*Parabolic Trough Technology Workshop*
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# Nitrate and Nitrite/Nitrate Salt Heat Transport Fluids

**Bruce Kelly**
**Nexant, Inc.**

**Daniel Barth**
**FRIATEC - Rheinhütte**

**Doug Brosseau**
**Sandia National Laboratories**

**Steven Konig**
**Bertrams Heatec**

**Fabrizio Fabrizi ENEA**

# *Topics*

- Concept
- Comparison with Therminol
- Salt components and systems
- Demonstration program
- Development program

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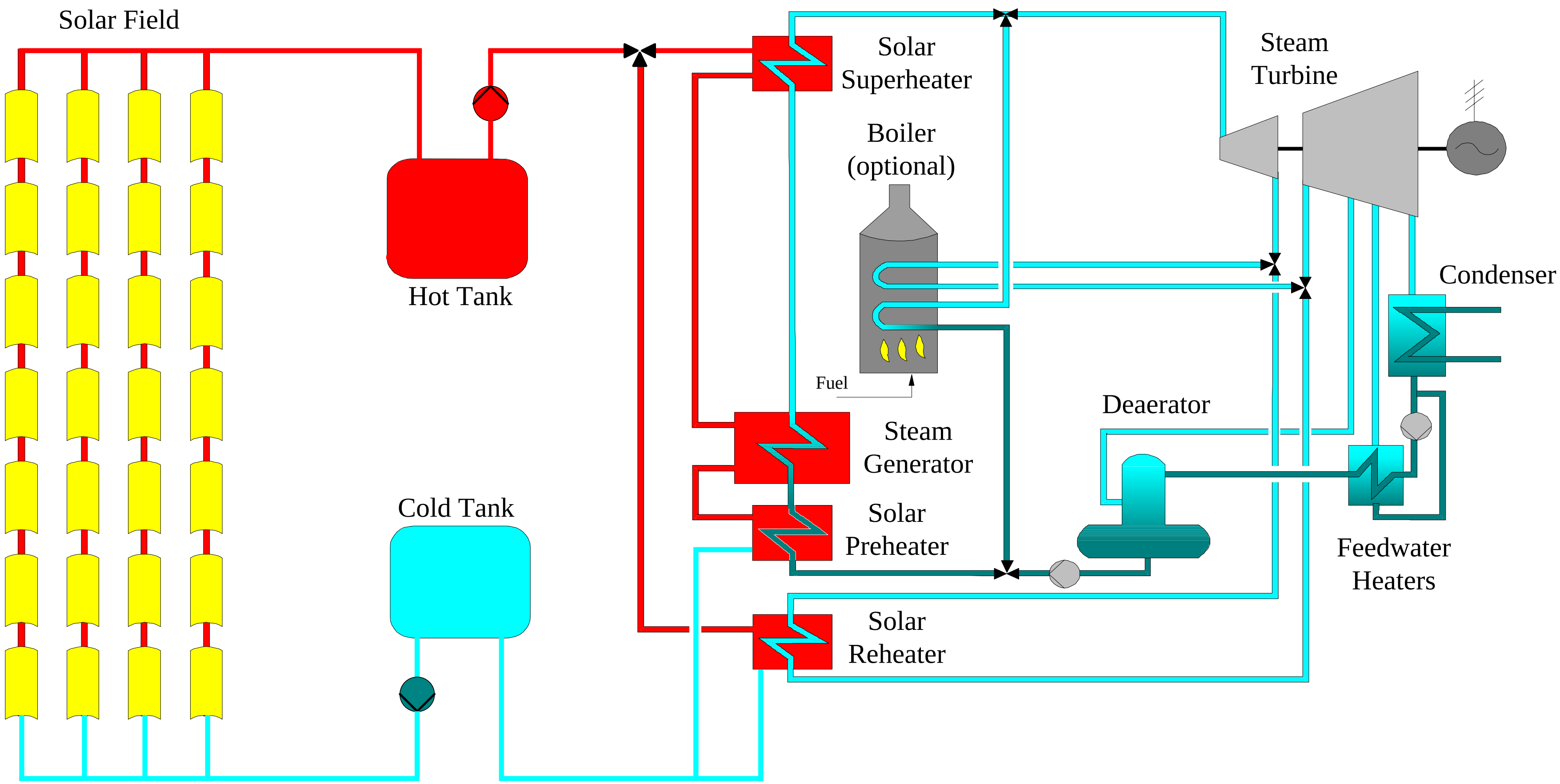
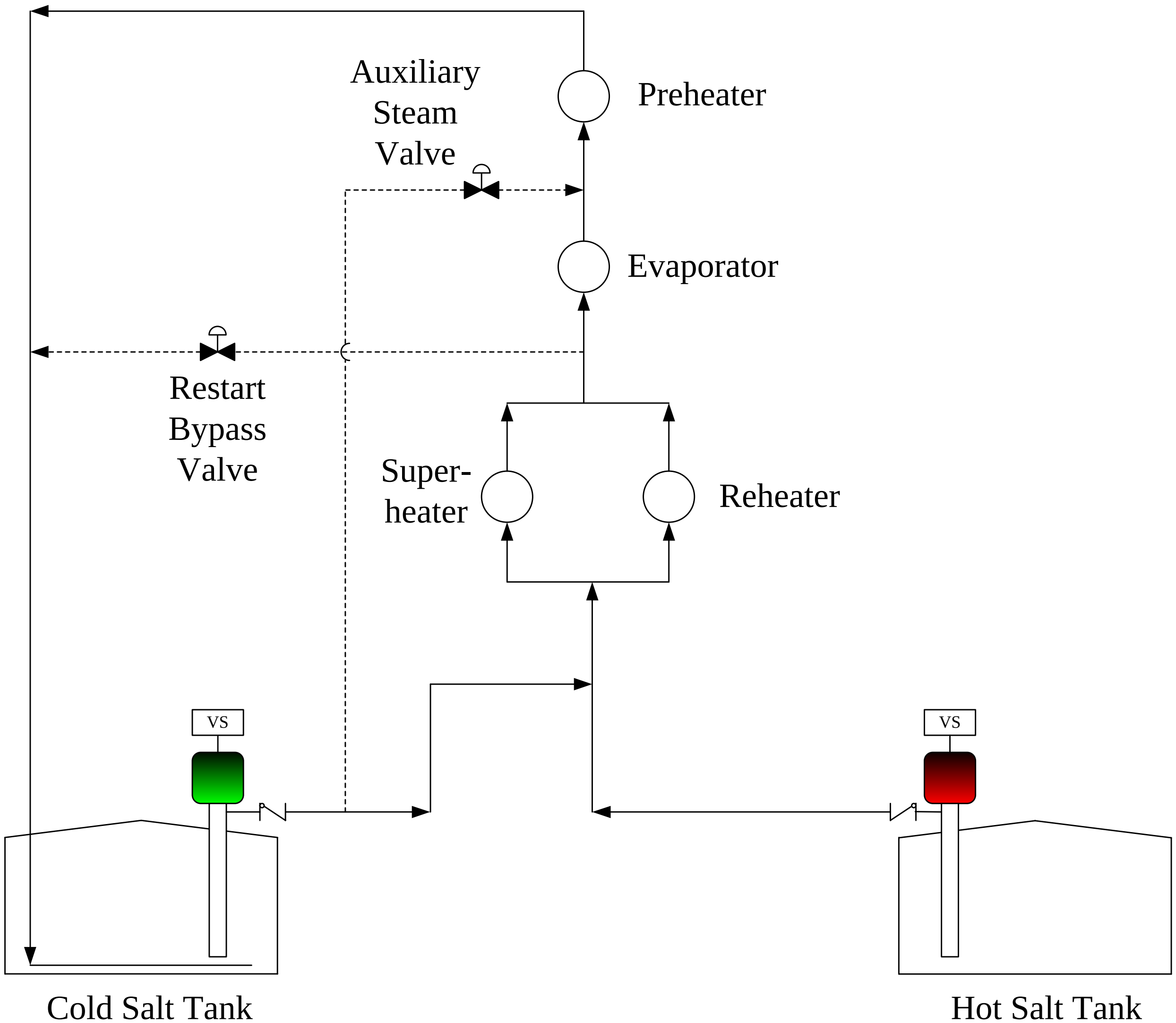
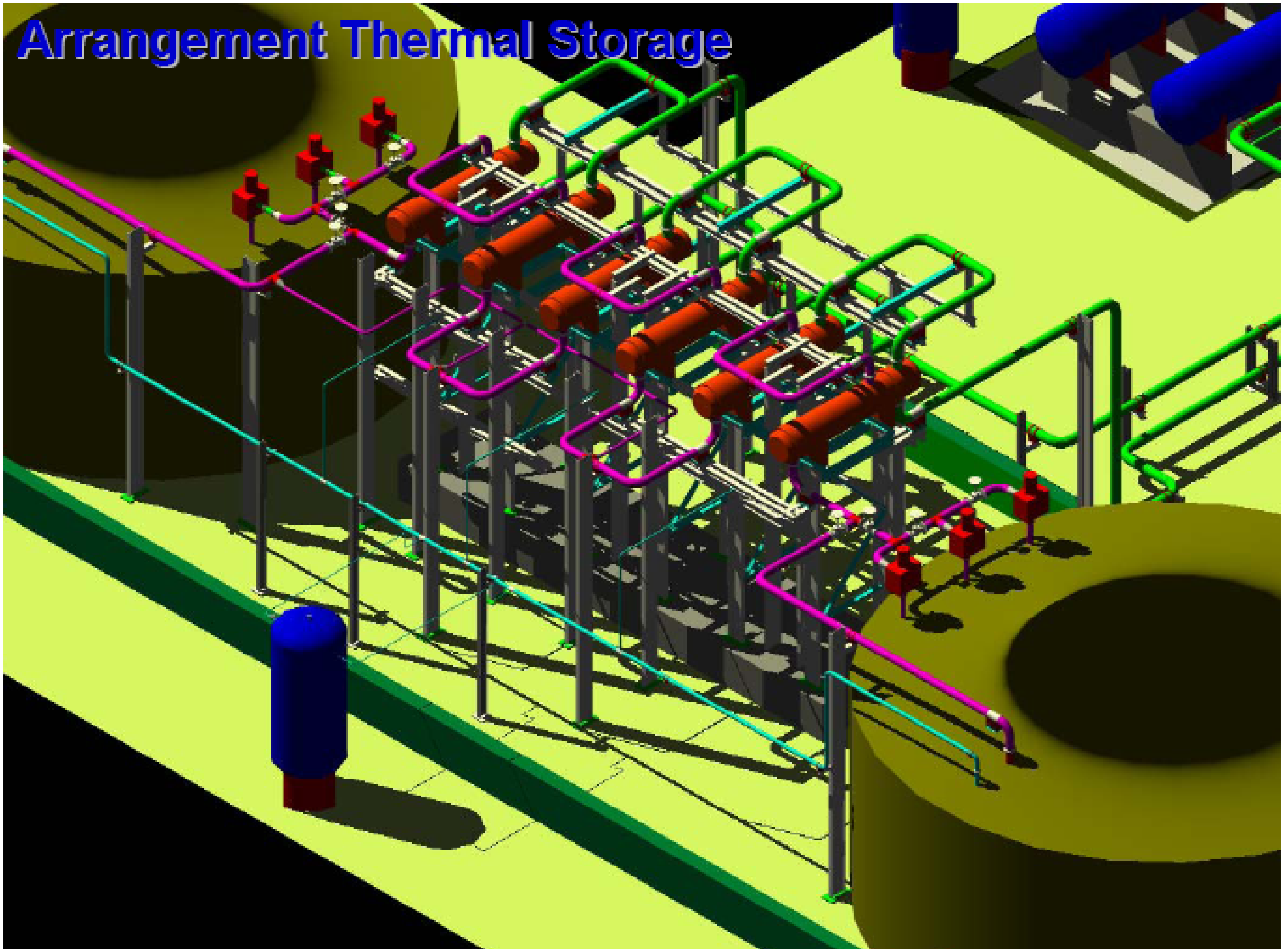
# Salt Heat Transport Fluid



# Steam Generator



# *Isometric View (Source: FlagSol)*



# *Candidate Salts*

- **Binary nitrate: 60% $NaNO_3$; 40% $KNO_3$; 190 °C (eutectic) → 600 °C**
- **Hitec : 7% $NaNO_3$; 53% $KNO_3$; 40% $NaNO_2$; 142 °C → 460 °C**
- **HitecXL : 15% $NaNO_3$; 43% $KNO_3$; 42% $Ca(NO_3)_2$ 140 °C → 500 °C**
- **Sandia molten salt: xx% $NaNO_3$; yy% $?NO_3$; zz% $?NO_3$; 100 °C → 500 °C**

## Advanced heat transport fluid

# *Topics*

- Concept
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# *Comparison with Therminol*

- **Collector field outlet temperatures**
  - **460 to 600 ˚C**
  - **Thermal stability limits on 3 of 4 salts as high as temperature limits on receiver selective surfaces**
  - **Improves Rankine cycle efficiency at expense of collector field efficiency; likely limit is perhaps 540 ˚C with current concentration ratios**
  - **Pipe, tank, and heat exchanger materials available for all combinations of salt temperatures and impurities**

# *Comparison with Therminol - Continued*

## Rankine cycle and annual field efficiencies

| | Gross cycle efficiency | Annual field efficiency | |
|---|---|---|---|
| | | Current | Prototype |
| Therminol | 0.377 | 0.483 | 0.540 |
| Salt | | | |
| - 450 C | 0.396 | 0.449 | 0.517 |
| - 500 C | 0.407 | 0.414 | 0.492 |
| - 510 C | 0.410 | 0.406 | 0.487 |
| - 540 C | 0.424 | 0.382 | 0.470 |

**Emissivity of 0.07 at 400 °C is essentially mandatory**

## *Comparison with Therminol - Continued*

- **Thermal storage**
  - **Heat transport fluid is thermal storage media**
  - **Avoid capital cost, and Rankine cycle performance penalty, of oil-to-salt heat exchangers**
  - **Larger temperature rise across collector field; reduces storage medium volume**
  - **Avoids parasitic energy demand of storage salt pumps**
  - **$35 to $40/kWht for indirect Therminol storage**
  - **$24/kWht for direct Hitec storage at 450 °C, decreasing to $13/kWht for binary salt storage at 540 °C**

# *Comparison with Therminol - Continued*

- **Overnight freeze protection increases auxiliary demand for thermal energy**
  - **10 hours per year for Therminol**
  - **600 hours per year for Sandia salt (130 °C)**
  - **2,300 hours per year for Hitec and HitecXL (175 °C)**
  - **4,200 hours per year for binary salt (250 °C)**
- **Capital investment in Joule and resistance heating systems**

# *Comparison with Therminol - Continued*

- **Higher temperatures and salt impurities require low alloy ferritic and stainless steel materials**
- **Ball joint seals are not yet available**
- **More complex maintenance procedures for draining and filling a collector loop**
- **Thawing a frozen loop, particularly with lost glass envelopes, will be a time consuming process**

# *Nitrate Salt*

## Design Parameters and Constraints

- Industrial grades, with total chloride contents up to ~0.6 percent, can be accommodated
- For 30 year project life:
  - Temperatures below 400 °C → Carbon steel
  - 400 to 480 °C → 9 Cr - 1 Mo low alloy steel
  - Above 480 °C → Stabilized stainless steels
- Optimum combination of salt impurities and equipment materials probably not yet identified
- $MgNO_3 \longrightarrow MgO_{\downarrow} + NO_2$ reaction may need to be promoted in some grades of industrial salt

# *Intergranular Stress Corrosion Cracking*

- **Susceptible materials: 'H' grades (C > 0.04%) of 304 and 316 stainless steel; chromium carbide formation at temperatures between 530 and 590 °C; chromium depletion at grain boundaries**
- **Residual tensile stresses: Welding**
- **Chlorides: 0.6 weight percent in industrial grade salt**
- **Water: Disassembly for maintenance**
- **Possible alternate materials: Stainless steels stabilized with titanium (Grade 321) or niobium (Grade 347)**

# *Intergranular Stress Corrosion Cracking*

**Heat affected zone of welds in stabilized stainless steels**

- **Weld temperatures dissolve titanium (niobium) carbides into titanium (niobium) and carbon**
- **As weld cools, carbon combines with chromium, forming chromium carbide; material then susceptible to stress corrosion cracking at grain boundaries**
- **Post weld heat treatment to 850 to 900 °C**
- **Chromium carbide dissolves to chromium and carbon**
- **Carbon preferentially recombines with titanium (niobium) to re-form stable carbides**

# *Sandia National Laboratories*

- **Plant dispatch**
- **Levelized cost of energy**

# *Topics*

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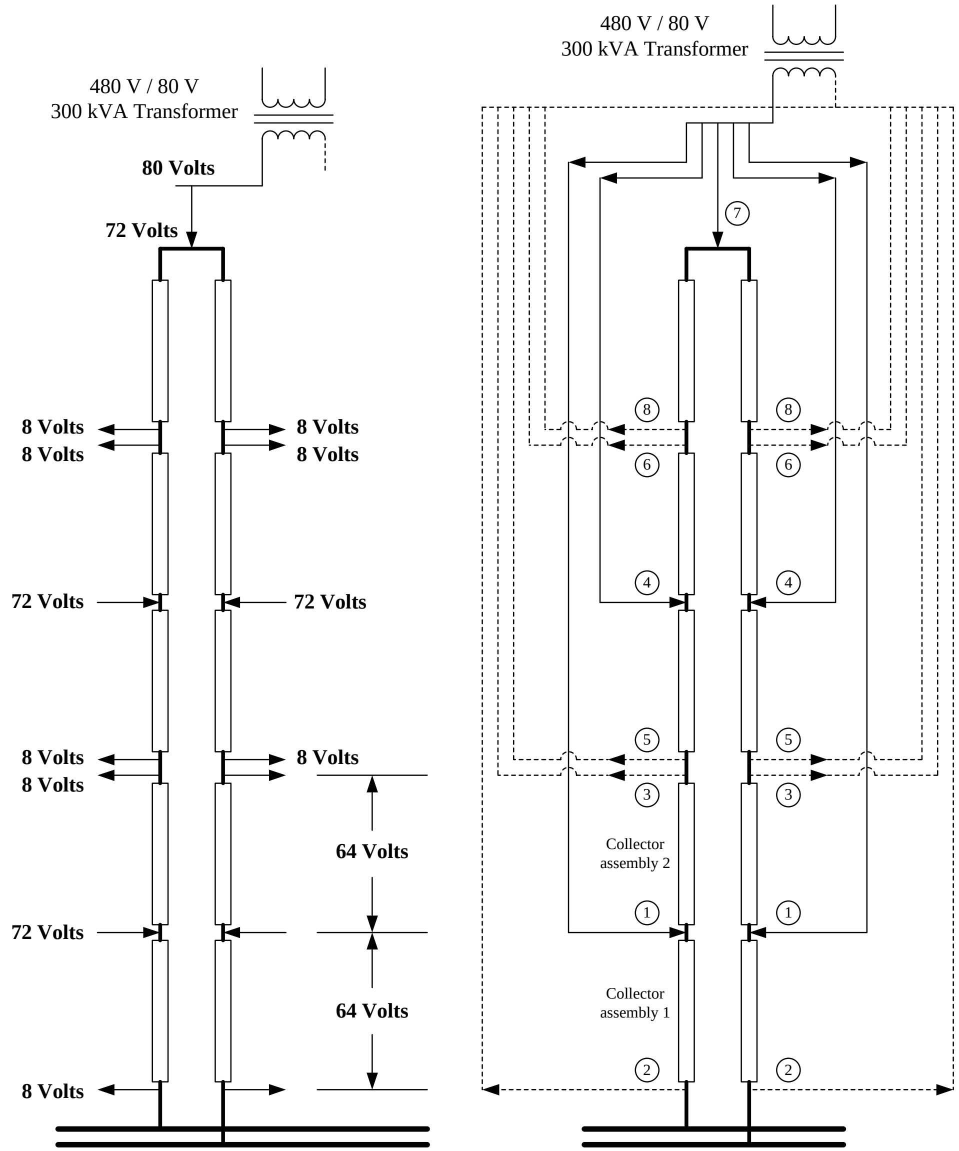
# *Salt Components*

- Joule heating
- Resistance cable heat tracing
- Pumps
- Tanks
- Steam generator
- Valves
- Instruments
- Needed, but not yet available
  - Ball joints
  - Selective surface for temperatures above 450 °C

# *Joule Heating*

## Heat collection elements

- $P = I^2 R$
- Uniform circumferential flux
- No vacuum or salt boundary penetration
- Demonstrated at ENEA and Sandia
- Considerable vendor experience



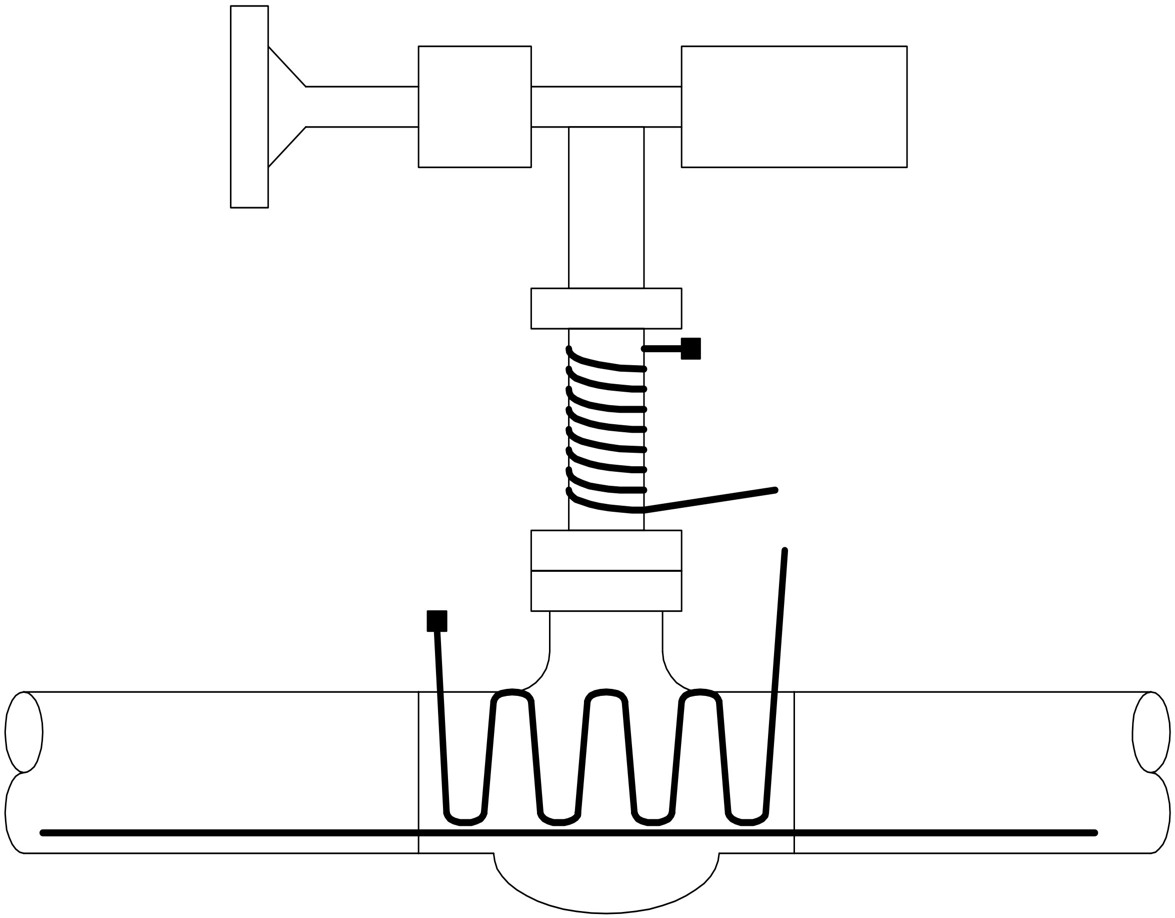
# Joule heating demonstration and analyses

# Resistance Heat Tracing

- **Description**
  - Heat exchangers, pumps, nitrate salt piping, nitrate salt valves, and Therminol piping:  Mineral insulated cables
  - Zone selection based on geometry; i.e., 1 heat exchanger would be a zone, as would a valve bonnet
  - Redundant cables provided in each zone
  - Storage tanks:  Immersion heaters
- **Suppliers**
  - Chromalox
  - Other competitive

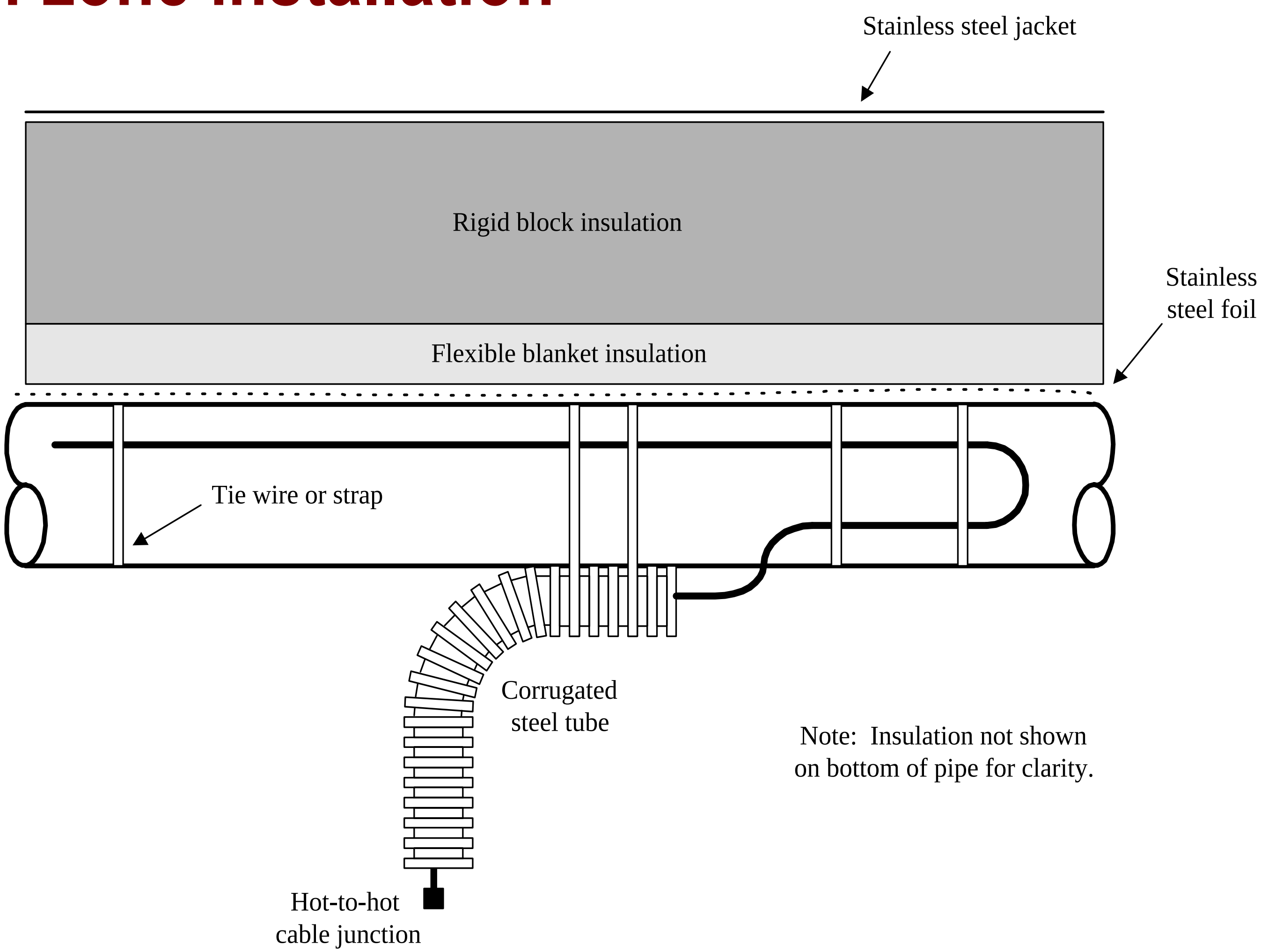
# *Resistance Heat Tracing - Continued*

## Pipe, valve body, and valve bonnet installation



# Resistance Heat Tracing - Continued

## End of zone installation



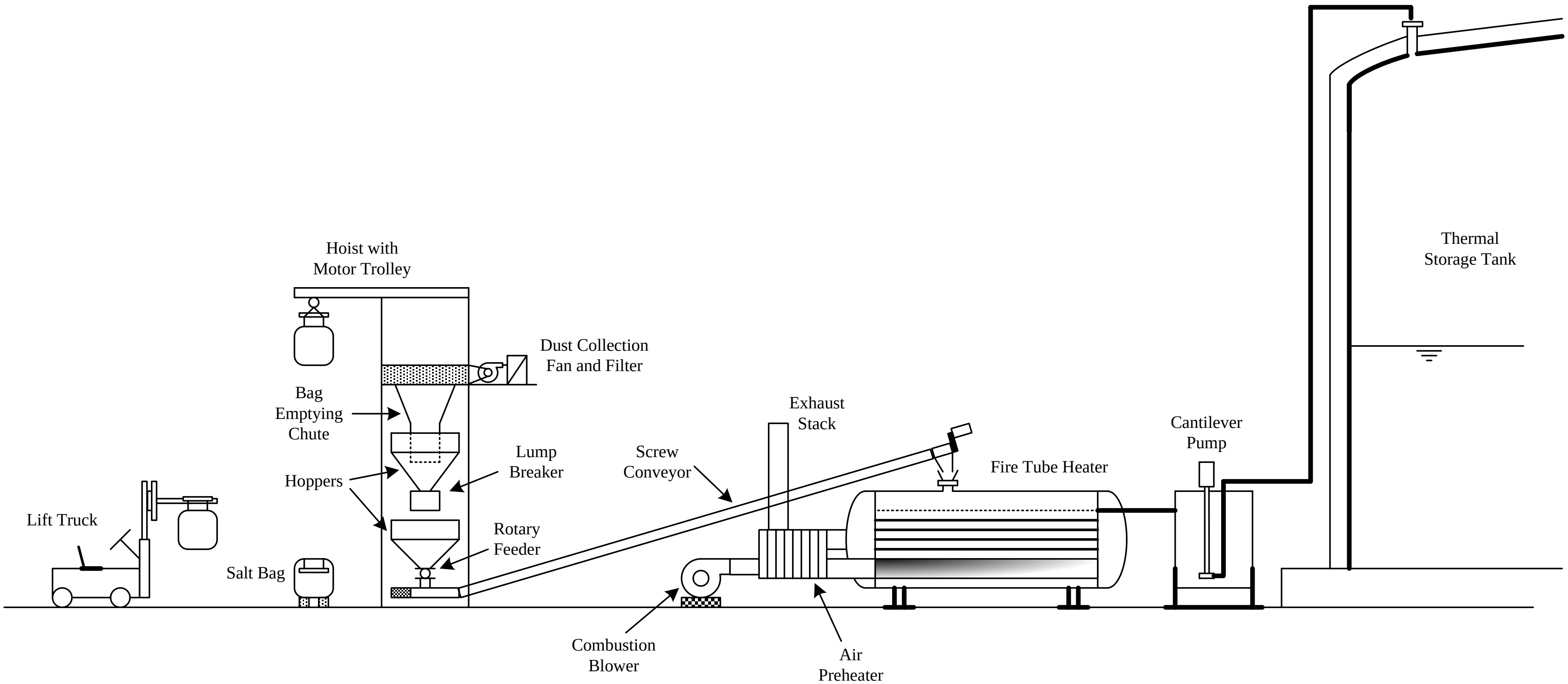
# *FRIATEC - Rheinhütte*

## High temperature pumps

# *Bertrams Heatec*

## Salt heat transfer systems

# Initial Fill of Nitrate Salt

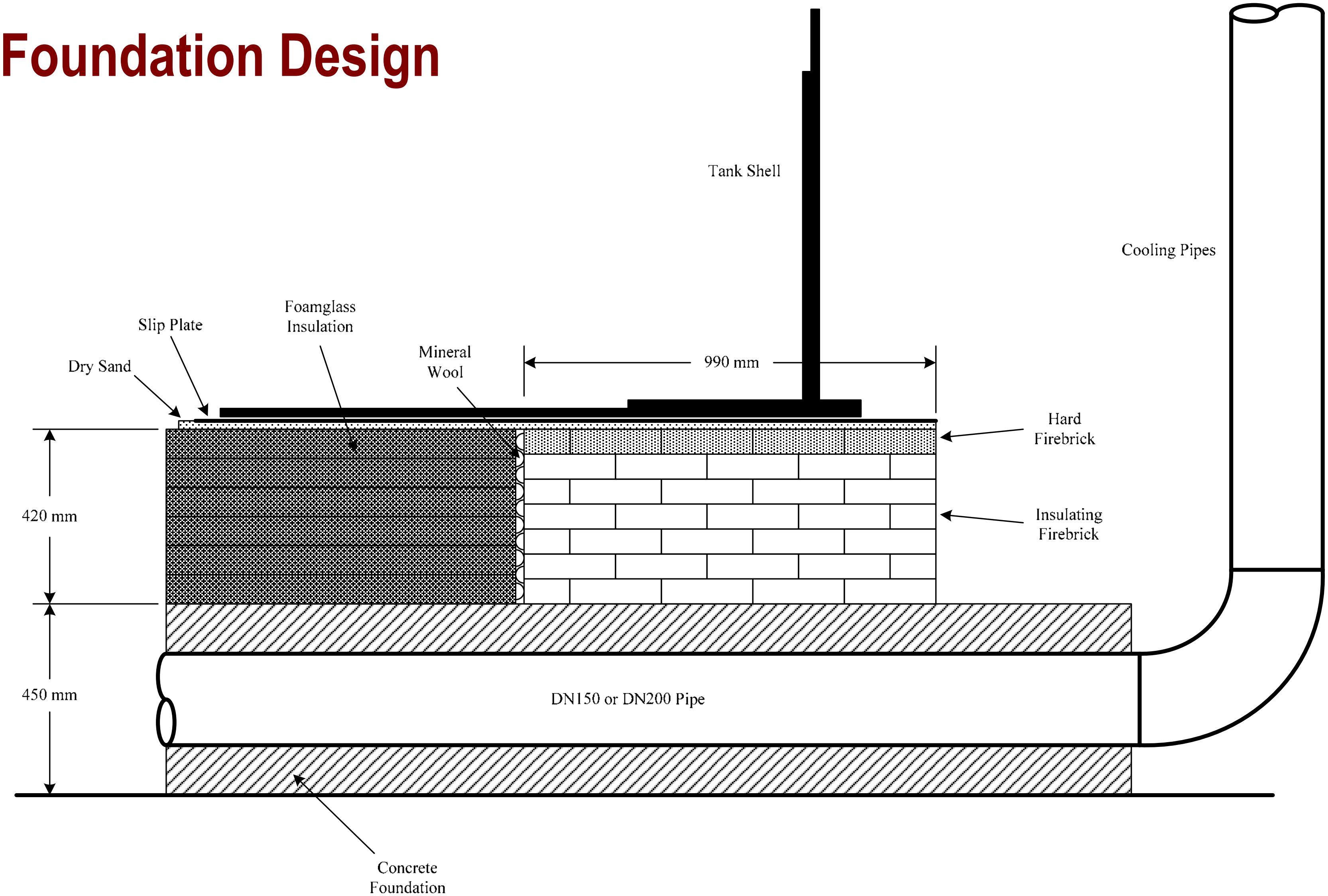


# *Two Tank Thermal Storage*

- Description
  - Vertical, cylindrical tanks with self-supporting roofs
  - Cold tank: SA 516 Grade 70 carbon steel
  - Hot tank: SA 387 Grade 91 low alloy steel for temperatures < 480 °C; SA 240 Grade 347 stabilized stainless steel for temperatures above
  - Mineral wool wall insulation; calcium silicate roof insulation
  - Foamglass and refractory brick foundation; passive air cooling

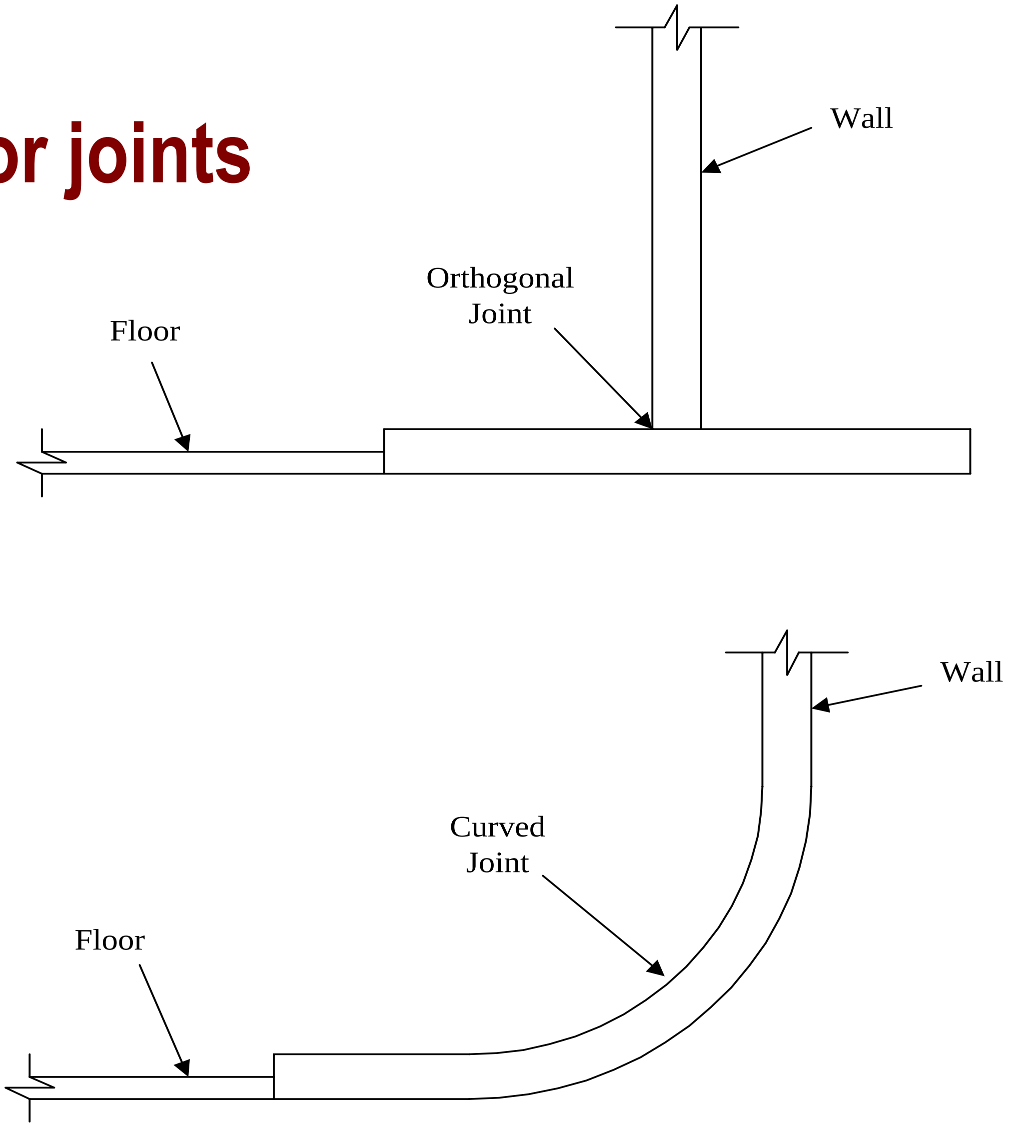
# Two Tank Thermal Storage - Continued

## Foundation Design



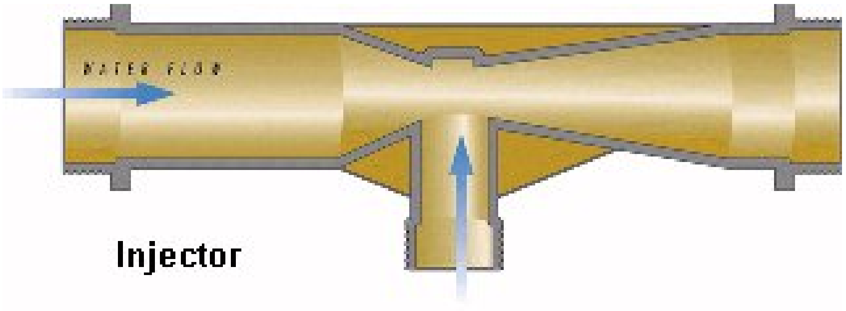
# *Two Tank Thermal Storage - Continued*

## Tank wall-to-floor joints



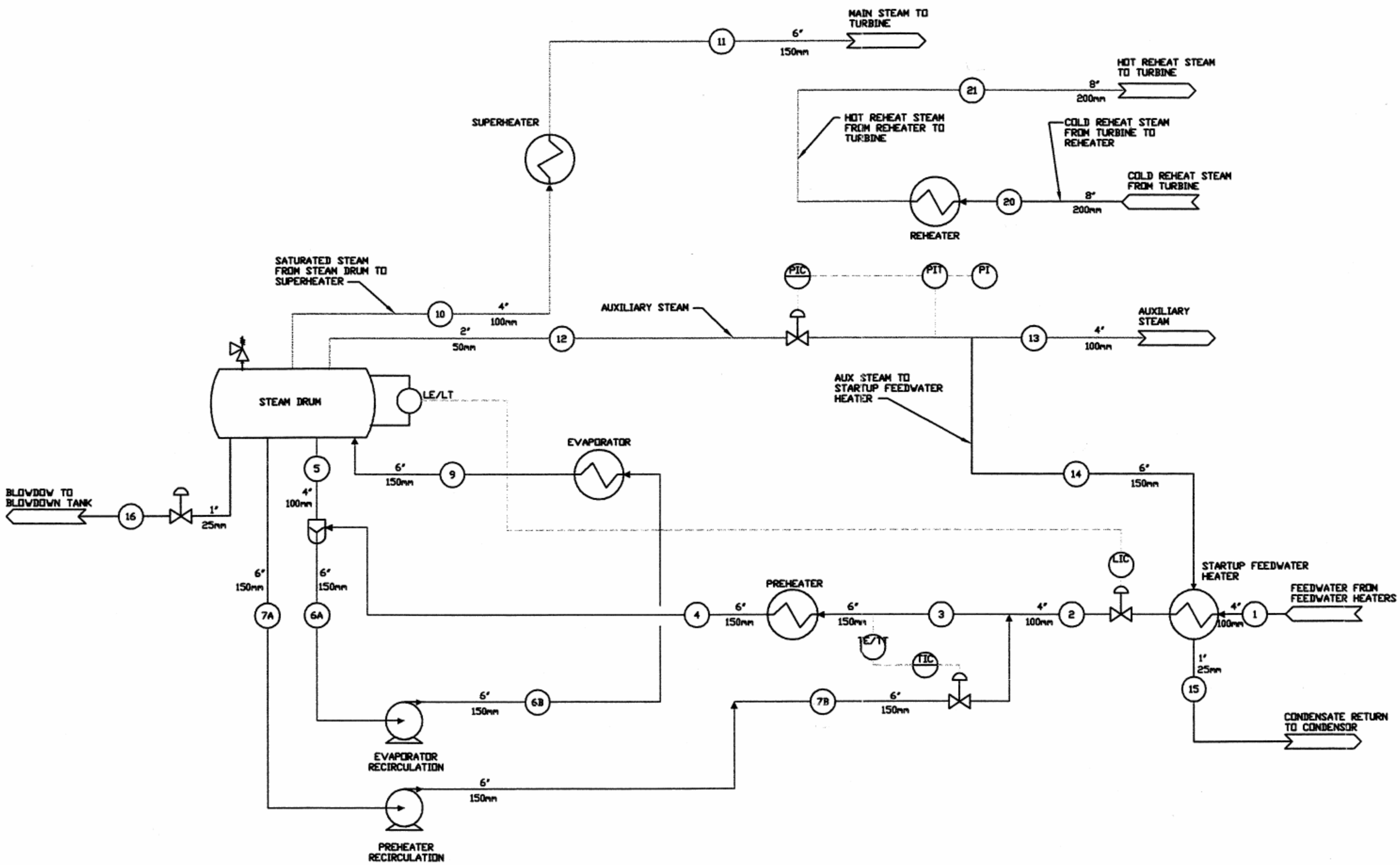
# *Two Tank Thermal Storage - Continued*

- Floor ring header with spargers
  - Limit stratification
  - Provide uniform source temperatures for steam generator and collector field




- Tank agitation
  - Fluid recirculation
  - Mechanical mixer

# Steam Generator



# *Steam Generator - Continued*

## Description

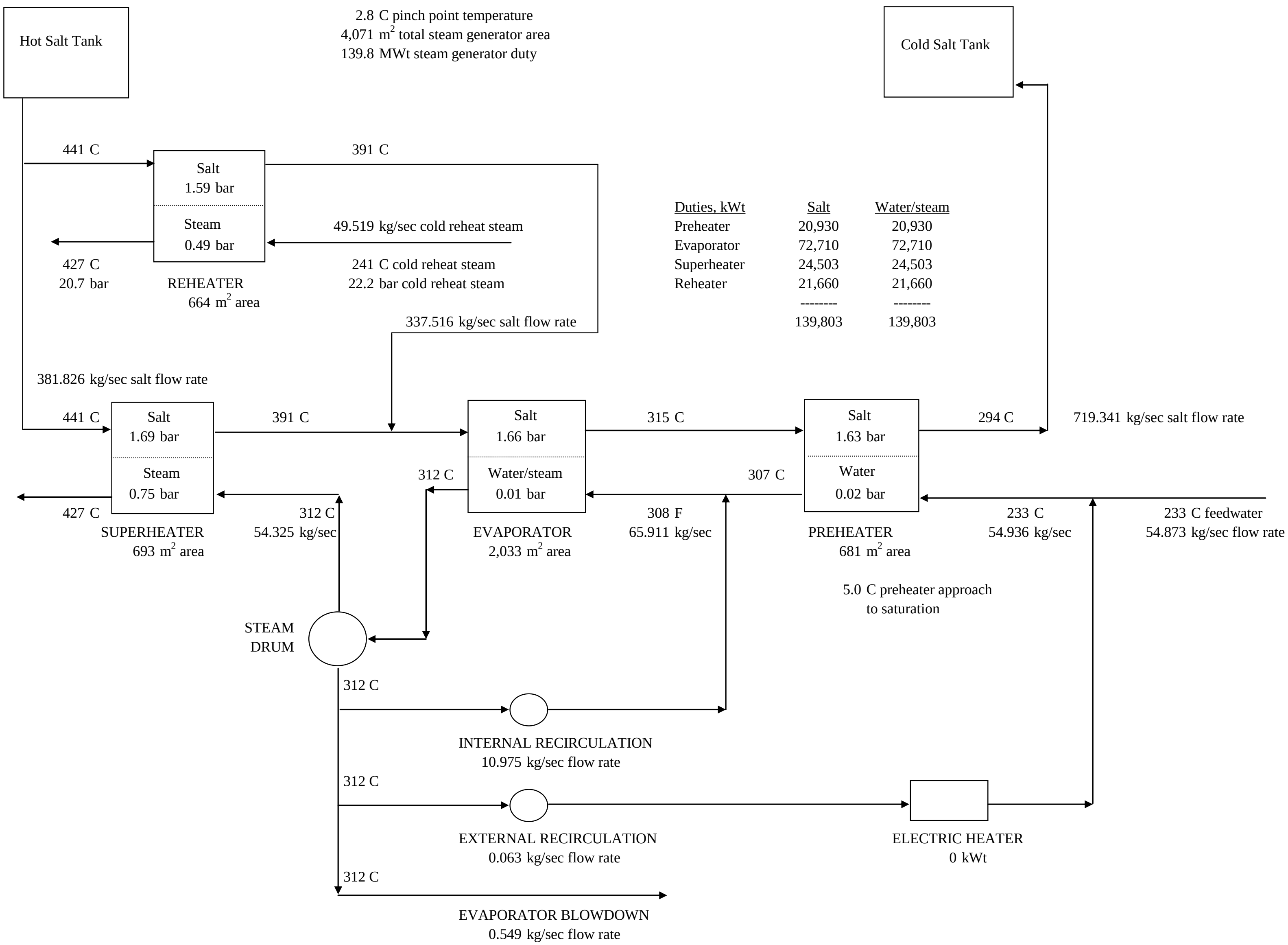
- Forced recirculation, with separate steam drum
- Separate superheater, reheater, evaporator, and preheater shells
- U-tube with straight shell and longitudinal baffle
- Nitrate salt on the shell sides, water or steam on the tube sides
- Startup feedwater heater

# *Steam Generator - Continued*

## Observations

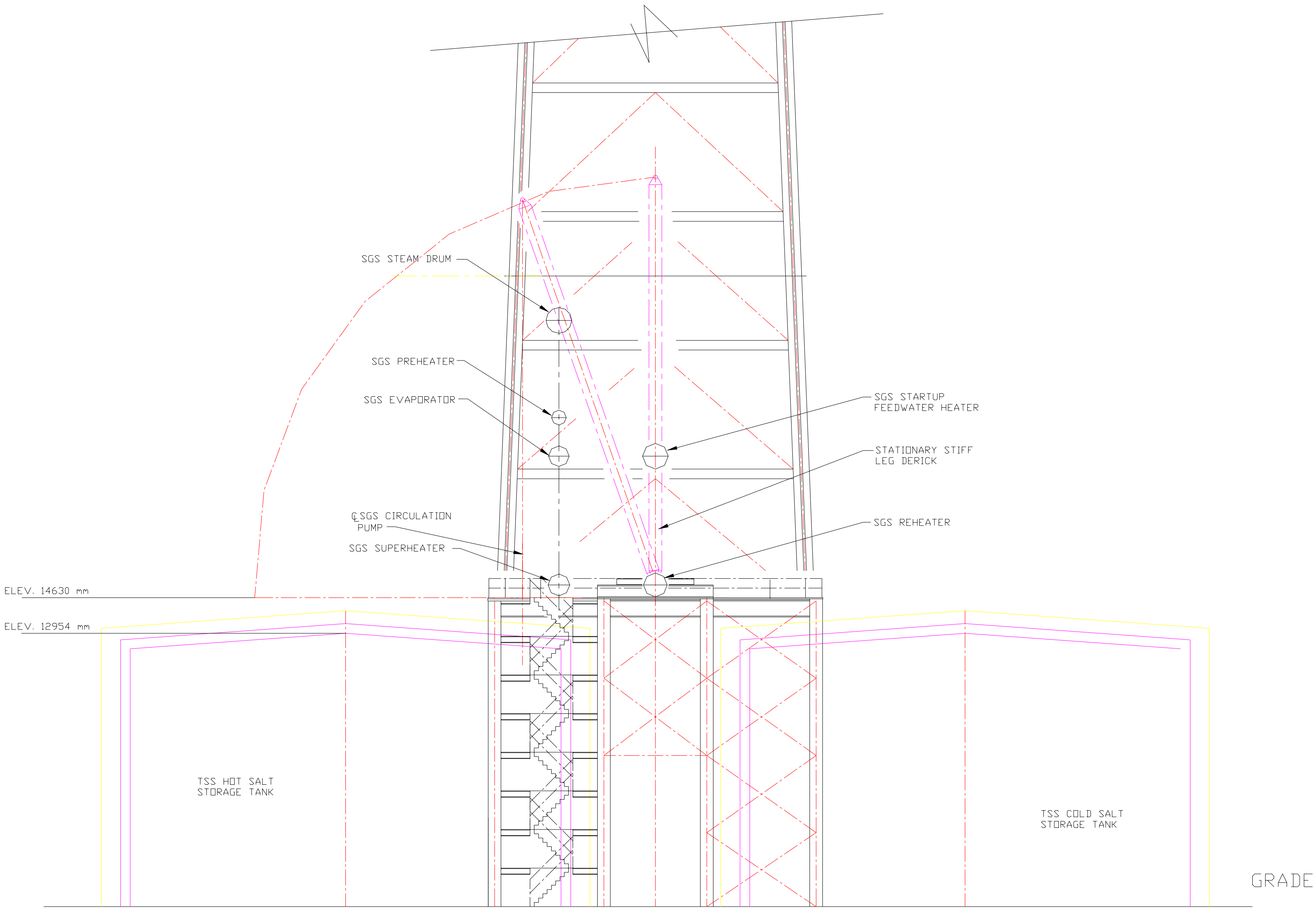
- Steam generator will operate more hours at no-load or low-load conditions than full-load conditions
- Thorough mixing must be maintained on both nitrate salt and water/steam sides at all loads
- Coupled Rankine cycle / steam generator model for part-load conditions is a necessary element
- Daily startup and routine operation was (eventually) demonstrated at Solar Two central receiver project

# Steam Generator - Continued

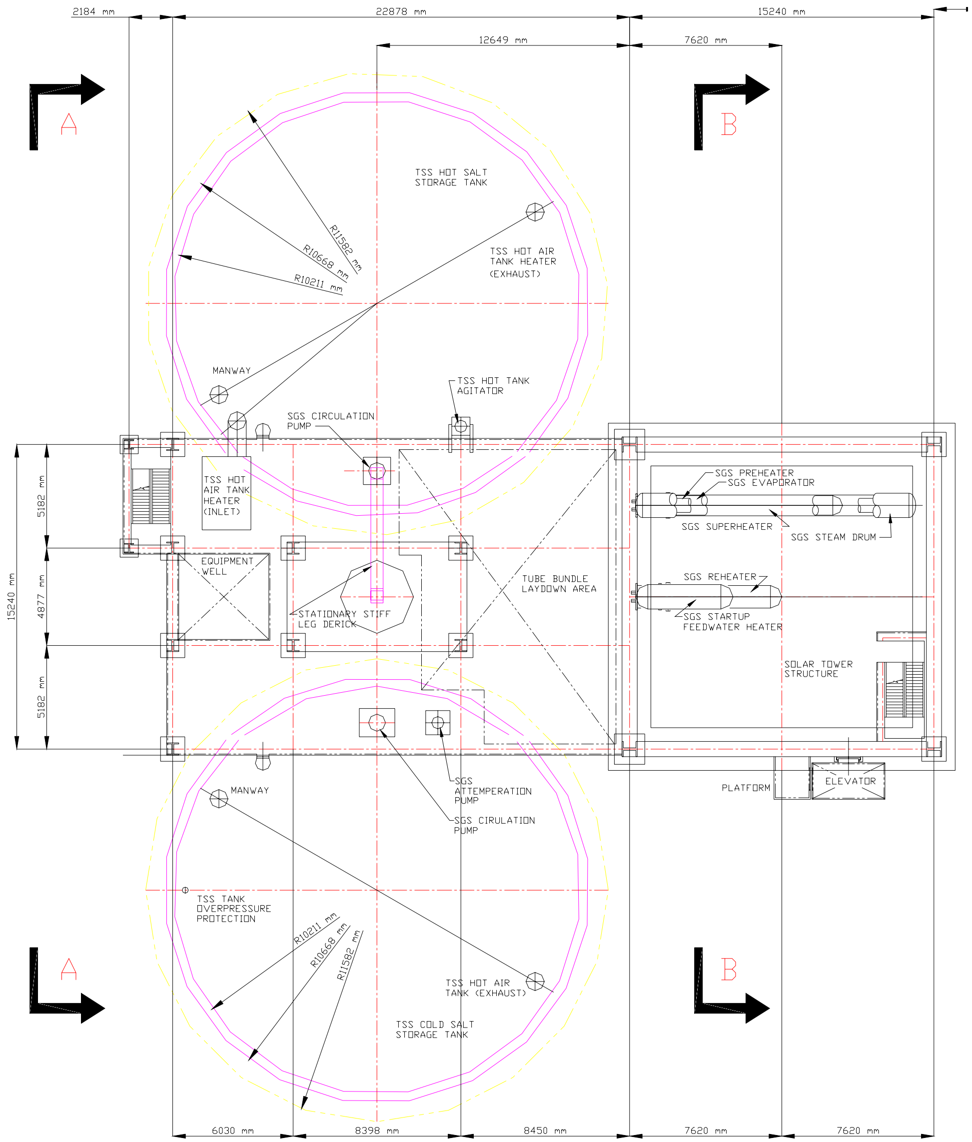



| Duties, kWt | Salt | Water/steam |
|---|---|---|
| Preheater | 20,930 | 20,930 |
| Evaporator | 72,710 | 72,710 |
| Superheater | 24,503 | 24,503 |
| Reheater | 21,660 | 21,660 |
| | -------- | -------- |
| | 139,803 | 139,803 |

# Steam Generator - Continued



# Steam Generator - Continued



# *Freeze Recovery in Steam Generator*

- **Nitrate salt is on the shell side in all heat exchangers**
- **Binary salt softens and melts over a narrow temperature range**
- **Geometry for melting salt on the shell side more favorable than on the tube side**
- **Solar Two superheater thawed once with no apparent damage**

# *Freeze Recovery in Steam Generator*

## Multiple sources of energy for freeze recovery

- Electric heat tracing on shells and channels
- Electric immersion heaters in steam drum; circulate saturated water from drum, to evaporator, to preheater, and return
- Send saturated steam from drum through superheater or reheater; exhaust to condenser

# *Nitrate Salt Valves*

- **Description**
  - ➢ **Gate valves for flow isolation, draining, and venting**
  - ➢ **Electric or pneumatic operators**
  - ➢ **Bellows stem seals, with backup combination of Teflon washers and graphite impregnated stainless steel braid packing**
  - ➢ **Catalog items only; specialty valves neither required nor desired**
  - ➢ **Globe valves are not desired; flow control is provided by pump variable speed drive**

# *FRIATEC - Rheinhütte*

## Nitrate salt valves

## *Instrumentation*

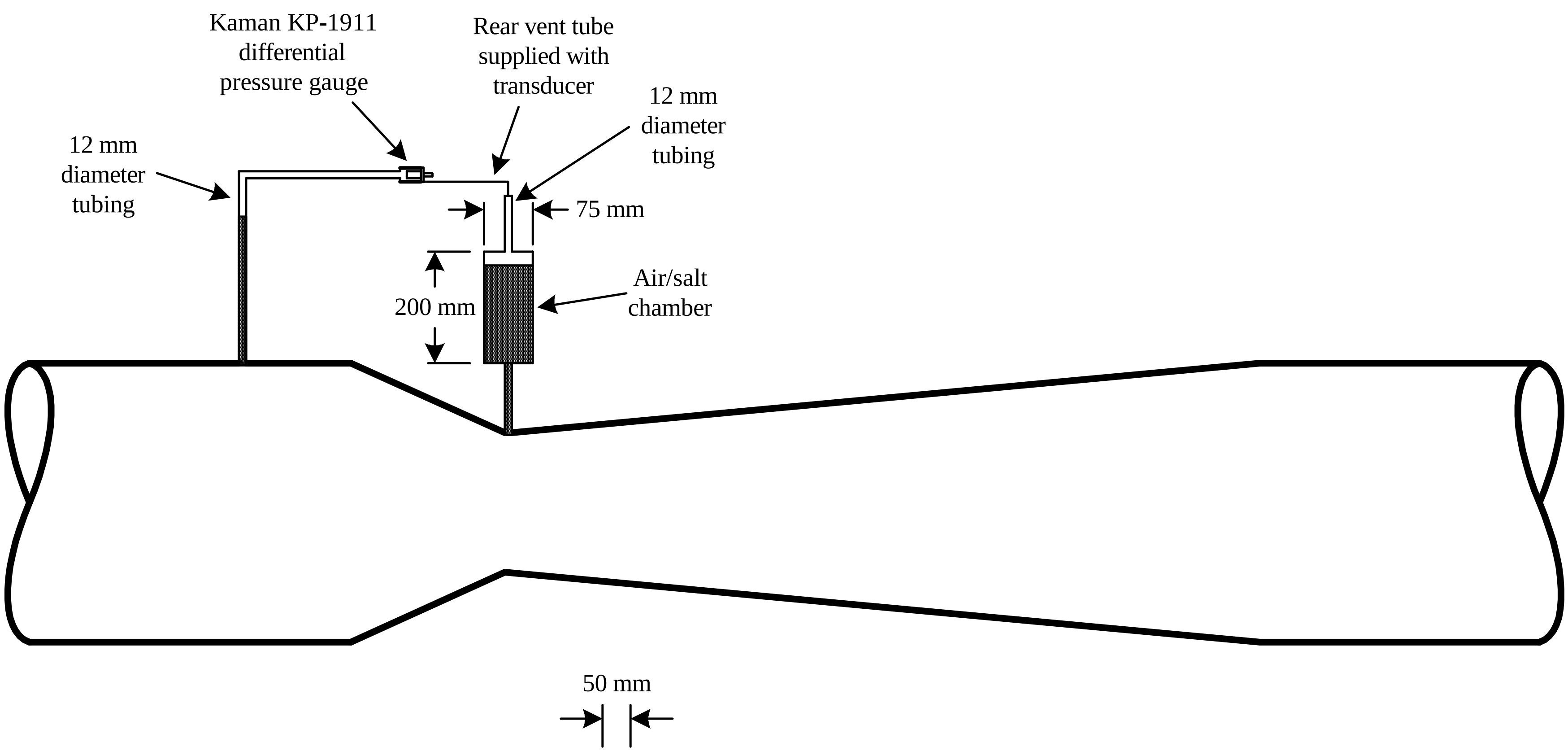
- **Description**
  - **Temperature:  Thermocouples in thermowells**
  - **Heat trace control:  Surface thermocouples or resistance temperature devices**
  - **Pressure:  Impedance coil; transmitters with remote diaphragms are not suitable**
  - **Flow rate:  Venturi, with differential impedance coil**
  - **Tank level:  Capacitance, based on dielectric properties of fluid**

# *Instrumentation - Continued*

## Design Parameters and Constraints

- Conventional capillary fluids are unsuitable, but NaK alternate requires heat tracing, and suppliers are limited
- Vortex shedding flow meters are reliable, but not available for large pipe sizes (measuring a portion of the flow may be possible), or for temperatures above 400 °C
- Impedance transducers must be kept above melting point of salt, or kept dry; salt freezing on the diaphragm ruins the transducer

# *Instrumentation - Continued*




Note: Dimensions of air/salt chamber selected to ensure nitrate salt level does not reach rear vent tube entrance at design salt flow rate and pressure.

# *Ball Joint Development*

## Sandia National Laboratories

# *Demonstration Program*

## ENEA

## *Topics*

- Concept
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# *Development Program*

- Performance models and economic analyses
- Salt analysis
- Ball joint development
- Component and system tests
  - Joule heating
  - Freeze/thaw demonstrations
  - Loop operation and maintenance
- Collector optimization

# *Performance and Economic Analyses*

- **Comprehensive study last conducted by Flabeg, Kearney & Associates, NREL, Sandia, and Nexant in 2002**
  - **Higher temperatures were beneficial only in conjunction with thermal storage; otherwise, increase in Rankine efficiency was offset by overnight thermal losses and the cost of heat tracing**
  - **A low emissivity coating for the heat collection elements was necessary**

# *Performance and Economic Analyses*

- **Recent data on prototype heat collection element emissivities, low melting point salts, and costs for multiple, large Therminol plants at a common site**
- **Confirm projected energy cost reductions for salt projects, and define applicable ranges of plant size and storage capacity**

# *Salt Development*

- **Sandia formulation**
- **Thermodynamic properties:  Melting point, density, specific heat, thermal conductivity, and viscosity**
- **Corrosion rates for carbon, low alloy, and stainless steels**
- **Eutectic stability**
- **Costs:  Capital, melting, and maintenance**

# *Ball Joint Development*

- Therminol:  Iron compression seals, a braided graphite packing, and a sealing chamber filled with graphite flakes
- In salt, graphite loss by oxidation negligible at 350 °C, appreciable at 400 °C, rapid at 500 °C
- Sandia tests
  - No suitable metal seals found
  - Boron nitride powder a possibility to replace graphite

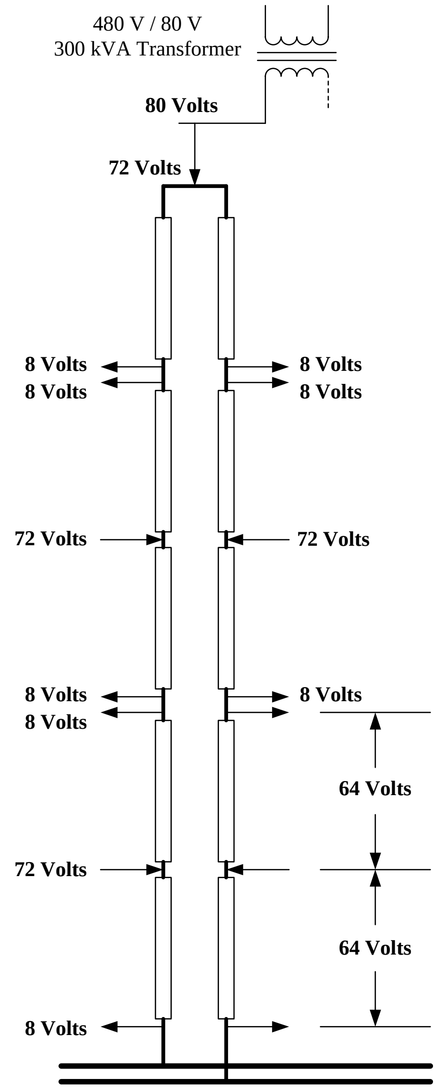
# *Ball Joint Development - Continued*

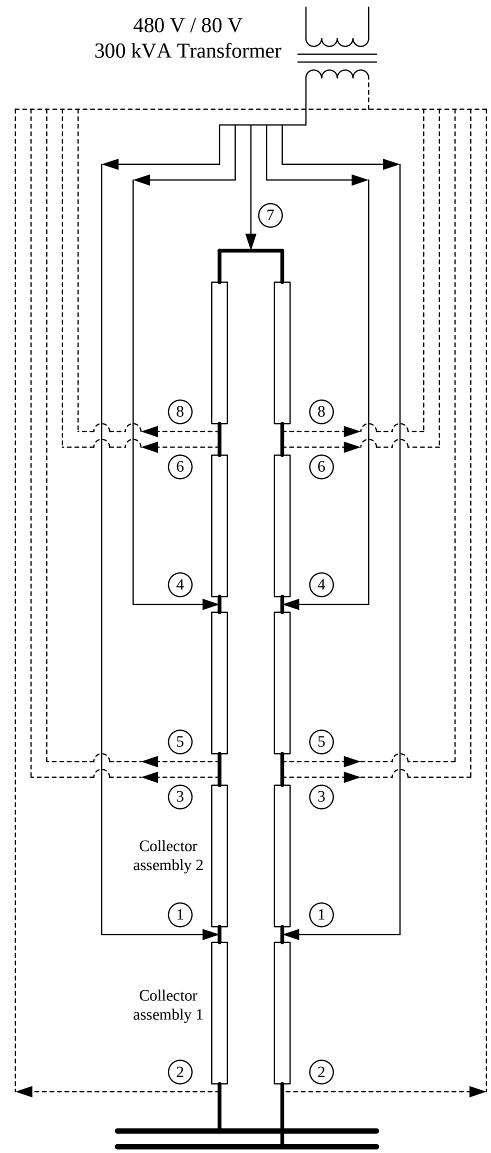
- **Internally insulated design, which maintains the graphite temperature below 300 °C, may be possible**
- **Alternate approaches**
  - **Flex hoses, with mesh liners to reduce pressure losses**
  - **Collector designs with fixed heat collection elements**

# Component and System Tests

## Joule heating

- High current, low voltages, long distances
- IEEE restrictions on maximum voltage
- Considerable vendor experience

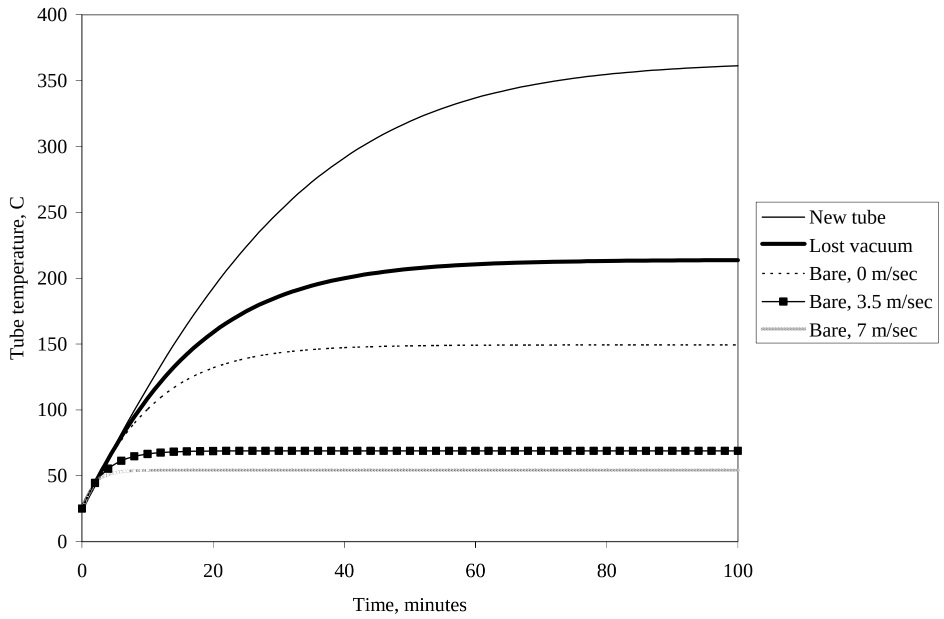


# Component and System Tests - Continued

## Joule heating

- Tests with full-size collector loop
- Current and voltage distributions over time
- Preheat and freeze recovery
  - Intact
  - Lost vacuum
  - Lost glass envelope
  - Supplemental insulation



# *Component and System Tests - Continued*

## Freeze / thaw experiments

- Heat collection element
  - Repeated freeze/thaw cycles to tube rupture
  - Demonstrate the ability to withstand a lifetime of cycles (30?) due to plant electric outages with simultaneous loss of fluid circulation and heat tracing
  - Assess supplemental insulation for tubes with lost vacuum or lost envelope

# *Component and System Tests - Continued*

## Freeze / thaw experiments - Continued

- **Heat collection element - Continued**
  - **Consider receiver tube material and tube fabrication process**

| Type | Annealed elongation, % |
|---|---|
| 301 | 60 |
| 304 | 55 |
| 321 | 45 |
| 347 | 45 |

# *Component and System Tests - Continued*

## Freeze / thaw experiments - Continued

- Collector loop
  - Inlet line, solar collector assemblies, ball joints, crossover pipe, outlet line, and isolation valves
  - Replicate geometry, thermal losses through insulation, voids during freezing, Joule/resistance heating boundaries, and various receiver conditions (intact, lost vacuum, and lost envelope)

# *Component and System Tests - Continued*

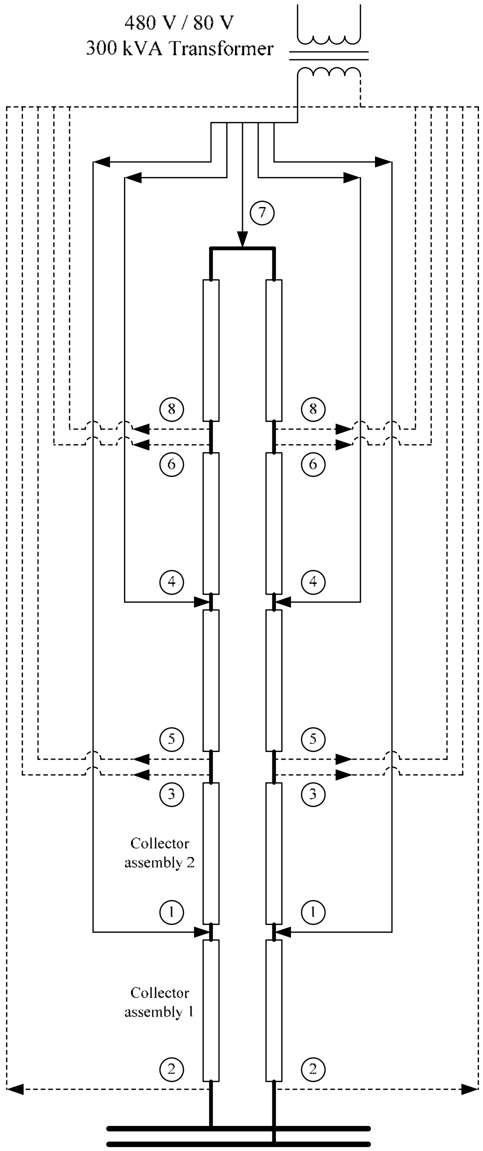
## Collector loop maintenance

- Therminol
  - Maintenance truck with vacuum tank
  - Air removed from loop prior to refilling
- Salt
  - Maintenance truck with heated vacuum tank
  - Cleaning procedures for weld zones
  - Air removed from loop prior to preheating

# *Component and System Tests - Continued*

## Collector loop maintenance - Continued

- Portable 300 kVA generator and 480 V / 80 V transformer on maintenance truck for Joule heating
- Permanent low voltage cables
- 3 trucks:  48 hours to preheat 1,000,000 $m^2$ field



# *Component and System Tests - Continued*

## Collector loop demonstration

- Lowest cost approach is to convert one loop to (binary) salt at a plant with indirect thermal storage
- Add cold salt pump, Joule heating, resistance heating, salt valves, and loop fill / drain equipment
- Outlet temperatures up to limits of selective surface
- Verify thermal performance, ball joint seals, freeze protection energy demands, and maintenance procedures

# *Collector Optimization*

## Collector tailored for salt

- Concentration ratio
- Receiver tube diameter
- High temperature selective surface
- Fixed receiver / rotating structure