test unit generator circuit breaker shall be opened, disconnecting the driving unit from the test unit, and readings of field current, field voltage, and armature voltage shall be taken at rated speed point only. During retardation the test rheostat or the motor-operated rheostat shall be adjusted in order to maintain constant generator field current. The test shall be repeated for various values of field current, to obtain sufficient points for plotting a core loss curve. Calculations shall be made by the loss equation stated in Test (1) above, which will give the combined friction and windage, core, and field I^2R losses of the unit under test. By subtracting the friction and windage, field I^2R losses, and exciter losses of the unit under test from the above losses, the core losses only of the unit under test can be obtained. The losses of the exciter to be subtracted from the total losses may be taken from the factory test data.

(3) Friction and windage and load loss by retardation.-This test shall be conducted in a manner similar to Test (2) above, except that after the temperature of the test unit is constant, the test shall proceed as follows:

Open the test and driving unit generator circuit breakers. Open the field of the unit under test following the procedure outlined in Test (1) above. Close the disconnect switch thus short circuiting the armature. Reclose the field of the unit under test, with all resistance in. Place the timespeed recorder or chronograph in service. Adjust the field current of the test unit to give rated armature current at rated speed. This value of field current shall be obtained from the curve drawn for the Direct-axis Synchronous Impedance Test. Readings of field current, field voltage, and armature current shall be taken at rated speed point only. At least four of the armature resistance temperature detectors shall be read following each retardation run. The test shall be repeated for various values of field current to obtain sufficient points for plotting a load-loss curve. Calculations shall be made by the loss equation stated in Test (1) above, which will give the combined friction and windage, field I^2R, and load losses of the unit under test, plus the external losses in the buses. Losses in the buses shall be obtained by measuring the resistance of the bus and short-circuiting cable, or by calculation. By subtracting the external losses in the buses, the exciter losses, and the field I^2R losses from the total losses in the test unit, the combined friction and windage and load losses of the unit under test can be obtained. By subtracting the friction and windage losses of the unit under test from the above losses, the load loss only of the unit under test can be obtained. The stray-load losses are found by subtracting the armature I^2R loss at a particular load from its corresponding value of load losses obtained above. A value of "R" at the temperature of the test, as determined by temperature detectors, must be used. The losses of the exciter to be subtracted from the total losses may be taken from the factory test data.

(4) Friction and windage and core loss by input.-The purpose of this test is to make a check on the friction and windage, core loss, and the accuracy of the calculated value of WR^2. The value of WR^2 shall be determined from the losses as determined by this test, and the rate of decelerations determined by test. This test value of WR^2 shall be used in computing the losses for efficiency.

The driving unit and the unit under test shall be brought to rated speed as in Test (1) above. The field current on the unit under test shall then be adjusted to give rated armature voltage, and the field current on the driving unit adjusted to give a minimum armature current. Three current transformers of sufficiently low ratio and acceptable accuracy for the loads to be measured shall be used for this test. During the starting and adjustment periods these current transformer primaries shall be short circuited if necessary to prevent overheating. In any event, the current transformer secondaries shall be short circuited during the starting and adjustment periods. Readings of armature voltage, armature current, field current, field voltage, watts input, and speed shall be recorded. Three-minute readings on rotating standards (or five complete readings on indicating wattmeters) shall be taken at each voltage step in order to obtain a good average reading. The tests shall be repeated for armature voltage settings ranging from 10 percent above rated voltage to the lowest value obtainable for stable readings. The friction and windage losses of the unit under test, plus the core loss of the test unit at various voltages, can be obtained by subtracting the calculated armature copper loss and field I^2R loss from the kilowatts input. With the remaining kilowatts loss as abscissae and armature volts squared as ordinate, a curve shall be plotted from the test data. Extrapolating this curve to zero voltage will give the combined friction and windage losses of the unit under test. By subtracting the armature copper loss, field I^2R loss, and friction and windage losses from the kilowatts input, the core loss of the test unit at various voltages can be plotted. Indicating wattmeters may be used on this test; however, if the readings are not stable enough to be accurate, rotating standards shall be used for reading the input.

(5) Sequence of tests.-A suggested sequence for performing the above tests is as follows:

(a) Run unit as synchronous motor for approximately 3 hours, to stabilize oil temperature, winding temperatures, and bearing friction.

(b) Perform h.(4)-Friction and windage and core loss by input.

(c) Perform h.(1)-Friction and windage loss by retardation.

(d) Perform h.(2)-Friction and windage and core loss by retardation.

(e) Repeat h.(1).

(f) Perform h.(3)-Friction and windage and load loss by retardation.

(g) Repeat h.(1).

i. Determination of WR^2.-The determination by test of the WR^2 of the rotating parts is described under the efficiency test.

j. Machine Characteristics and Curves.-

(1) Open-circuit Saturation Test.-The unit under test shall be driven by its turbine at no-load rated speed, and with the armature leads open circuited. Readings of field current, field voltage (for checking purposes only), armature voltage and speed shall be recorded for various values of field current increased in successive steps, until a value of armature voltage at least 15 percent above rating is reached. Readings should be taken approximately as follows: Four points below 60 percent normal voltage, 2 points between 60 and 90 percent, 4 points between 90 and 110 percent, including 1 point at approximately normal, and 3 points between 110 percent voltage and full field excitation. Points must be taken on the ascending part of the curve. Since voltage varies with speed, voltage corrections may be made should the frequency vary during the test. A curve shall be plotted using field current as abscissae and armature voltage as ordinate. Oscillograms for the deviation factor test may be taken at the same time as this test. Suggested connections and instruments are shown on Figure 4.

(2) Direct-axis Synchronous Impedance Test (short-circuit saturation).-The unit under test shall be driven by its turbine at rated speed, and with armature leads short circuited. Readings of field current, field voltage (for checking purposes only), armature current in each phase, and speed shall be recorded for various values of decreasing field current. Readings should be recorded for armature currents of 125, 100, 75, 50, and 25 percent of rated current. Small variations in speed will have very little effect on the armature current. A curve shall be plotted using field current as abscissae and armature current as ordinate. Suggested connections and instruments are shown on Figure 7.

(3) Full-load saturation, zero power factor lagging test.-The test unit and another unit shall be brought up to rated speed by means of their own turbines. Each generator shall be excited by means of its direct-connected exciter. The two units shall be synchronized and connected in parallel. The turbine connected to the test unit shall furnish only enough power to supply all of the losses in the test unit. The field current on the test unit shall be increased and simultaneously the field current on the other unit shall be decreased sufficiently to obtain rated voltage and rated current on the armature of the test unit. This is the setting for rated current zero-power factor. Readings of armature voltage, armature current, field current, field voltage (for checking purposes only) and speed shall be recorded. Reducing the voltage in suitable steps, making field adjustments as required to maintain rated current, complete sets of readings shall be recorded at each step. Plotting field amperes against armature volts will give the desired saturation curve. Additional synchronous apparatus may be used if necessary to obtain the desired points for the saturation curve. Suggested connections and instruments are shown on Figure 5. Excitation on both generators shall be placed on manual control.

As an alternate to the test procedure outlined above, the following method may be used:

A driving unit (or units) and the unit under test shall be brought to rated speed with the test unit uncoupled from its turbine and operating as a motor. The field current on the test unit shall be increased and simultaneously the field current on the driving unit shall be decreased sufficiently to obtain rated voltage and rated current on the armature of the test unit. This is the setting for rated current at zero-power factor. Readings of armature voltage, armature current, field current, field voltage (for checking purposes only) and speed shall be recorded. Reducing the voltage in suitable steps, making field adjustments as required to maintain rated current, complete sets of readings shall be recorded at each step. Plotting field amperes against armature volts will give the desired saturation curve.

k. Heat Runs

The unit under test shall be driven by its turbine, at rated speed and rated voltage with all coolers in service and with rated current at rated power factor feeding into the system load. The unit shall be run for at least 2 hours after constant temperatures as shown by detectors are reached. The following temperatures shall be read every half hour until constant temperature is reached, and every half hour for at least 2 hours after constant temperature is reached.

(1) The temperature of the stator windings shall be read in 12 places by means of resistance temperature detectors.

(2) The temperature of the stator core shall be read in at least six places by means of resistance temperature detectors, thermocouples, or thermometers.

(3) The temperature of the upper guide, lower guide, and thrust bearing metal shall be read by means of detectors. The temperature of the lower guide and thrust bearing

oil shall be read by means of thermometers. (Station thermometers may be used for this purpose.)

(4) The temperature of the ingoing water to the surface coolers and to the bearings, and the temperatures of the discharge water from the surface coolers, thrust bearing, and lower guide bearing shall be read by means of thermometers. (Station thermometers may be used for this purpose.)

(5) The temperature of the air entering each cooler shall be read by means of thermometers, thermocouples or resistance temperature detectors. The devices shall be located so as to detect local variations in air temperatures.

(6) The temperature of the air leaving each cooler shall be read by means of thermometers, thermocouples, or resistance temperature detectors. Sufficient devices shall be placed in the cooled air discharge not more than 6 inches from the surface coolers to obtain accurate average temperature information. The following procedure shall be used for locating the thermometers in the cooler air discharge in order to obtain accurate average temperature:

> Not less than 20 temperature devices shall be installed in the path of the discharge air from one cooler. The devices shall be installed not more than 6 inches from the face of the cooler, and shall be spaced at approximately equal intervals. With the generator operating under approximately rated load and with the cooling water supply adjusted as it will be used during the heat run test, temperature readings of all thermometers on this one cooler shall be observed and recorded and the readings shall be averaged. The average temperature so determined shall then be used to locate at least four thermometers in the air discharge from each cooler in positions which will represent average temperature. The average of all thermometers (at least four per cooler) will then represent the ambient air temperature for the generator during the period of constant temperature. The average reading of all thermometers (at least four per cooler) during the period of constant temperature will be used as the ambient temperature upon which to base the temperature rise of the various machine parts.

The value of the reference ambient temperature to be used for the test is the mean of the ambient temperature values for the last three half-hourly readings.

If an automatic cooling water control system has been provided, it shall be taken out of service. The rate of flow of water through the air coolers shall adjusted to normal full flow.

The temperature rise corresponding to the readings of the temperature measuring devices is obtained by subtracting the above-reference ambient temperature from the average of the last three half-hourly readings of the device.

The temperature of the field shall be calculated from simultaneous readings of field current and field voltage (taken across the collector rings). The readings of temperature detectors shall be taken by standard temperature indicators.

The above heat run at rated output shall be repeated with one cooler removed from service by blocking waterflow, but permitting airflow through the one cooler.

l. Short-circuit Test

The unit under test, while operating at no-load, rated speed, and 110 percent rated voltage, shall be abruptly short circuited by means of a circuit breaker, through a temporary 3-phase short-circuit connection. The voltage regulator should be out of service and the rheostat setting should remain unchanged throughout the test. Readings of armature volts, field amperes, and field voltage before the short circuit shall be recorded. If the first short circuit at 110 percent voltage does not produce a practically completely offset current wave on 1-phase, additional short circuits shall be placed on the test unit until such is obtained. Suggested connections and instruments are shown on Figure 8. This test should be performed after the short-circuit tests under Subparagraph m.(1) below.

m. Synchronous Machine Quantities

(1) Direct-axis, rated-current, and rated voltage transient reactance test.–The direct-axis, rated-current, and rated-voltage transient reactance shall be determined with the aid of an oscillograph from sudden 3-phase short-circuit tests performed on the unit when operating at no-load, rated speed, and voltages corresponding to the following values:

(a) Approximately 10 percent below, equal to, and 10 percent above the calculated rated current value of direct-axis transient reactance.

(b) 100 percent rated voltage, unless it corresponds to the highest test taken in (a) above.

These results shall be used to construct a curve of reactance plotted against voltage or reactance plotted against stator amperes for determining the rated current value. The voltage regulator should be out of service and the rheostat setting should remain unchanged throughout the test. Oscillograms of the 3-phase currents, field current, and a timing wave shall be taken on the same film. The direct-axis transient reactance will be obtained by plotting current against voltage. The direct-axis rated current transient reactance (per unit) will be equal to the initial voltage (per unit), which gives a transient value of short-circuit current plus the sustained value equal to the rated current neglecting the high-decrement currents during the first few cycles. The direct-axis rated voltage transient reactance will be the ratio of the no-load full rated terminal voltage to the corresponding value of armature current given by the extrapolation of the envelope of the current wave to the instant of sudden application of a symmetrical short-circuit, neglecting the high decrement current during the first few cycles. Suggested connections and instruments are shown on Figure 8. If desired for safety reasons, the shorting connection may be grounded.

(2) Direct-axis, rated-current, and rated-voltage subtransient reactance test.–The values of direct-axis, rated-current, and rated-voltage subtransient reactance will be obtained from the tests in (1) above.

(3) Direct-axis, transient, open-circuit, time-constant test.–The unit under test shall be driven by its turbine at no-load, rated speed and rated voltage with the armature leads open circuited. A resistor with resistance approximately equal to that of the main generator field shall be placed in series with the field of the test unit between the exciter and the short-circuiting circuit breaker. The field is then suddenly short circuited and oscillograms taken of the armature voltage waves. Suggested connections and instruments are shown on Figure 9. The voltage regulator should be out of service.

The direct-axis, transient, open-circuit time constant equals the time in seconds for the rms alternating-current value of armature voltage on open circuit to decrease to 0.368 of an initial value corresponding to the extrapolation of the envelope of the symmetrical voltage wave to the instant of short circuit, neglecting the high-decrement components during the first few cycles, and the residual voltage, when the field is suddenly short-circuited with the machine running at rated speed.

(4) Direct-axis, rated-current, and rated voltage, transient short-circuit time-constant test.–The direct-axis, rated current, and rated voltage, transient, short-circuit time constant shall be determined from the rated current and rated voltage oscillograms obtained in the determination of machine reactances.

The direct-axis, transient, short-circuit time constant is the time in seconds required for the rms alternating-current value of the slowly decreasing component present in the direct-axis alternating-current component of the armature current under suddenly applied 3-phase short-circuit conditions with the machine running at rated speed and no-load to decrease to 0.368 of an initial value corresponding to the extrapolation of the envelope of the symmetrical current wave to the instant of short circuit, neglecting the rapidly decreasing currents during the first few cycles, and the sustained short-circuit current.

(5) Rated-current and rated voltage values of negative sequence reactance test.–The values of negative sequence reactance shall be obtained as listed below:

(a) Rated current.–The unit under test shall be driven by its turbine at rated speed with a sustained single-phase short circuit between two of the armature line terminals. Suggested connections and instruments are shown on Figure 11. With the machine excited at reduced field current a series of readings is taken of the ammeter, voltmeter, and wattmeter for increasing values of field current. The rotor should be guarded against overheating, and allowed to cool between readings if necessary.

The negative sequence impedance is obtained from the following formula:

$$Z_2 = \frac{E}{I} \text{ per unit}$$

where E is the per unit voltage based on rated line-to-line voltage, and I is the per-unit short circuit current based on rated phase current.

The negative-sequence reactance is obtained from the following formula:

$$X_2 = Z_2 \frac{P}{EI(\sqrt{3})} \text{ per unit}$$

where $P =$ wattmeter reading in per-unit of base single-phase power.

(b) Rated voltage.–The rated-voltage value shall be determined from the oscillograms of a single-phase line-to-line short circuit between two terminals performed on the unit when operating at no-load rated speed. The value of reactance shall be obtained from the following formula:

$$X_2 = \frac{\sqrt{3}\,E}{I''} - X''_d \text{ per unit}$$

where E is the per-unit open circuit armature voltage before the short circuit, I'' is the root-mean-square value of the initial alternating-current component of armature current in per unit, and X''_d is the rated voltage value of subtransient reactance determined from Test(2) above. Suggested instruments and connections are shown on Figure 8, with a line-to-line instead of a 3-phase short circuit connection.

(6) Determination of the ratio of the rated-voltage value of quadrature-axis subtransient reactance to the rated-voltage value of direct-axis subtransient reactance.–This ratio shall be obtained from the following formula:

$$\frac{X''_q}{X''_d} = \frac{2X_2}{X''_d} - 1$$

where X_2 and X''_d are the rated-voltage values of negative sequence reactance and direct-axis subtransient reactance, respectively, determined in Tests (5) and (2) above.

n. Excitation system voltage response ratio test.–The excitation system voltage response ratio shall be determined with:

(1) Excitation system at no-load.

(2) The initial excitation system voltage equal to the synchronous machine rated load field voltage.

(3) All rotating components of the excitation system at rated speed.

(4) The manual control means adjusted as it would be to produce the rated voltage of the excitation system, if this manual control means is not under the control of the voltage regulator when the regulator is in service. (The means used for controlling the exciter voltage with the voltage regulator out of service is the manual control means.)

(5) The voltage sensed by the synchronous machine voltage regulator reduced from 100 to 90 percent.

Results shall be plotted in graph form.

(6) The exciter armature terminals shall be disconnected from the main generator field. An external, 60-cycle voltage signal corresponding to rated voltage at the generator terminals shall be connected to the regulator input circuit. The generator shall be operated at rated speed. With the regulator adjusted to maintain a value of field voltage corresponding to generator rated kva load, the outside source of a-c voltage to the regulator shall be adjusted so that the regulator is in balance, and is producing no corrective action in the excitation circuit. The magnitude of the input signal to the voltage regulator shall be suddenly reduced by 10 percent. An oscillograph shall be used to record the following quantities during the period following the reduction in voltage regulator signal:

(a) Regulator input voltage

(b) Exciter terminal voltage

(c) Exciter field voltage

(d) Exciter field current (if available)

The above test shall be repeated and the same quantities observed and recorded for a 10 percent increase in the input signal to the voltage regulator.

The excitation system voltage response ratio shall be determined from analysis of the above oscillograms. This response ratio is defined as the nominal value which is obtained when the excitation system voltage response in volts per second measured over the first 1/2-second interval is divided by the rated load field voltage of the synchronous machine. Suggested connections are shown on Figure 12. The response ratio is illustrated on Drawing No. 8 (577-D-2289) in the invitation.

o. Test to demonstrate the performance of the voltage regulator and excitation system.

(1) Ability of voltage regulator to maintain voltage under steady load conditions.-The generator shall be synchronized with the system with the voltage under control of the voltage regulator. The regulator shall be adjusted to produce approximately rated voltage at the machine terminals under no load. The generator shall be loaded in five steps from 0 to 115 percent kilowatt load. Machine electrical quantities shall be observed and recorded in each step.

(2) Load rejection.-The generator shall be operated at 100 percent kilowatt load, 105 percent voltage, and rated power factor. The load shall be suddenly disconnected by opening the generator circuit breaker. An oscillograph shall be used to record the following quantities and operations during the overspeed following load rejection:

(a) Armature voltage (between two phases)

(b) Armature current (one phase only)

(c) Field voltage

(d) Field current

(e) Speed

(f) Operation of overspeed switches and overvoltage relay

(g) Regulator output

(h) Timing wave

The above test shall be repeated at 115 percent of rated kilowatt output at rated power factor and 100 percent rated voltage. The governor setting for the tests shall be 10 seconds for full gate closure time. The station-service connection shall be such that the voltage available for operation of the control devices and magnetic and rotating amplifiers will be obtained from a constant 60-cycle source.

(3) Ability of regulator to maintain voltage under overspeed condition.-The generator shall be operated at rated speed and rated voltage with the generator circuit breaker open. The station-service connection shall be such that the voltage available for operation of the control devices and magnetic and rotating amplifiers will be obtained from a constant 60-cycle source. The generator speed shall be increased in five steps up to 180 percent of normal (steps of 120, 140, 150, 160, and 180 percent). Readings of terminal voltage and excitation circuit voltages and currents shall be recorded at each step after the speed has become constant. This test may be combined with Test f.

(4) Range of regulator control.-The range of control of the voltage adjusting device shall be observed and recorded. Readings of terminal voltage shall be taken at the minimum and maximum settings of the rheostat.

(5) Operation with negative field current.-The test generator shall be operated at no load and rated voltage in parallel with the other generator. With the test generator excitation under control of the voltage regulator, the incoming reactive shall be increased to its maximum permissible limit, in order to produce negative field current in the test unit. If the negative excitation cannot be reached with the test unit operating at rated voltage, the setting of the voltage adjusting rheostat should be lowered until the definite reversal

of field current is reached. The underexcitation limiter should be removed from service. It will probably be necessary to have both generators connected to the system. This test may be performed in connection with the line charging test. The following readings shall be recorded:

(a) Armature voltage

(b) Armature current

(c) Generator field current

(d) Exciter voltage

(6) Test of overexcitation limiter. -

(a) Low-range limiter.–Both generators shall be brought to synchronous speed and synchronized with the system. The excitation of the test generator shall be under control of its voltage regulator. The excitation of the other generator shall be placed on manual control with its loss-of-field relay blocked. Adjustments shall be made so that both units are operating at rated voltage with zero vars and 100 percent rated mw on the test unit with zero power output on the second unit.

The voltage adjusting rheostat on the test unit shall be set so that the regulator maintains rated generator voltage. Timing relays 45X and 45Z should be blocked so that they will not interfere with the test and relay 45Y should be maintained in the energized position. These connections place the low-range limit determined by rheostat 61RH in the circuit. The settings of compensating devices shall be adjusted so that the regulator will maintain constant voltage regardless if real or reactive load.

The following quantities should be measured and recorded:

(aa) Armature voltage

(bb) Armature current

(cc) Generator field current

(dd) Exciter voltage

(ee) Megawatts

(ff) Megavars

(gg) Limiter output current through CRA-1 and CRA-2 coils in the maximum excitation limiter circuit

(hh) Position of voltage adjusting control

To perform the test, the second generator should be underexcited until a value of 10 MVAR OUT is noted on the control board varmeter (or the test varmeter, if used) for the test unit. Read and record all values on the meters. The unit under manual control should then be further underexcited until the test unit produces 20 MVAR OUT of the test unit until the limiter operates, which should occur at a field voltage of approximately 240 volts. Limiter operation should be indicated by a sharp rise in the current through the CRA coils. Read and record all values when the limiter operates.

The above procedure establishes a point on the P–Q diagram which is a limit in the overexcited region.

The unit under test should next be loaded at a value of 15 mw and the procedure repeated to give another point on the P–Q diagram. The procedure should then be repeated for a value of zero MW load.

(b) High-range limiter.–The connections should be changed so that the high-range limit determined by rheostat 62RH is in the circuit. Relay 45Y should be blocked in the deenergized position. The test procedure should be repeated at the three values of loading described in Subparagraph (a) above. In this case the limiter should limit at a field voltage of 300 volts.

(c) Alternate test.–If the system conditions do not permit the test unit to be sufficiently overexcited, then the following alternate method shall be used:

The test generator shall be operated at rated voltage and 100 percent rated mw load. The excitation shall be increased in selected steps of 10 volts each by raising the voltage adjusting control to its limit. Quantities shall be measured and recorded as in Subparagraph (a) above.

The high-range limiter shall be tested with the generator at rated voltage and 100 percent rated mw load but with relay 45Y blocked in the deenergized position. The excitation shall be increased by raising the voltage adjusting control until the limiter operates at a field voltage of 300 volts.

Care should be exercised in making the above tests so that dangerous overheating of any system component is avoided. Readings should be taken as quickly as possible.

(7) Underexcitation limiter.–The generator should be operating on the system at no load and rated voltage, with excitation under control of the voltage regulator. Lower the excitation of the test unit until the regulator is operating against the reactive ampere limiter. Increase the kilowatt load on the generator from zero to full load, with all other adjustments remaining unchanged as the load is increased, record the following quantities on the test generator at 0, 25, 50, 75, 100, and 115 percent kilowatt load:

(a) Megawatts

(b) Megavars

(c) Armature voltage

(d) Armature current

(e) Limiter output current

(f) Position of voltage adjusting control

(g) Generator field current

This test will be used to check the setting and operation of the limiter. This test may also be conducted by decreasing the load from 115 percent kilowatt load to zero load.

(8) Interruption of power supply.–The generator shall be operated at rated speed and rated voltage with the generator circuit breaker open. Move the voltage adjusting powerstat

to call for a 10 percent increase in voltage. After 5 seconds, open the disconnect switch of the motor-generator motor starter. An oscillograph shall be used to record the following quantities:

(a) Armature voltage

(b) Exciter voltage

(c) Regulator output voltage

p. Measurement of main exciter field rheostat travel time. The exciter field rheostat shall be operated over its entire range and the time to make full travel shall be observed and recorded.

q. CO_2 Test

The generator housing shall be tested to demonstrate the ability of the generator to maintain the required concentration of carbon dioxide for a specified time. This test shall be conducted concurrently with a 100-percent load rejection test. All carbon dioxide gas, analyzing equipment, manometer, and stop watches shall be furnished by the contractor. Suggested connections and instruments are shown on Figure 10.

The necessary pipe and hose connections shall be installed for connection to the CO2 sampling connections. The analyzing equipment shall be checked for zero point test with the external hose connections attached to the instrument but with the opposite end of the hoses in atmospheric air. After the zero point test has been made, connect the hoses to the generator and check that the open end of the fresh air hose is far enough away from the generator so that escaping CO2 will not enter it. Inspect the generator housing for tightness. Close all access openings and check floor drains within the generator housing for adequate seal. Check the generator relief doors for free swing.

(1) Test procedure. -

(a) Take initial readings at all stations

(b) Obtain the static reading on the housing pressure manometer. This reading should be taken with both legs of the manometer open to atmospheric pressure. Then take the initial reading of the manometer with one leg connected to the generator air housing with the generator running. This will be called the initial reading. The water column height on the legs under this condition will no longer be the same as the static reading because of the pressure in the generator housing caused by the rotation. Throughout the actual test after the CO_2 has been discharged, read both manometer legs every 30 seconds until the end of the test. In a few seconds after the discharge of the CO_2, the manometer reading will be at a maximum. Record this peak and time of peak.

(c) With the test generator under full load at normal speed, trip the generator differential relay. Take readings from the CO_2 analyzer at 5-second intervals until maximum concentration is reached and take readings at 1-minute intervals from zero test time until end of test. The delayed cylinders should be blocked so that they do not discharge.

(d) Read the revolutions per minute by the governor tachometer. Record the maximum unit overspeed and time in seconds it occurred after zero test time. Record unit speed at 15-second intervals until the unit comes to rest. Also, note time and revolutions per minute at all brake applications.

(e) Note the time of opening and closing of generator housing pressure relief doors.

(2) Results of test.–Curves shall be plotted as follows:

(a) Time-Minutes Elapsed after Initial Discharge vs CO_2 Concentration–Percent of Volume.

(b) Time-Seconds Elapsed after Initial Discharge vs CO_2 Concentration–Percent of Volume (to include the period from initial discharge to maximum concentration).

(c) Revolutions per minute vs Time–Minutes Elapsed after Initial Discharge.

(d) Housing Pressure–Inches of Water vs Time–Minutes Elapsed after Initial Discharge.

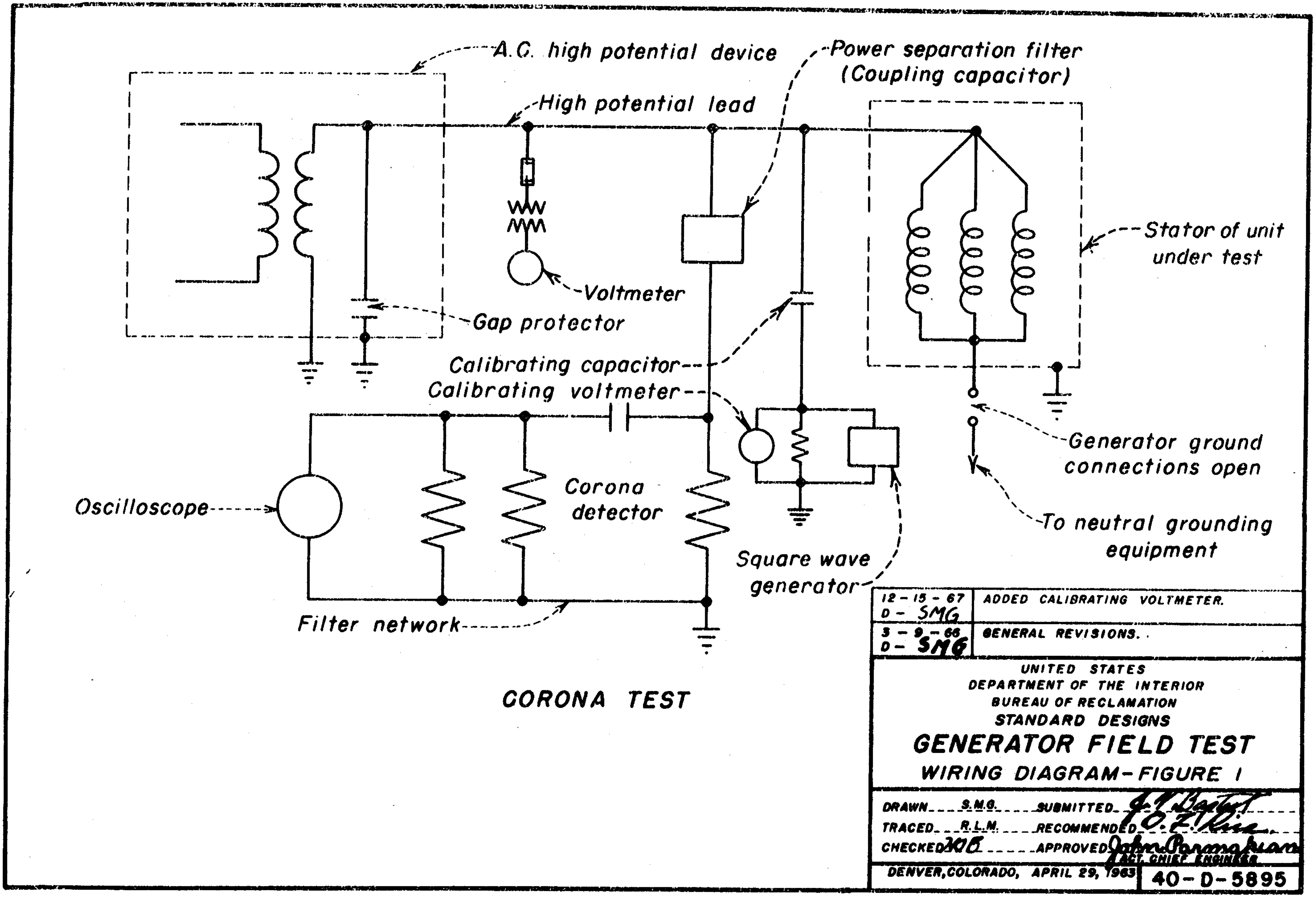


Figure C-1. — Generator field test — wiring diagram.

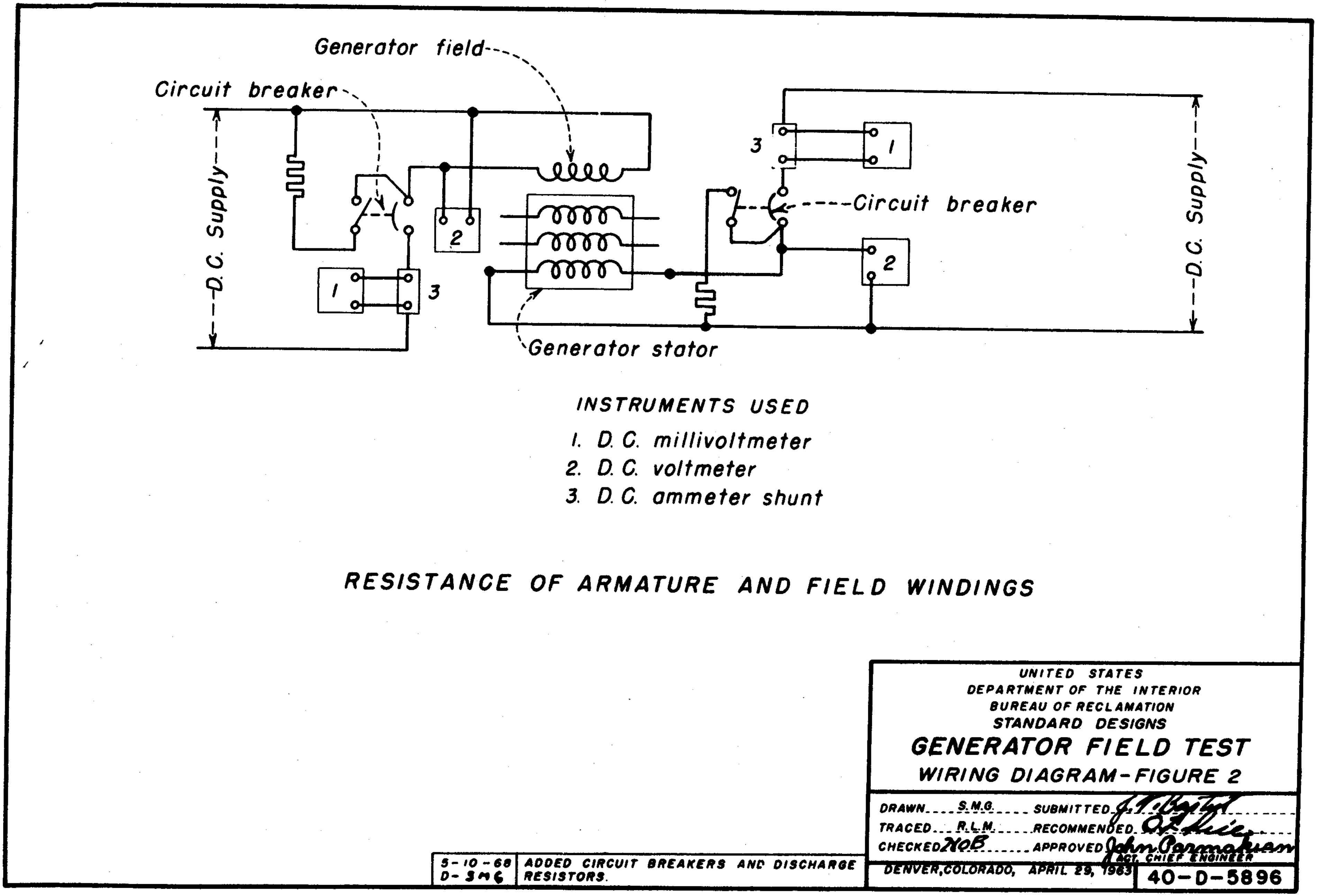


Figure C-2. — Generator field test — wiring diagram.

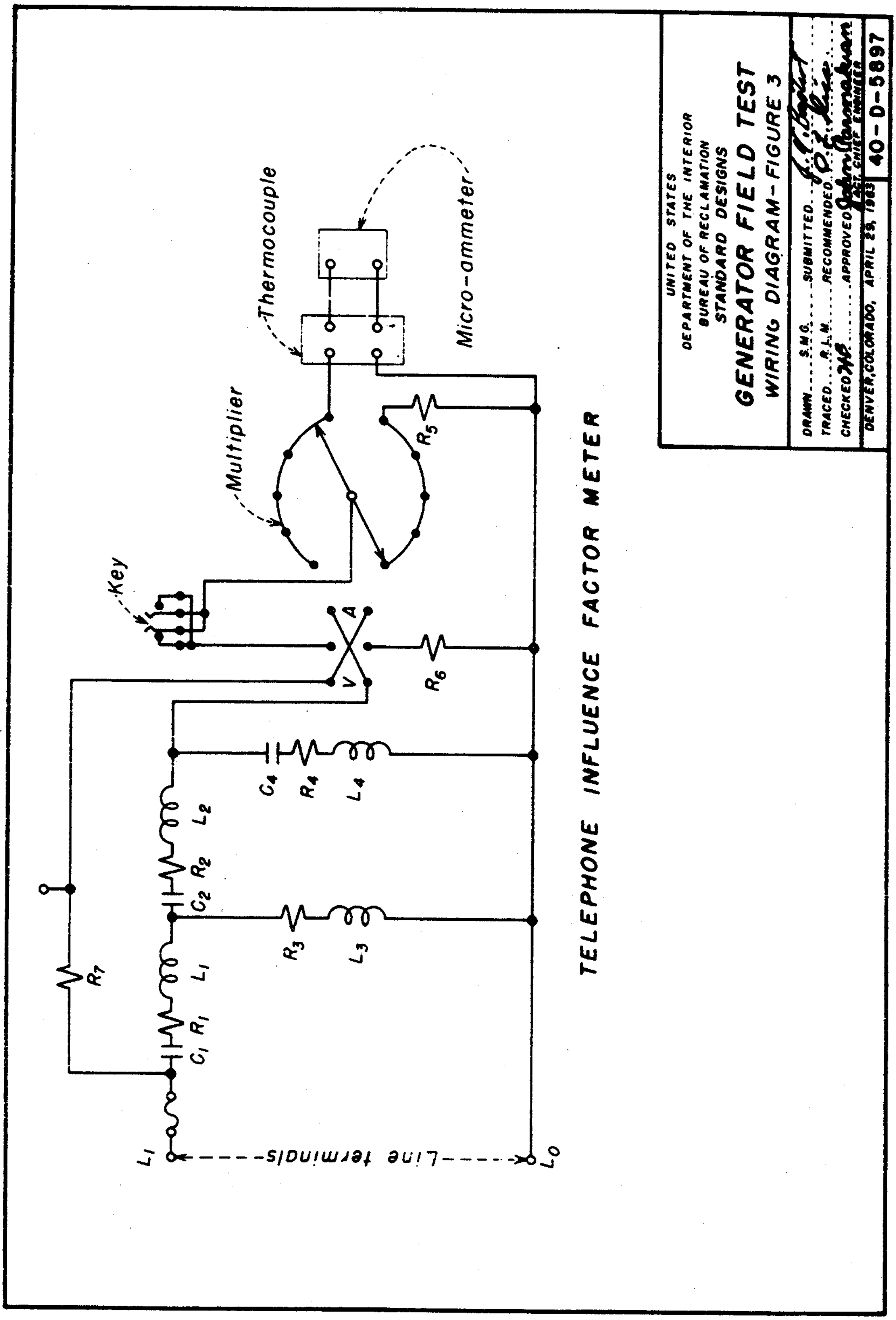


Figure C-3. — Generator field test — wiring diagram.

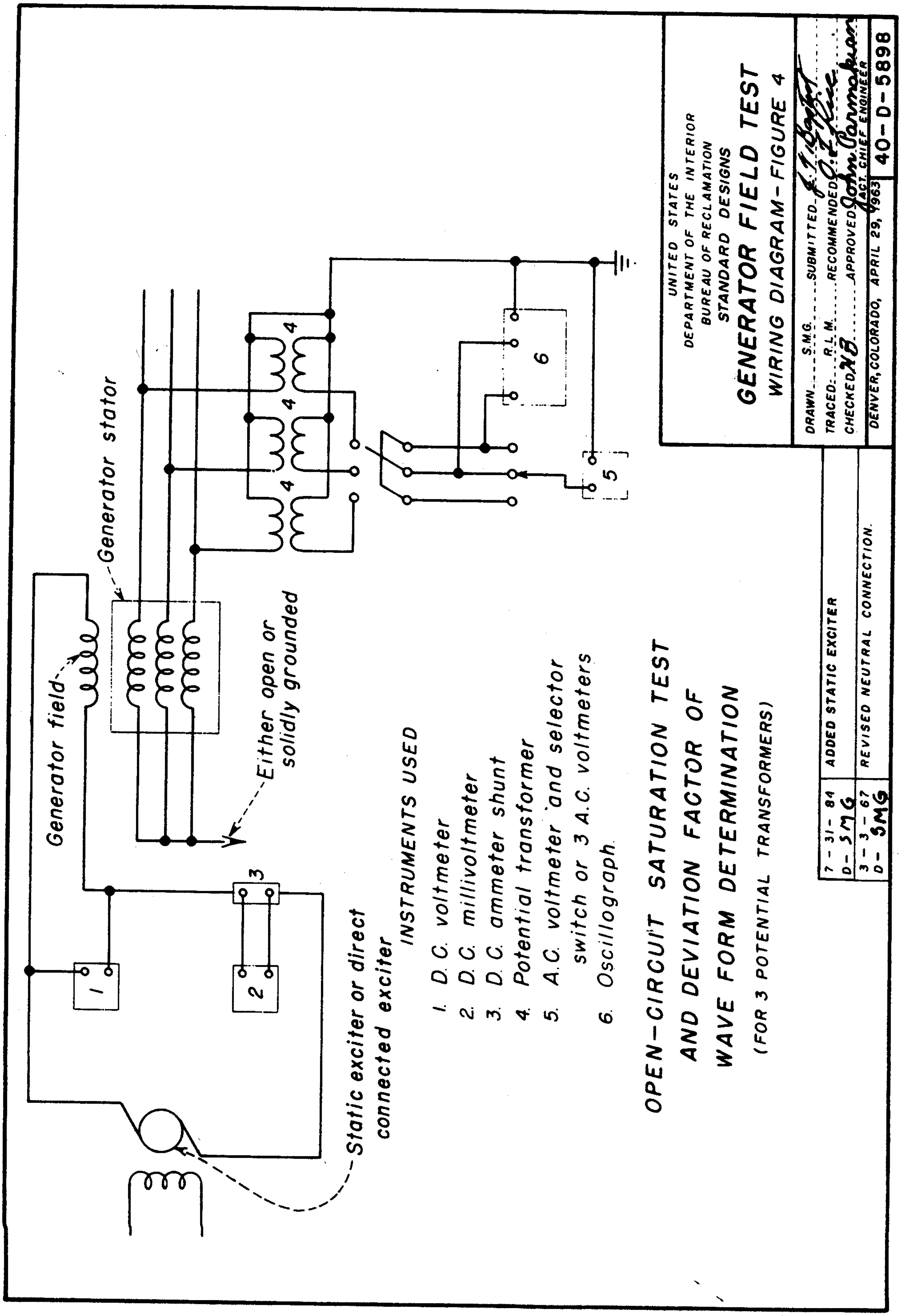
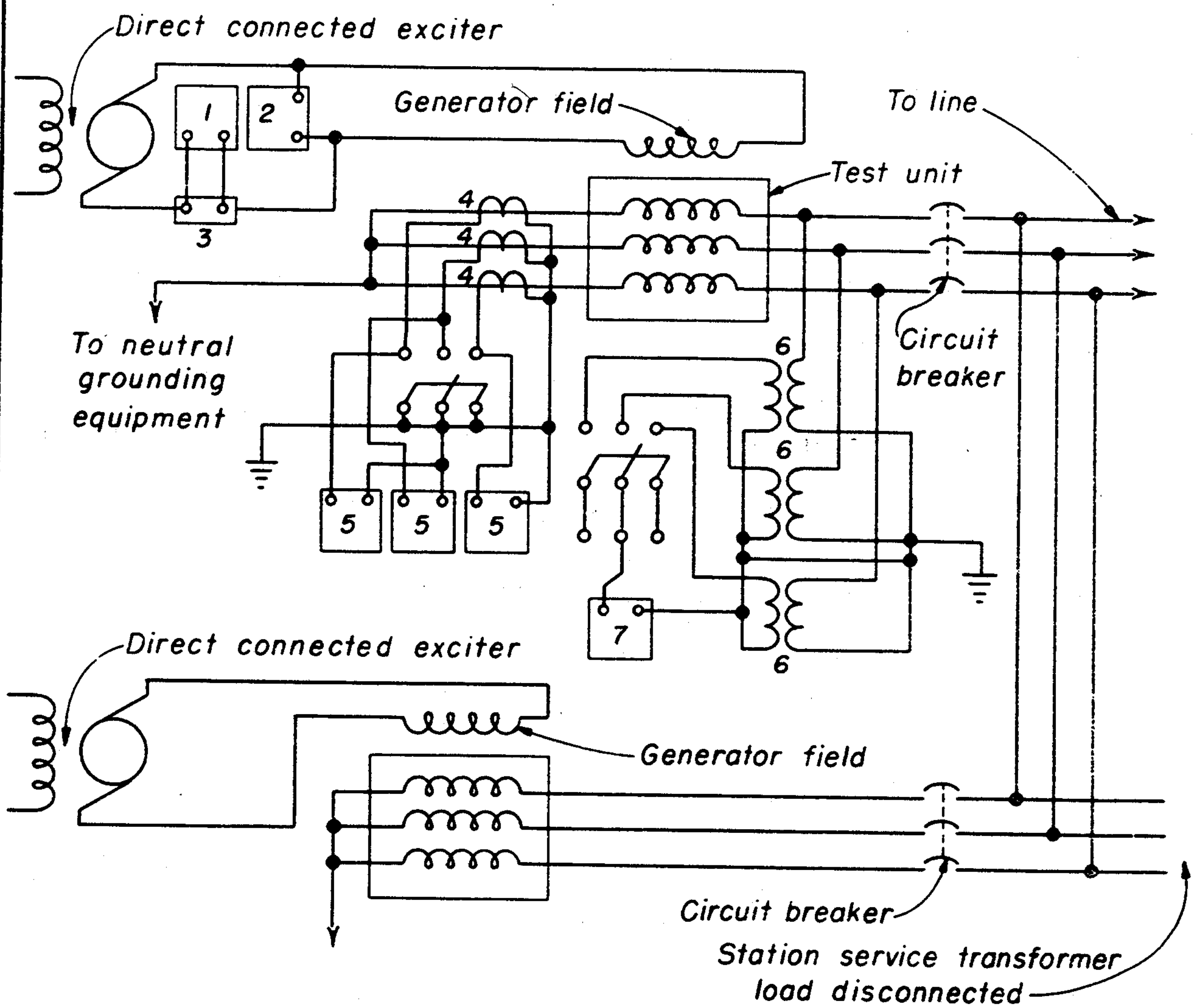


Figure C-4. — Generator field test — wiring diagram.



FULL-LOAD SATURATION, ZERO POWER FACTOR LAGGING TEST
(RATED CURRENT, ZERO POWER FACTOR SATURATION)
AND LINE-CHARGING CAPACITY TEST

INSTRUMENTS USED

1. D.C. millivoltmeter
2. D.C. voltmeter
3. D.C. ammeter shunt
4. Current transformer
5. A.C. ammeter
6. Potential transformer
7. A.C. voltmeter

ALWAYS THINK SAFETY

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
STANDARD DESIGNS

GENERATOR FIELD TEST
WIRING DIAGRAM-FIGURE 5

DRAWN S.M.G. SUBMITTED
TRACED L.L.M. RECOMMENDED
CHECKED APPROVED
DIRECTOR OF DESIGN AND CONSTRUCTION

DENVER, COLORADO, MAY 14, 1971 | 40-D-6249

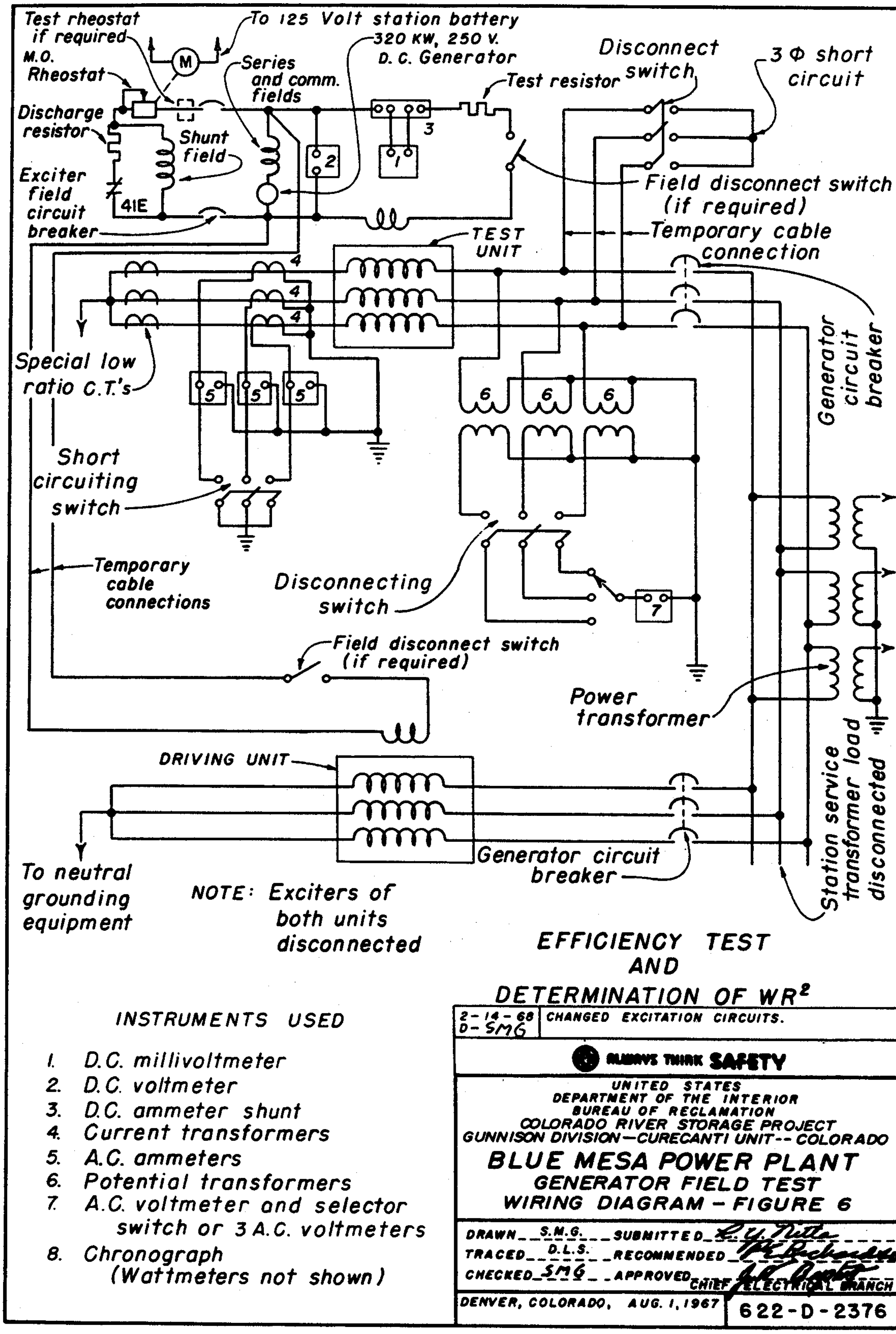


Figure C-6. — Generator field test — wiring diagram.

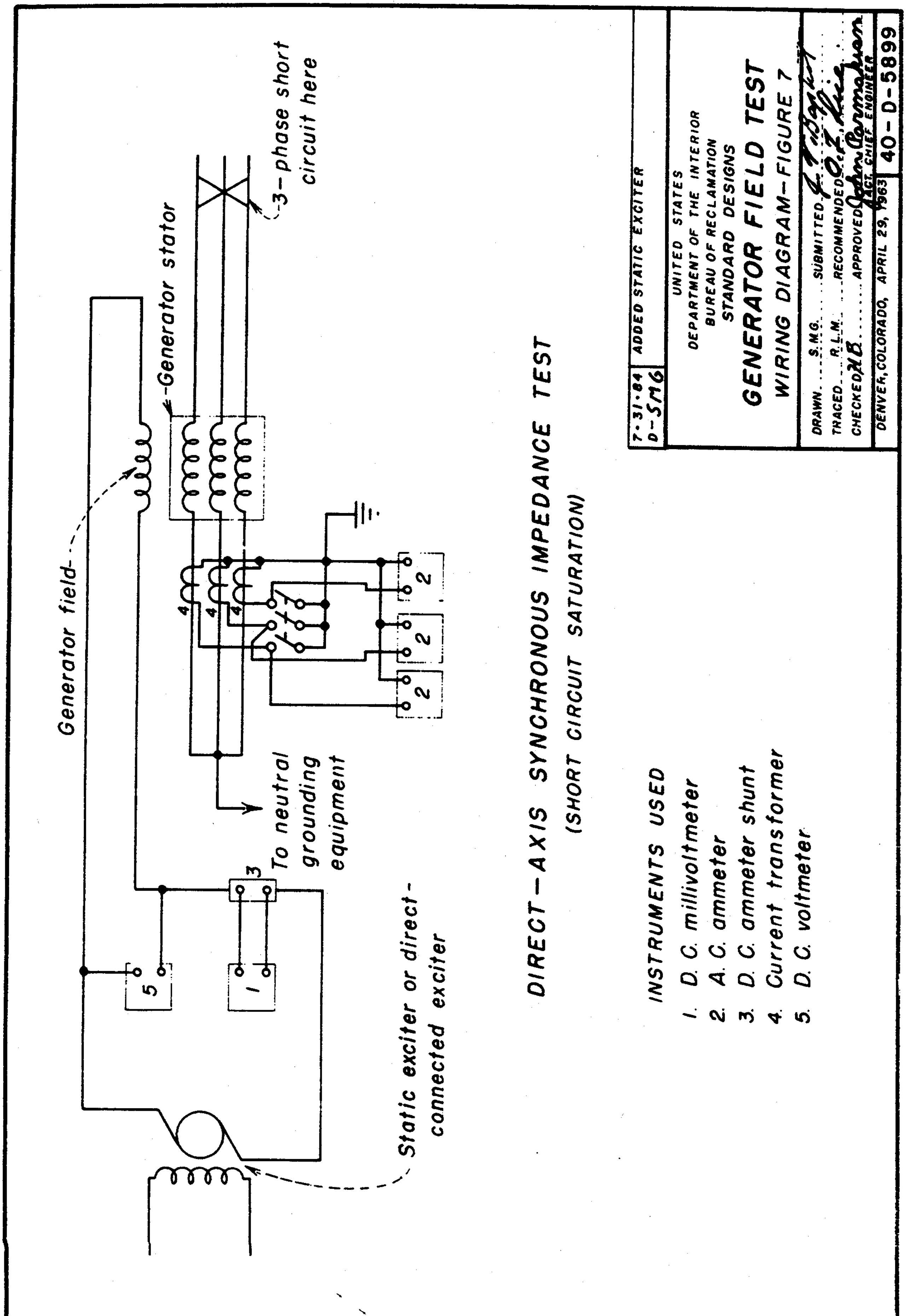


Figure C-7. — Generator field test — wiring diagram.

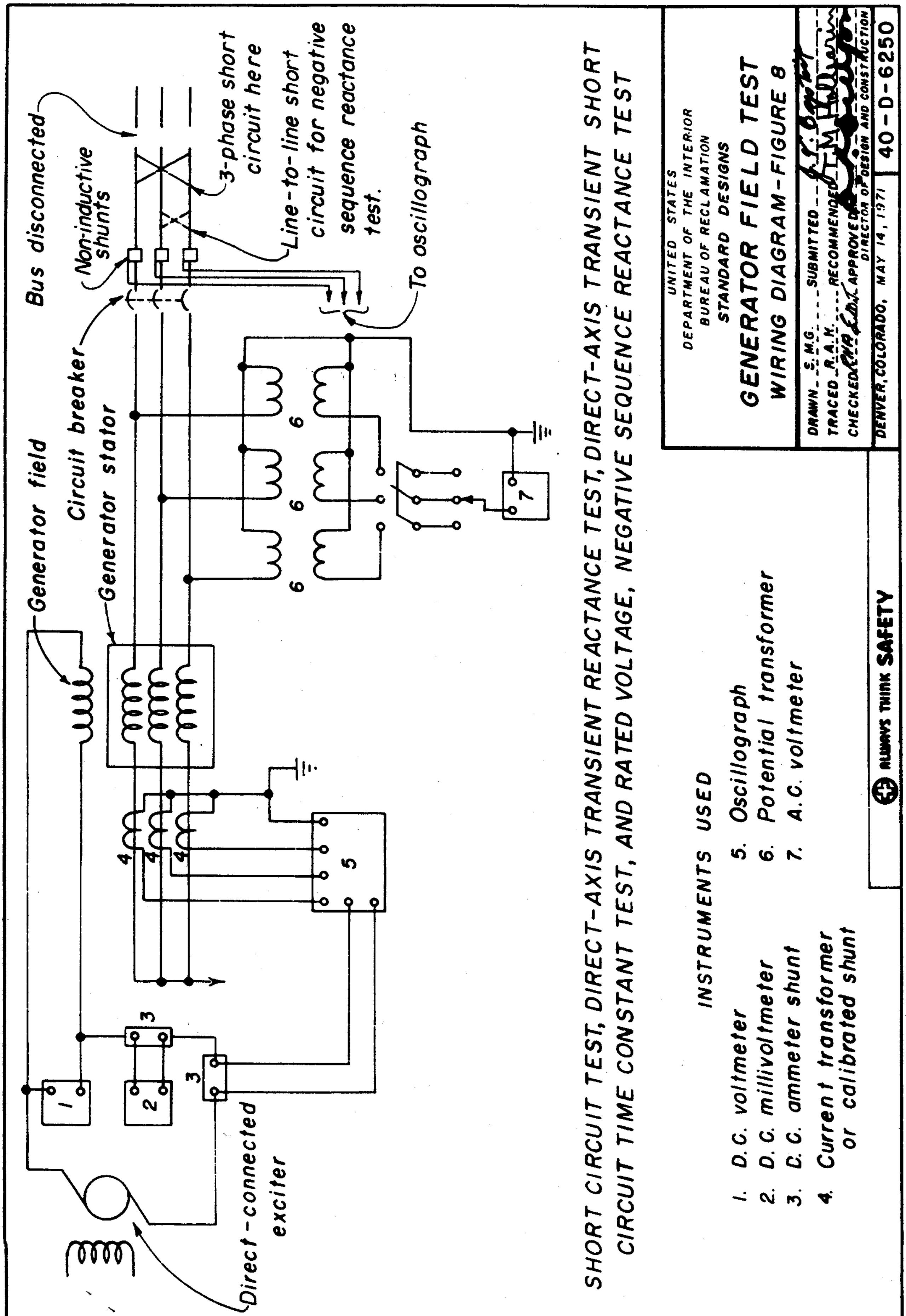


Figure C-8. — Generator field test — wiring diagram.

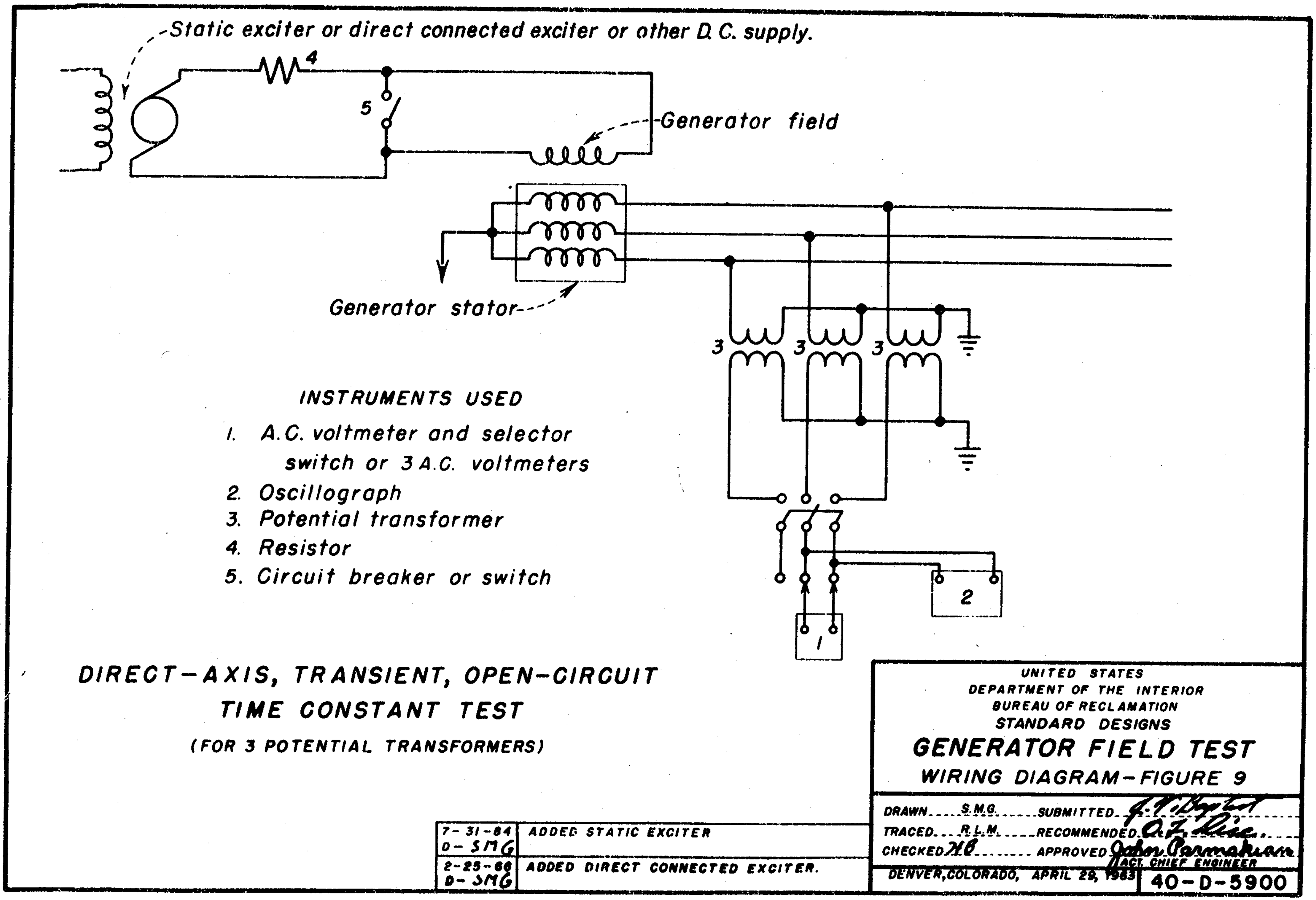


Figure C-9. — Generator field test — wiring diagram.

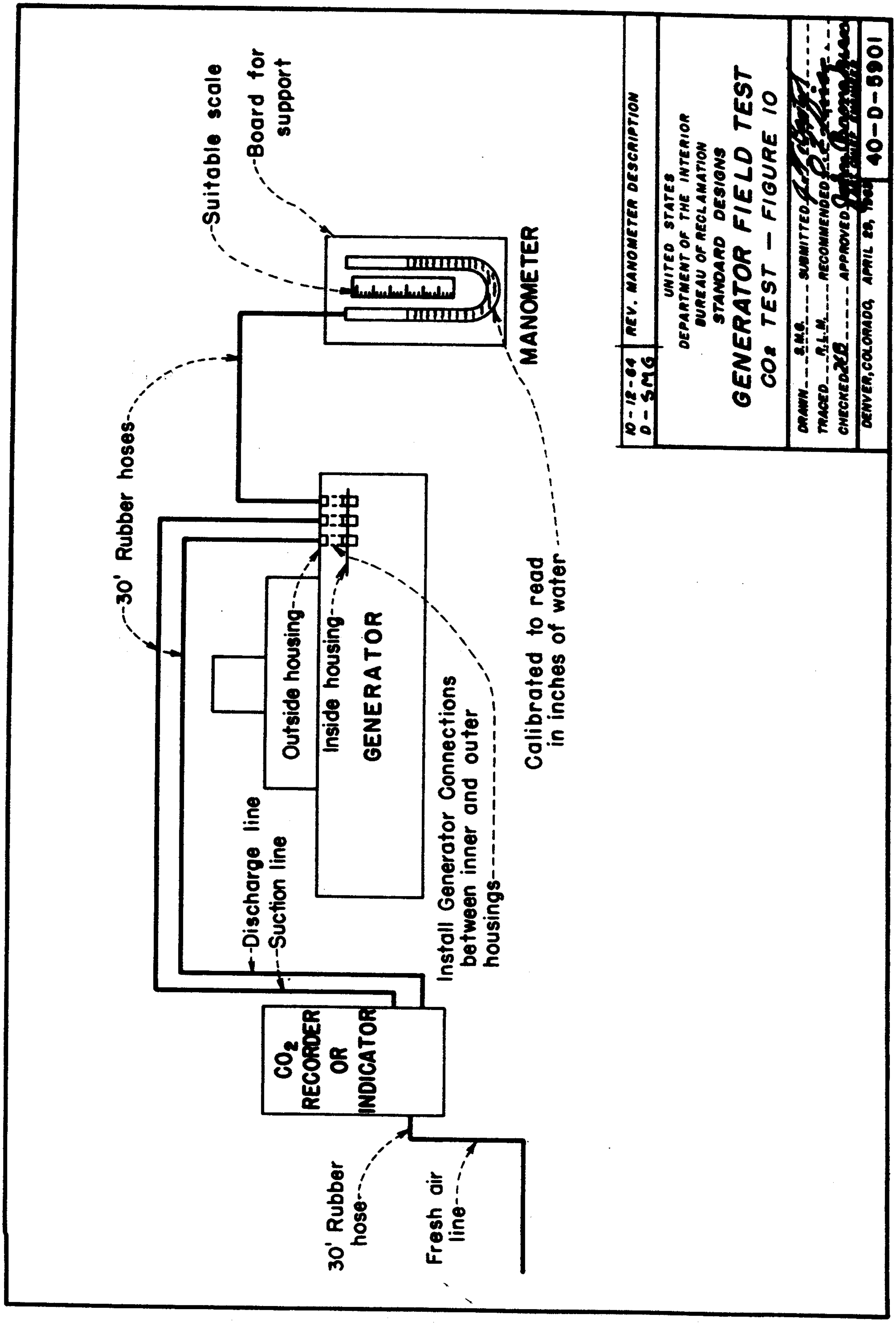


Figure C-10. — Generator field test — wiring diagram.

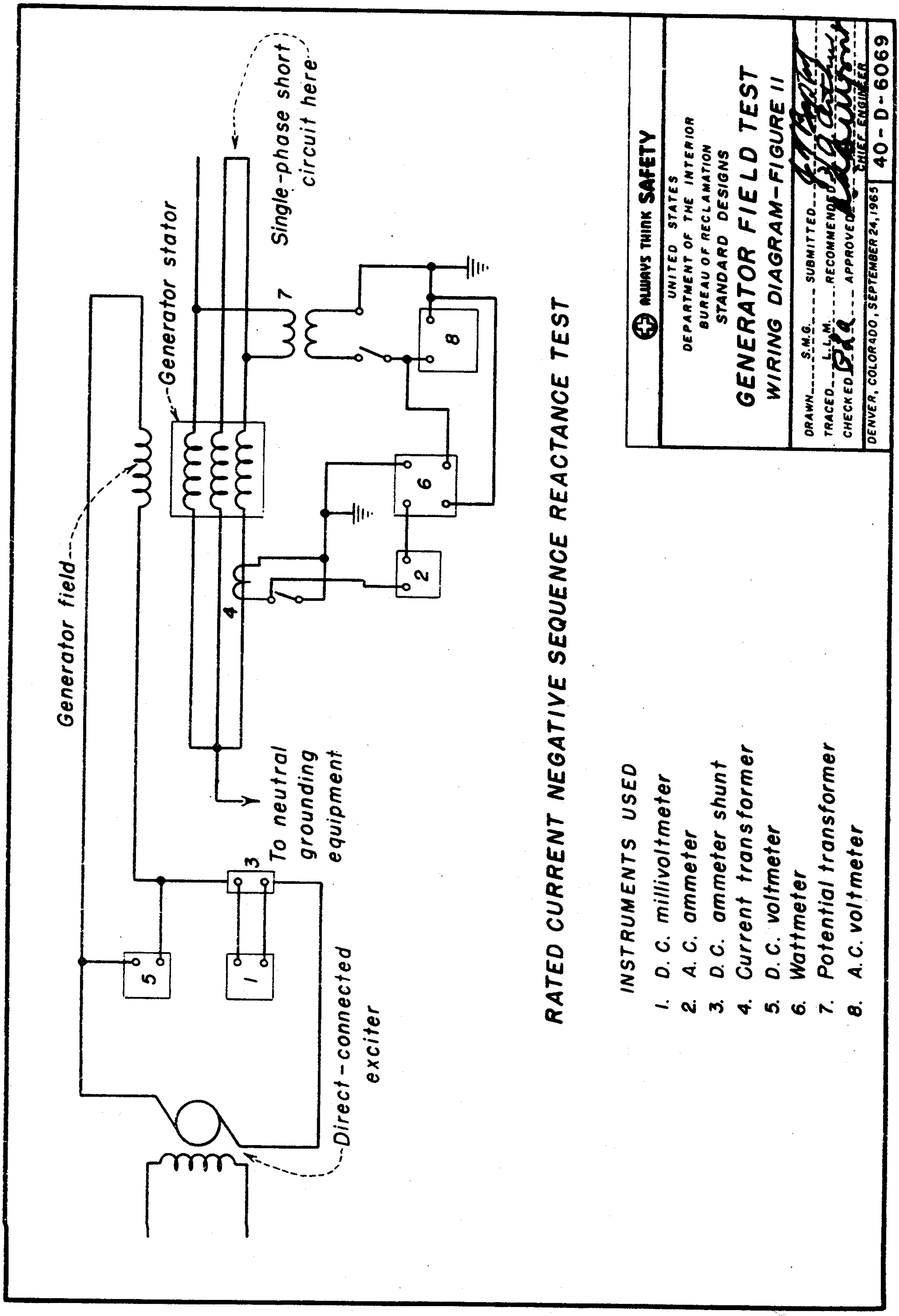


Figure C-11. — Generator field test — wiring diagram.

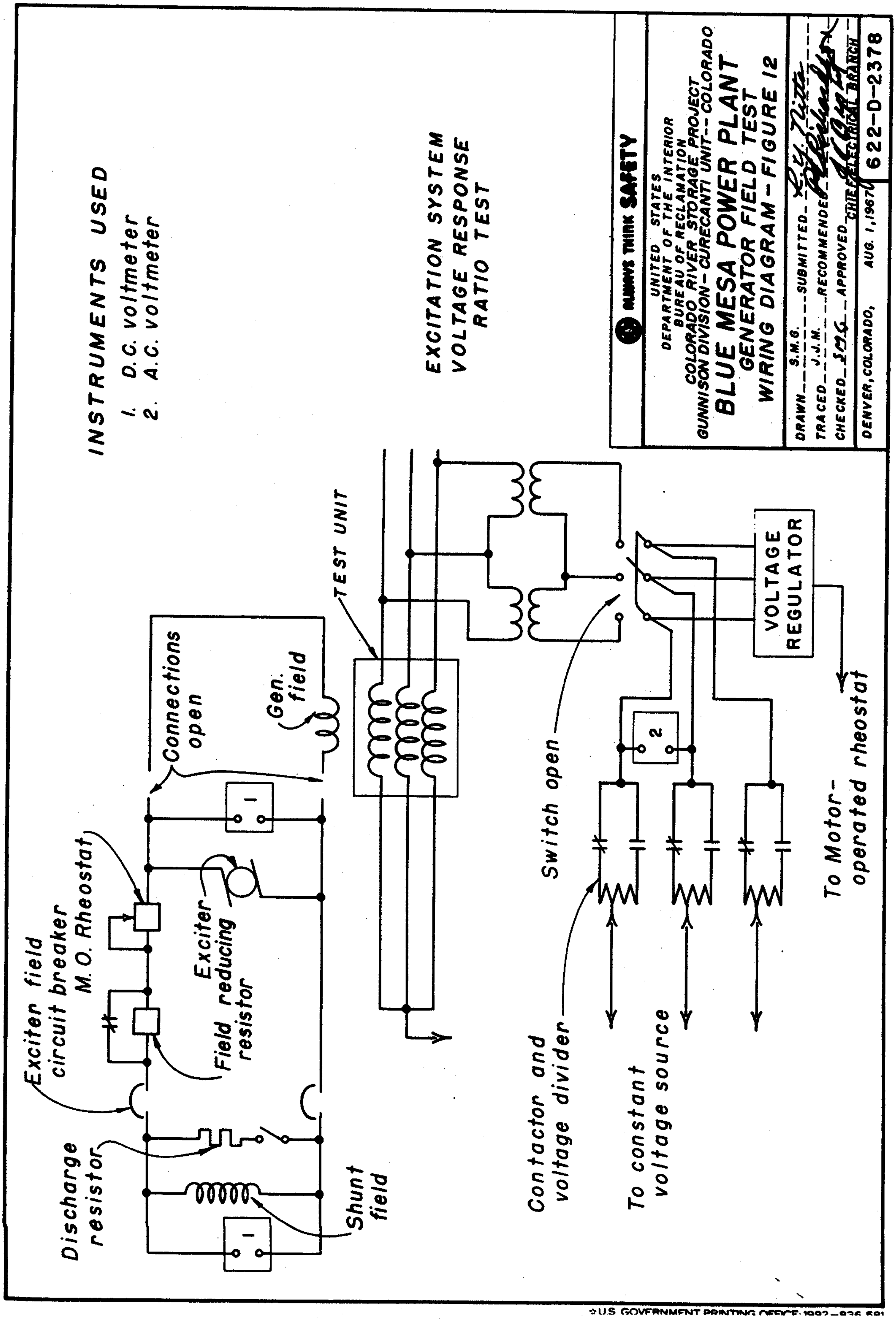


Figure C-12. — Generator field test — wiring diagram.