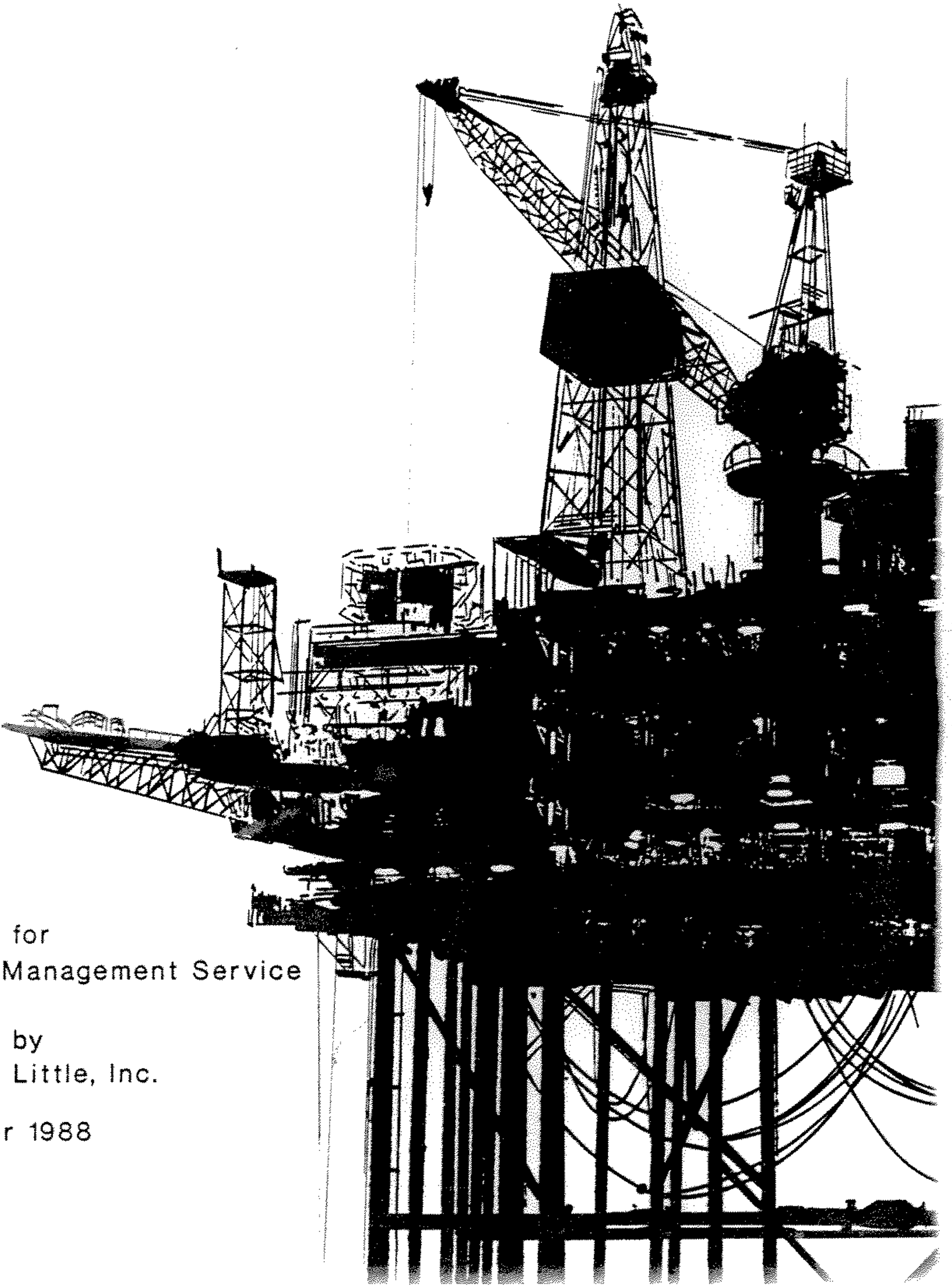
FINAL
REPORT

OFFSHORE OPERATIONS
NO_X CONTROL
DEVELOPMENT PROGRAM



Prepared for
Minerals Management Service

Prepared by
Arthur D. Little, Inc.

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OFFSHORE OPERATIONS NO_X CONTROL DEVELOPMENT PROGRAM

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for:
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1.0 INTRODUCTION

This report describes a long-term technology program to develop advanced NO_x control techniques for offshore operations. It is organized as follows:

Chapter 2, background and scope, presents background on the role of NO_x emissions related to OCS development activities. It includes a discussion on the evolution of NO_x control for offshore operations to the present day.

Chapter 3, NO_x sources for OCS development, presents a description of the equipment that are responsible for OCS NO_x emissions. Equipment types, applications, duty cycles and manufacturers are described.

Chapter 4, NO_x control techniques for offshore operation, presents a description of available and emerging NO_x control technologies that have potential applicability to offshore operations. It also presents a prioritization of these techniques vis-a-vis the requirements of OCS activities.

Chapter 5, long-term technology development program, presents the research program which has been designed to advance the most promising NO_x control technologies. Separate programs are described for gas turbines and diesel engines. Management and sponsorship of the program are also discussed.

The appendices contain more fullsome descriptions of the NO_x control technologies, describing their effectiveness, cost and critical issues related to their development. An extensive bibliography is also included.

2.0 BACKGROUND AND SCOPE

2.1 NO_X Emissions and OCS Development

Emissions of NO_X have posed as an obstacle to development of OCS reserves offshore California. NO_X is a precursor to the photochemical formation of near ground level ozone. Many of the areas in the vicinity of OCS developments are in non-attainment with the federal and state standards for ambient ozone concentrations. These regions include the areas around Los Angeles, Ventura, and Santa Barbara.

Federal standards under the Clean Air Act consider an area to be in non-attainment with respect to ozone if, for more than one hour per year, the ozone level exceeds 12 parts per 100 million. Revisions to the Clean Air Act, now in committee, might result in the adoption of a more stringent definition of non-attainment. In considering these regulations, state and local regulators as well as members of the public have developed serious concern over the adverse impacts on air quality which are associated with OCS development activities.

A variety of disputes have arisen as a result of the interest in developing OCS reserves and in protecting or improving regional air quality. One controversy is the extent of the impact of OCS emissions on onshore regional air quality. Disagreement among experts in this field still persist today. In an effort to resolve this dispute, extensive photochemical modeling has been undertaken. Another area of disagreement is the regulatory role of federal, state, and local agencies over OCS activities. Again, much of the cause for this dispute has been generated from the magnitude of the onshore air quality impact from offshore emissions.

Air quality issues and OCS development is generally seen to be in a state of conflict and dispute. This context has led to delays in implementing OCS development projects, as well as in the leasing program of the Minerals Management Service. Previous efforts at resolving the conflicts through regulatory or legal processes have added to the time required for OCS development.

The purpose of the technology development program outlined in this report is to reduce the significance of NO_X emissions as a barrier to OCS development. A large reduction in NO_X emissions from OCS development activities would lessen the concern of regulators and the public alike on the potential impacts of OCS emissions on onshore air quality.

2.2 Present NO_x Control Techniques

As part of existing OCS developments, various measures have been employed to reduce NO_x emissions. One NO_x control measure that has received considerable attention is platform electrification. This measure is viewed as an alternative project design and therefore is discussed separately.

2.2.1 OCS Control Technology

During the last five years, a considerable amount of regulatory pressure has been placed on the oil industry to install various NO_x control measures on OCS sources. Many of these controls are currently being used on the majority of new platforms offshore California. Table 2.2-1 provides a list of the NO_x control measures that are currently employed offshore. For turbines, the use of natural gas fuel coupled with water or steam injection is currently practiced on many of the new platforms. Minimizing the amount of diesel fuel used in the turbines will also substantially reduce NO_x emissions. Large reciprocating diesel engines are used on platforms as the prime movers for cranes, firewater pumps, mud pumps, and cement pumps. NO_x controls that are currently proven and acceptable for large reciprocating diesel engines include the use of California certified engines where applicable, and the use of turbocharging/intercooling with ignition timing retard. An alternative to these controls could be the use of a precombustion chamber designed engine. For crew and supply boats these same types of diesel engine controls are used. For gas fired heaters or boilers on platforms, low NO_x burners are used.

2.2.2 Electrification of Platforms

Electrification should be viewed as an alternative design for offshore platforms. The ultimate goal of this alternative is to reduce to a minimum the amount of fuel burning equipment at the platform. This could involve electrifying the platform cranes, mud pumps, cement pumps, logging units, power tongs, drilling rigs, etc.

For the case where a platform's electric power is generated by on platform gas fired turbines, the effect of electrifying various equipment is to reduce the amount of diesel fuel burned and increase the amount of gas fired in the turbines. Since gas fired turbines with water injection have lower NO_x emissions than diesel engines, the net effect of equipment electrification is to reduce annual NO_x emissions.

TABLE 2.2-1

LIST OF NO_x CONTROL MEASURES THAT ARE CURRENTLY USED OFFSHORE

Control Technology	Source Applicability
1. Use of Natural Gas as Fuel	• Turbines • Heater and Boilers
2. Water/Steam Injection	• Turbines
3. Low NO_x Burners	• Heaters and Boilers
4. Use of California Certified Engines	• Reciprocating Diesel Engines (High-Speed)
5. Precombustion Chamber Design	• Reciprocating Stratified Charged Engine
6. Injection Timing Retard	• Reciprocating Diesel Engines
7. Turbocharging and Aftercooling	• Reciprocating Diesel Engines

Platform NO_X emissions can be reduced even further by providing the necessary electric power via a subsea cable. The power can either come from the utility grid or an onshore private power generation or cogeneration facility. Both of these options while technically feasible, can be extremely expensive in terms of both capital and operating costs. This is particularly true for the utility grid option due to the cost of purchased electricity. The alternative of providing a platforms electrical needs from an onshore source must be evaluated on a project-by-project basis to determine the net cost and benefit.

2.3 Benefits of Advanced NO_X Control

All recent California OCS projects have had to offset their NO_X and ROC emissions at a considerable cost. If this trend continues, there could be insufficient offsets available to allow for increased oil development. A significant benefit to reducing the NO_X emissions from OCS sources is to reduce the need for these NO_X offsets, thereby reducing both the cost of offsets and the drain on the available offset pool. Furthermore, by minimizing the NO_X emissions associated with new projects and reducing NO_X emissions from existing OCS sources, a greater supply of OCS offsets would be created. It is this creative approach to management of OCS emissions that could allow for the maximum development in an area where NO_X emission sources are difficult to permit.

Another significant benefit to NO_X controls on OCS sources is to assist the local and state governments in achieving attainment of the federal ambient air standards. In Southern California, OCS and related sources can represent a measurable portion of the area's total NO_X emissions inventory. Helping to reduce these emissions, which can produce a net air quality benefit from new OCS projects, can only help to promote the future attainment of these federal standards.

2.4 Scope of Assignment

The scope of the assignment which was conducted by Arthur D. Little, Inc., consisted of three principal tasks:

1. Identify NO_X Emission Sources and Control Technologies
2. Outline a Technology Development Program
3. Foster Participant Cooperation

Each of these three tasks are further described below.

Task 1 - Identify NO_x Emission Sources and Control Technologies

This task consisted of:

- Review of significant OCS sources for emissions of NO_x. This consisted of a survey of major projects and the particular individual sources for emissions. For the major emission sources, typical applications and duty cycles were also analyzed.

- Review of emerging NO_x control techniques and their potential applicability to the major OCS sources of NO_x emissions. Included in this review was an analysis of the technical and financial feasibility of these measures, as well as identifying institutional issues which would impact their acceptance.

- Screening analysis of the identified NO_x control techniques to select those which appear most promising for application in OCS projects, following their development and demonstration.

The review of OCS sources for NO_x emissions is presented in Section 3 of this report. The review of NO_x control techniques is presented in Section 4, along with detailed profiles of these techniques in Appendices B and C.

Task 2 - Outline a Technology Development Program

For each of the promising NO_x control technologies identified in Task 1 a specific technology development program was outlined which, if implemented, could result in bringing the identified technology to a status where it could be considered available for OCS activities. These development program outlines, as provided in Section 5, include a description of the program elements, and estimated cost and schedules for completion.

Task 3 - Foster Participant Cooperation

In the course of conducting this assignment, many individuals and organizations which would be interested in participating in the OCS NO_x control technology development program were contacted. The technology development programs (outlined in Section 5 of this report) were developed taking into account the participation of a number of these organizations. Based upon these interactions, a number of OCS technology programs are in the process of being established.

3.0 NO$_X$ SOURCES FOR OCS DEVELOPMENT

This section provides a description and background for major NO$_X$ emission sources located in the OCS. The duty cycles of these emission sources are also described, since any control technique which is developed under this NO$_X$ control program should not interfere with normal operations.

3.1 Important NO$_X$ Sources

Chevron's Point Arguello Field Project and Exxon's Santa Ynez Unit (SYU) are the two largest Pacific OCS developments to date. The significant sources of NO$_X$ emissions from the two projects are reviewed in this section.

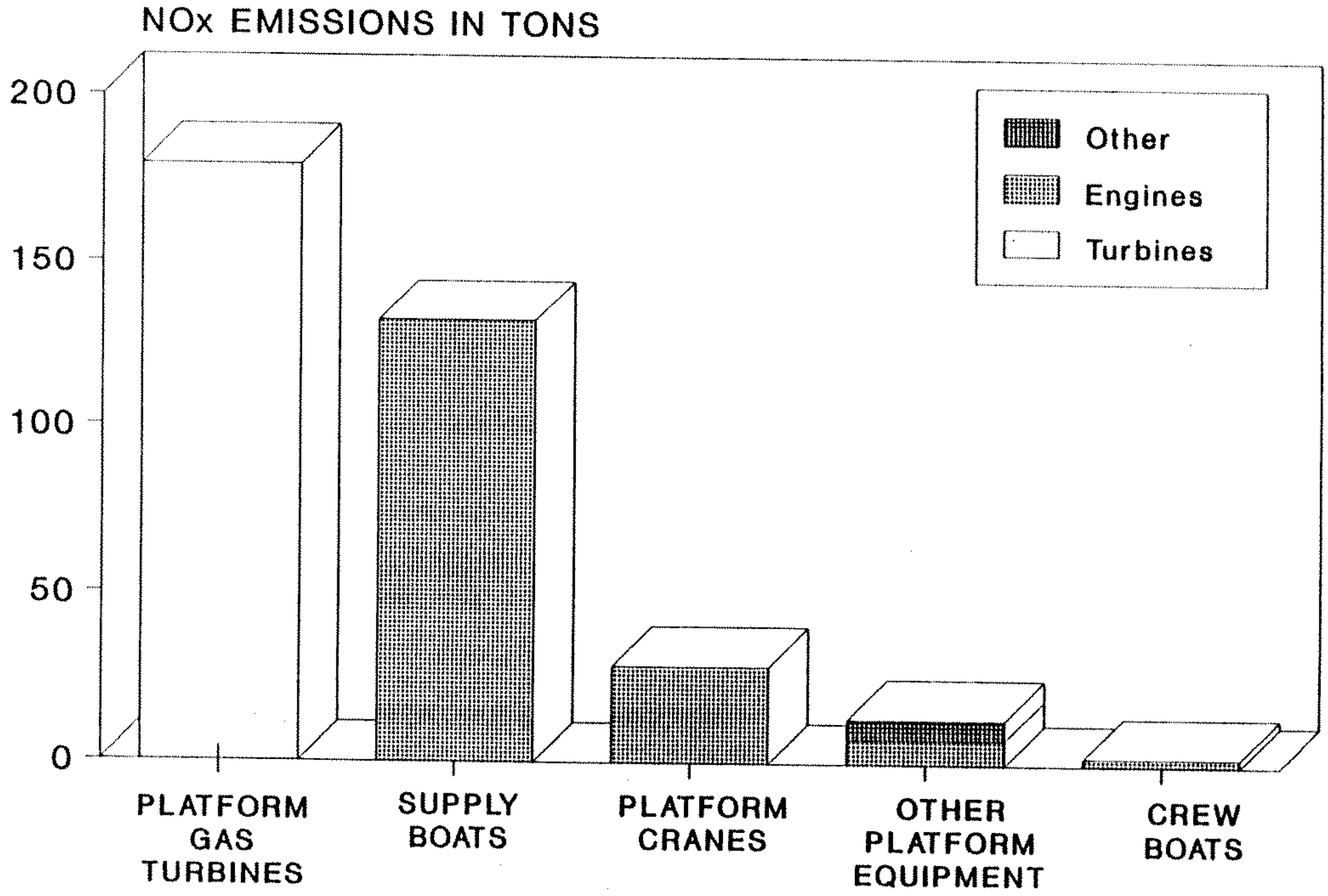
3.1.1 Point Arguello Field Project

The Point Arguello Field was discovered by Chevron in 1981, and lies in Federal waters 10-15 miles west of Point Conception, California. Primary recoverable reserves from this field are estimated at 300-500 million barrels of oil, which is 10-17 percent of the estimated 3 billion barrels in place. Chevron's initial development of the field consists of the following onshore and offshore components:

- Two Chevron oil and gas drilling and production platforms (Hermosa and Hidalgo),
- One Texaco oil and gas drilling and production platform (Harvest),
- An oil and gas processing facility capable of handling 250,000 barrels per day of wet oil and 60 million standard cubic feet per day (scfd) gas, and
- A system of consolidated offshore and onshore pipelines to carry the produced oil and gas from the platforms to the processing facility.

Figure 3.1-1 shows the major sources and amounts of OCS NO$_X$ emissions estimated from the Point Arguello Field Project for 1988. The emissions are broken down by source and equipment. As seen in this figure, the platform gas turbines will be the primary generators of

FIGURE 3.1-1
POINT ARGUELLO FIELD PROJECT
1988 OCS NOx EMISSION SOURCES



Source: Estimated Emission Liability for 1988

NO_x emissions in the Federal OCS. Drilling and production operations on the platforms will produce emissions from the following sources:

- Power generation for the operation of the drilling equipment,
- Transportation of workers and supplies to and from the platform by use of helicopters and work boats,
- Cranes, fire pumps, emergency generators, etc., operated on diesel fuel, and
- The flare pilot.

The electrical energy required for drilling and production operations on the Point Arguello platforms will be produced by gas-fired turbines driving electrical generators, equipped with a waste heat recovery system which supplies the heating requirements of the platform. Water injection is used on the platform's gas turbines to reduce NO_x emissions by up to 70 percent from uncontrolled levels. NO_x emissions from platform gas turbines are expected to reach 180 tons in 1988.

Chevron and Texaco have planned to primarily use helicopters for crew transport and boats to carry supplies to the platforms. Port Hueneme will be used as the supply base, although it is over 120 miles to the southeast of Point Conception. It was calculated that supply base support activity emissions for 1988 in the OCS would produce 132 tons of NO_x, the second highest source in the OCS for this project.

The standby power on all platforms will be provided by diesel powered generators, until fuel gas becomes available from production wells. Diesel fuel will be used for power generation during initial platform start-up, or in case of emergencies. Platforms Hermosa and Hidalgo each are equipped with two large 335 hp diesel cranes, which will produce approximately 30 tons per year of NO_x.

3.1.2 Santa Ynez Unit

The Santa Ynez Unit (some 83,000 acres) is believed to contain the largest undeveloped oil reserve in the lower 48 states. Exxon estimates that approximately 300 to 400 million barrels of oil, and 600 to 700 billion standard cubic feet of natural gas could be produced through primary recovery over 25 to 35 years.

The first phase of Exxon's development consisted of one offshore platform named Hondo placed on the Hondo Field, and an offshore production vessel known as the Offshore Storage and Treating Vessel, (OS&T). Platform Hondo was installed in 1976, and its 28 wells were built to provide 40,000 barrels of oil and 30 billion standard cubic feet of gas per day. The platform supports a drilling rig, production equipment, and personnel quarters.

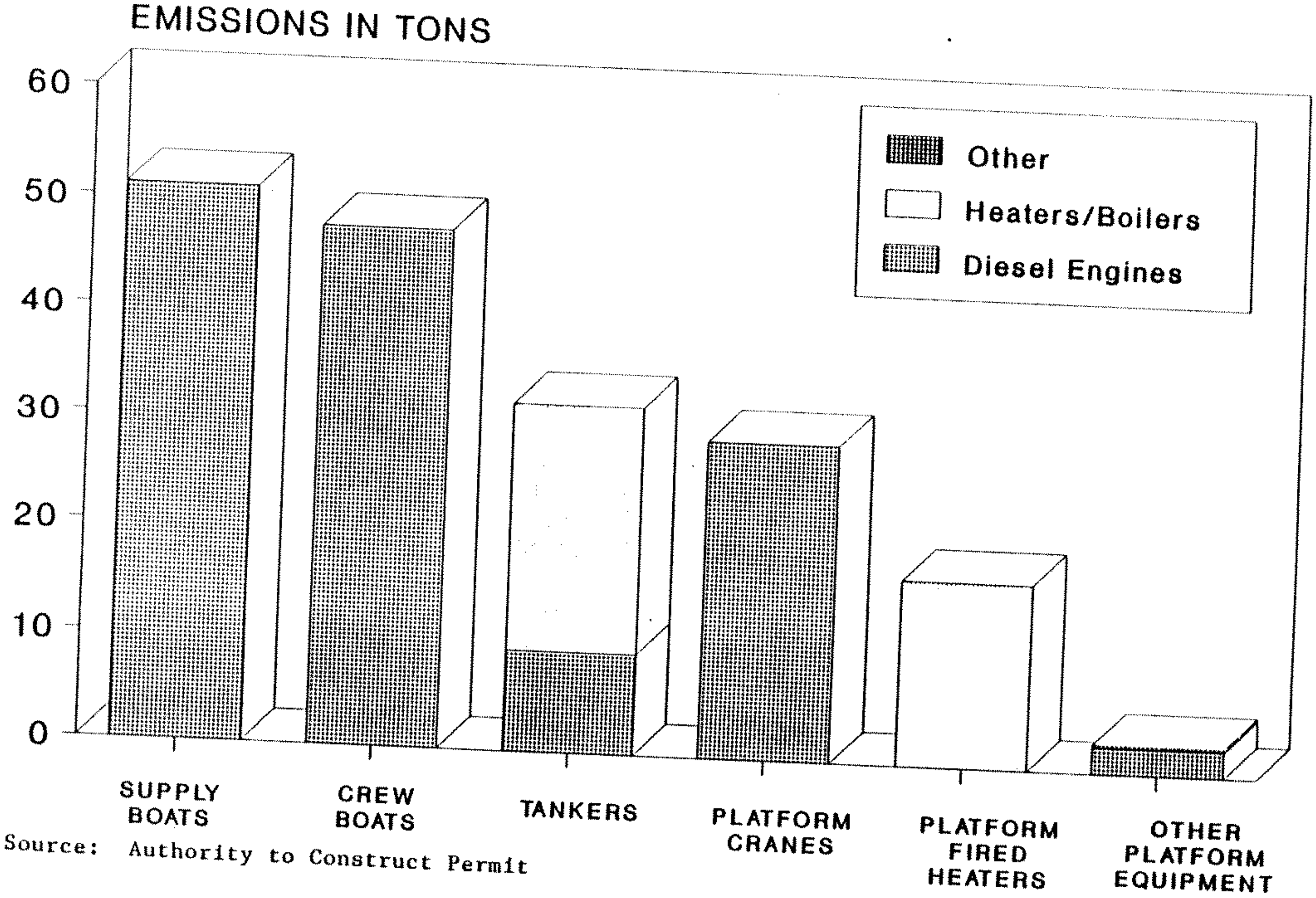
In early 1988, Exxon obtained the final permits required to expand their offshore and onshore facilities. The new components include three drilling and production platforms (Harmony, Heritage, and Heather), and a Single Anchor Leg Mooring (SALM) in nearshore waters, onshore oil and gas treating facilities, and a cogeneration power plant. The OS&T will be decommissioned when the new onshore oil and gas treating facility, being built in Las Flores Canyon, can process the platforms' production. Exxon's new expanded project design incorporates electrical power to the platforms from a nominal 49MW cogeneration facility. This design provides a substantial emission reduction and reduced air quality impacts over the usual on-platform turbine generators such as are used for power in Chevron's Point Arguello Project. Onshore Best Available Control Technology (BACT) will be placed on the cogeneration facility, reducing the gas-fired turbine NO_X emissions by up to 90 percent.

As shown in Figure 3.1-2, major sources of air emissions from drilling and production offshore include crew and supply boats, tankers, crane engines, process heaters, and other platform equipment such as emergency generators and firewater pumps. Figure 3.1-2 also shows the NO_X emissions from the types of equipment used on the platform during production. Diesel engines are the major contributor to NO_X emissions related to the SYU.

Crew and supply boats will service the platforms BACT and these boats will include turbo charging/intercooling and ignition timing retard or the equivalent. Crew boats will be based out of Ellwood Pier, and supply boats will be based from Port Hueneme. Oil will be taken out of the Santa Barbara Channel by tankers, being pumped through a subsea pipeline from onshore storage tanks to the SALM, and then loaded on to the tankers. Tanker operations are expected to produce 32 tons of NO_X a year in the OCS.

To reduce air emissions in the future, Exxon has agreed to look at the economic feasibility of using the All-American interstate pipeline to Texas to transport their crude once this pipeline is completed. This would eliminate all the NO_X emissions generated by tanker traffic for the SYU Project.

FIGURE 3.1-2
SANTA YNEZ UNIT PROJECT
ESTIMATED ANNUAL OCS NOx EMISSIONS



Source: Authority to Construct Permit

3.1.3 Other Projects and Sources

The two OCS development projects described in the previous sections are the largest Pacific OCS projects to date. In addition, they represent developments where a single project includes production platforms, transportation facilities, and processing capabilities for different offshore fields located in the same general area. This type of development, owing to its efficiency from economies of scale, is preferred by regulators and developers as the course for development of OCS reserves.

NO_X emissions do vary significantly among projects. There are a number of factors which affect OCS emissions of NO_X. The main phases of development which produce emissions are:

- Exploratory Drilling
- Construction
- Production

Of these three, production generates by far the largest quantity of emissions. However, aspects of the other two will be considered in the context of this program as contributors to OCS NO_X emissions.

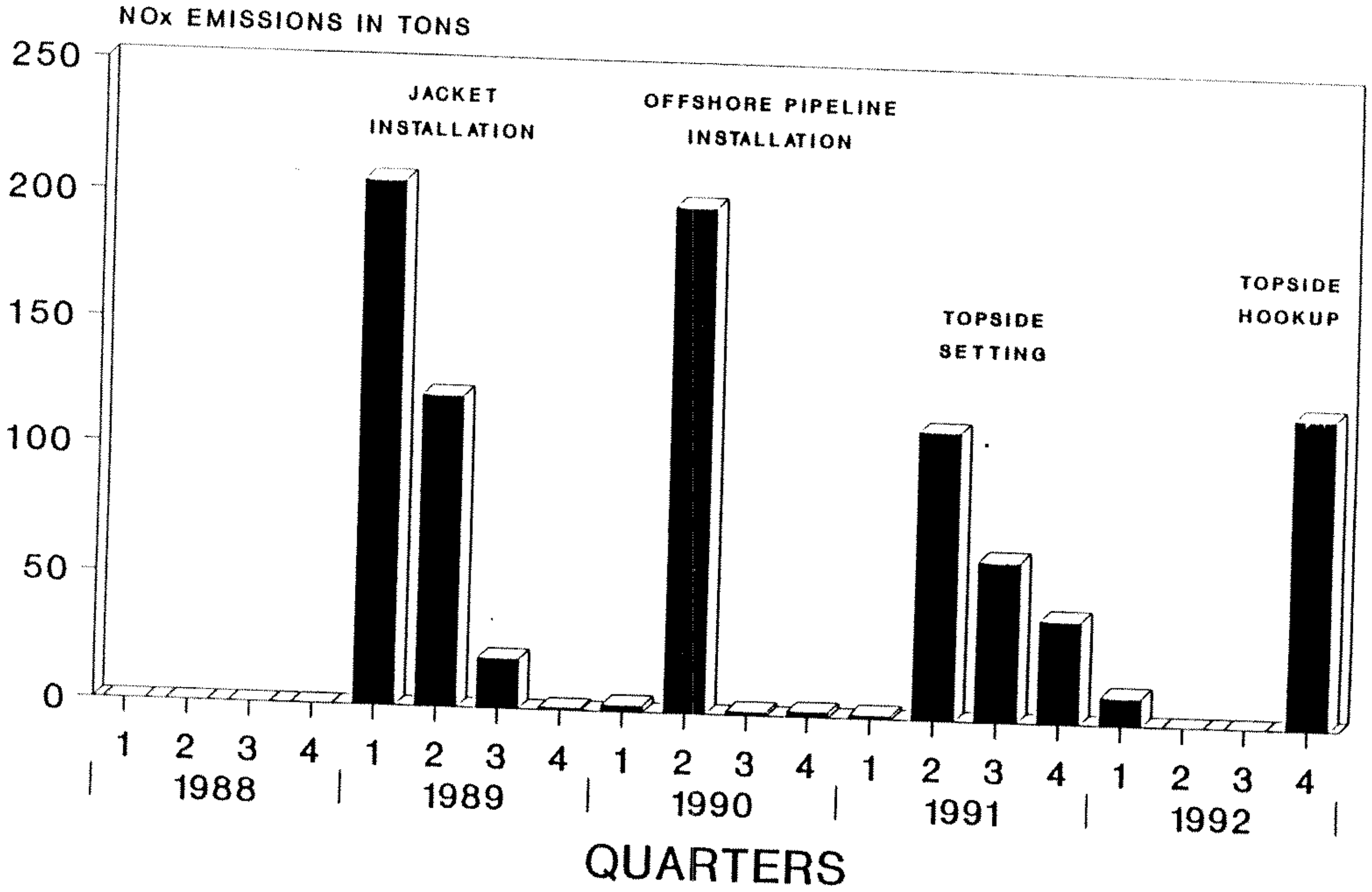
Exploratory Drilling

Exploratory drilling on an individual tract can last for a period of several months. As the power requirements of drilling platforms (semi-submersibles or jack-ups) or of drill ships are large, the NO_X emissions from these sources are significant while the rigs are deployed. Furthermore, emissions from exploratory drilling operations are of interest due to their timing in the sequence of development.

Construction

Construction of offshore facilities can take a number of years to complete. However, peak construction activities typically last for a shorter period of time. Figure 3.1-3 shows the estimated NO_X emissions from the offshore portion of Exxon's Santa Ynez Unit over the course of its five year construction schedule. Emissions of NO_X can vary significantly over the construction period. In Figure 3.1-3 peaks are seen during jacket installation, offshore pipeline installation, topside settings, and topside hook-up.

FIGURE 3.1-3
SANTA YNEZ UNIT PROJECT
ESTIMATED OCS CONSTRUCTION NOx EMISSIONS



Production

The level of production emissions are dependent on a variety of factors, such as the project methods for power generation and the type of support transport, production strategy, and production enhancement methods. The use of helicopters instead of crew boats can significantly reduce emission levels associated with the transport of personnel. As mentioned before, helicopters are used as the primary crew transport mode for the Point Arguello Field Development. Electrification of platforms can also reduce emissions considerably, yet at great cost. According to current permit conditions, Platform Hacienda when installed in the Point Arguello Field, will be connected to the electric utility grid. Oil and gas properties, and the oil to gas ratio can also affect power needs.

In spite of all the variables which can affect NO_X emissions from OCS developments, the primary sources of emissions are those stemming from power generation and marine transport.

3.1.4 Priority NO_X Sources

The purpose of the review of NO_X sources from OCS developments is to identify the ones which pose the most significant barriers to the development of OCS reserves. The two criteria used in determining this status are the quantity of NO_X emissions and the timing of those emissions. From this analysis, the most important NO_X sources are:

- Production platform gas turbines,
- Crew and supply boat main engines, and
- Exploratory drilling rig diesel engines.

Typical applications, manufacturers, and duty cycles for these three sources are described in the following sections.

3.2 Production Platform Gas Turbines

As explained above, production platform gas turbines have been identified as being one of the most significant sources of NO_X emissions associated with OCS development projects. Platform gas turbines are commonly used for power generation when coupled to electrical generators. Additionally, the turbines are sometimes used as prime movers for platform gas compressors. Whether they are used for power generation or as prime movers, the gas turbines are frequently outfitted with waste heat recovery units. These units utilize the waste heat in the turbine exhaust gas to heat a medium such as an organic heat transfer fluid. With the waste heat recovery, the gas turbines are an energy efficient means of providing both useful thermal energy and shaft power for a variety of production platform purposes.

Typical platform gas turbines have a maximum continuous rating of about 4,000 horsepower. Both industrial type turbines (pressure ratios less than 10 to 1) and aeroderivative turbines are used in OCS applications. Various configurations of the Allison 501 engine and the Solar Centaur engine are most commonly found in OCS applications in the Pacific region.

Water injection is presently used for NO_x emission control on platform gas turbines. Actual tests indicate that water injection at a ratio of 0.8 lb water per pound fuel reduces NO_x emissions by about 70 to 75 percent from their uncontrolled levels. Manufacturers guarantee approximately 60 percent NO_x emission reduction at full rated load with this water injection level.

Platform gas turbine generators operate in a load following manner. Thus the output of the machines can vary over time as a function of demand for electricity on the platform. Their duty cycles can be estimated by examining the individual load centers. The major load centers are:

- Gas Compression,
- Oil Pumping,
- Drilling (when drilling),
- Oil and Gas Processing,
- Production Enhancement (if applicable), and
- General Platform and Quarters.

Power requirements for gas compression, oil pumping, and processing will vary with the rate of production. Similarly, production enhancement (gas lift, downhole submersibles, etc.) is related to the levels of production. The load for general platform requirements and crew quarters can be expected to show a nighttime increase due to the lighting of the platform.

The operation of drilling equipment can be expected to have the most significant impact on load variations. This would be especially true during the early stages of drilling, when the quantity of fluids being produced is small and thus the loads from other requirements (except general platform and crew quarters) would also be small. The drilling rig itself represents a large load. Its mode of operation is such that large fluctuations of demand could be expected rather frequently.

Although reviewing the causes of load variations is helpful in understanding why a unique duty cycle is experienced by turbine generators in OCS applications, there is a scarcity of published data on the duty cycles of these turbines. Thus, one of the testing programs which is outlined in Section 5 of this report is a program to monitor the duty cycles of gas turbines during drilling operations. As drilling represents the most varied duty cycle under which OCS turbines could be expected to operate, a quantification of this duty cycle would represent a worst case for analysis.

3.3 Crew and Supply Boats

Oil production and exploration from California's offshore platforms is directly dependent on receiving support services and equipment from onshore sources. The most common procedure to transport personnel and supplies from shore to the platforms is through the use of crew and supply boats. These boats are usually based out of the closest possible onshore location to the platform serviced, and the base must have the necessary services and equipment needed to adequately support the operations of the platforms.

Along California's central regional coastline, Port Hueneme is generally used as a supply base, and Ellwood and Carpinteria are frequently used as crew landings. For projects located too far from a crew port to make crew boat trips economically feasible, helicopters are generally used for transport, and are based out of the Santa Barbara and Santa Maria Airports. As described previously, Chevron has opted to use helicopters in their Point Arguello Field Project as the primary means of transporting their personnel to and from the shore, since their platforms are located over a hundred miles away from Carpinteria Harbor.

Support boats that are used for OCS oil operations can vary in their size and design. Depending on the engines used on the boats, the emissions produced can be diverse. Emission rates are also dependent on the duration of time the boat is operating, and the amount of time the boat is idling.

A survey was recently conducted on crew and supply boats operating in the Santa Barbara Channel. The survey items included boat and engine type, as well as some of the boat's operating parameters. Specifications of the study are presented in Table 3.3-1. All but one supply boat were based out of Port Huemene, and the crew boats came from either Carpinteria or Ellwood.

TABLE 3.3-1

OIL AND GAS WORK BOATS
SANTA BARBARA CHANNEL

OWNER	BOAT NAME	OVERALL LENGTH	BOAT TYPE	MAIN ENGINES NUMBER	MANUFACTURER *	MODEL	ENGINE SPEED (RPM)	ENGINE OUTPUT (HP)
C & C BOATS	Aces Wild	97	Crew	3	DDA	12-V-71-TI	1750	500
C & C BOATS	Aces High	96	Crew	3	DDA	12-V-71-TI	1750	500
FARRIS MARINE	Samuel B.	78	Utility	2	DDA	8-V-71	1500	250
FARRIS MARINE	Samson	43	Utility	1	DDA	6-71	1500	165
JACKSON OFFSHORE	Clipper Hamilton	100	Crew	3	DDA	12-V-71-TI		539
JACKSON OFFSHORE	Clipper Larry	100	Crew	3	DDA	12-V-71-TI		539
OFFSHORE TANKER SERVICE	Sea Rich	110	Crew	4	DDA	12-V-71	1800	450
OFFSHORE TANKER SERVICE	Mr. Clean	135	Special	2	DDA	12-V-149	1200	800
LOGAN AND LOGAN, INC.	Crow Arrow	140	Supply	2	DDA	12-V-149	1800	700
LOGAN AND LOGAN, INC.	Nautilus I	116	Utility	2	DDA	16-V-92	1800	600
TIDEWATER MARINE SERVICE, INC.	Alberta Tide	194	Supply	2	EMD	16-645-E7	900	2875
TIDEWATER MARINE SERVICE, INC.	Toby Tide	180	Supply	2	CAT	D-399	1200	1125
TIDEWATER MARINE SERVICE, INC.	Uric Tide	180	Supply	2	CAT	D-399	1200	1125
TIDEWATER MARINE SERVICE, INC.	Manny Tide	65	Crew	2	DAA	12-V-71	2100	510
TIDEWATER MARINE SERVICE, INC.	Murdock Tide	65	Crew	2	DAA	12-V-71	2100	510
TIDEWATER MARINE SERVICE, INC.	Smith Tide	65	Crew	2	DAA	12-V-71	2100	510
HALLIBURTON SERVICES	MV22	180	Supply (Drilling)	2	CAT	D-398	1225	850
DOWELL SCHLUMBERGER	Big Orange 23	217	Supply (AHTS)	3	DDA	V-16-149TI	1800	1800
ZAPATA GULF PACIFIC INC.	Tampa Seahorse	160	Supply	2	CAT	D-398-TA	850	850
ZAPATA GULF PACIFIC INC.	Gulf Fleet 69	190	Supply	2	EMD	12-645-E7C	900	2305
ZAPATA GULF PACIFIC INC.	Gulf Fleet 49	185	Supply	2	CAT	D-399-TA	1225	1125
ZAPATA GULF PACIFIC INC.	Brazos Seahorse	185	Supply	2	CAT	D-399-TA	1225	1125
ZAPATA GULF PACIFIC INC.	Chesapeake Seahorse	185	Supply	2	EMD	12-645-E7A	900	2150
ZAPATA GULF PACIFIC INC.	Victory Seahorse	198	Supply	2	EMD	16-645-ED3A	900	5000
ZAPATA GULF PACIFIC INC.	Pacific Seahorse	210	Supply (AHTS)	2	EMD	16-645-E5	900	2875

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* CAT: Catapillar
EMD: Electromotive Division of General Motors
DDA: Detroit Diesel Allison

The text table below provides a listing of the major types of engines used in supply boats working in the Pacific OCS and the U.S. Fleet in general. Eighty-four percent of the engines in the supply boats working in the Pacific OCS are either EMD or CAT type, while in the U.S. Fleet, 51 percent of the supply boats are equipped with these types of engines.

MAIN ENGINES OF SUPPLY BOATS
(IN %)

	PACIFIC OCS	U.S. FLEET
EMD	38	35
DDA	16	32
CAT*	46	16
OTHER	0	17

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* All Pacific OCS supply boats with CAT engines have D-398, D-399 series engines.

In 1987, duty cycle tests were performed on two boats which Chevron is operating in the Santa Barbara Channel: a crew vessel (Clipper Hamilton), and a supply boat (Chesapeake Seahorse). These tests determined the average amount of time in cruise, maneuver, or idling mode for the boats.

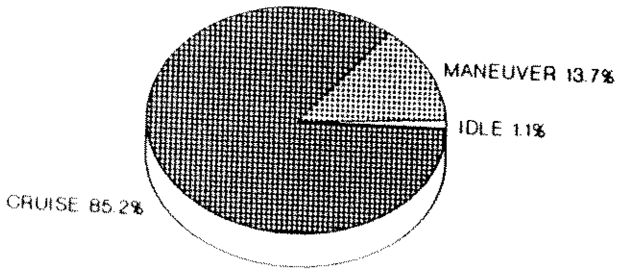
The Clipper Hamilton operation was divided among the cruise mode (22.7 percent of time), the maneuver mode (18.5 percent of time), and the idle mode (12.0 percent of time); for the balance of the time the vessel's engines were off (46.8 percent of time). The Chesapeake Seahorse operation was divided among the cruise (37.9 percent of time), maneuver (42.7 percent of time), and idle (6.5 percent of time) modes; for the balance of the time the vessel's engines were off (12.9 percent of time). These mode profiles are, of course, applicable only to these two vessels, or to other vessels operating on routes, schedules, and duties similar to those encountered during the test program. Nevertheless, they do provide insight into the operation of crew and supply boats.

Figure 3.3-1 shows the comparison of the supply and the crew boat operations based on fuel use and time in mode. Although the duty cycles of the two vessels vary considerably, both vessels consume most of their fuel in the cruise mode.

FIGURE 3.3-1
MEASURED DUTY CYCLES FOR CREW AND SUPPLY BOATS

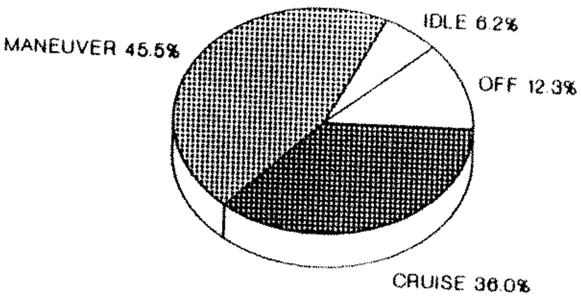
SUPPLY BOAT

CHESAPEAKE SEAHORSE
FUEL USE IN MODES



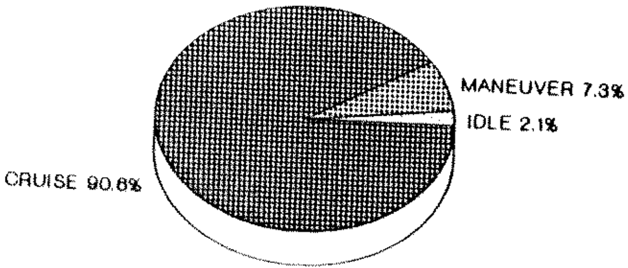
SUPPLY BOAT

CHESAPEAKE SEAHORSE
TIME IN MODES



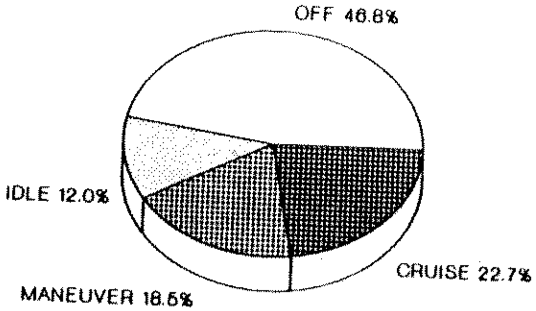
CREW BOAT

CLIPPER HAMILTON
FUEL USE IN MODES



CREW BOAT

CLIPPER HAMILTON
TIME IN MODES



Source: Crew and Supply Boat NO_x Control Development Program

3.4 Exploratory Drilling Rig Diesel Engines

Exploratory drilling rig diesel engines have been identified as being one of the more significant sources of NO_X emissions associated with initial OCS development projects. This section describes their typical application, manufacturers and duty cycles.

A variety of types of exploratory rigs have been used as part of developing the Pacific OCS. Table 3.4-1 lists drilling rigs which have been used over the past decade in support of Pacific OCS activities. As can be seen from this table, rigs have included semi-submersibles, jackups, and drill ships.

The main sources of NO_X emissions on the exploratory rigs are the generators in the case of rigs with electric motor drives and the drilling engines in the case of rigs with prime movers. The main power sets on most rigs consist of two to six engines of 800 to 2,500 hp each. As is true of supply boats in the Pacific OCS, most drilling rigs have EMD or CAT engines (88 percent of those in the survey).

Exploratory rigs can be deployed for periods ranging from several months to several years. The rigs are also supported by crew and supply boats during their drilling period.

Drilling activities themselves dominate the demand for electrical or shaft power on a rig. Thus the duty cycle on rigs with electric motor drives versus engine drives does not differ significantly. Due to the nature of drilling activities, significant and frequent variations in engine load are experienced.

TABLE 3.4-1
SURVEY OF DRILLING RIGS
CALIFORNIA OCS DEVELOPMENT

GENERAL RIG DESCRIPTION				MAIN POWER EQUIPMENT (Set 1)			MAIN POWER EQUIPMENT (Set 2)			CALIFORNIA OCS ACTIVITIES		
RIG NAME	OWNER	TYPE	MAXIMUM WATER DEPTH (feet)	QUANTITY	MANUFACTURER	MODEL	QUANTITY	MANUFACTURER	MODEL	OIL COMPANY	FIELD/ TRACT	YEAR
Glomar Atlantic	Global Marine	drillship	2000	4	GE	7FDL Diesel				ARCO	South Ellwood Field	1981
										Conoco	Tract 322	1982
										Champlin Petro.	Tract 333	1983
										Chevron	Pt. Arguello Field	1984
Glomar Coral Sea	Global Marine	drillship	1500	6	CAT	D-399				Chevron	Tract 443	1981
										Phillips	Tract 397	1983
										Exxon	Santa Ynez Unit	1984
Glomar Pacific	Global Marine	drillship	2000	4	EMD					Exxon	Point Sal	1981
										Exxon	Tract 440	1983
JFP III	JFP	jack-up	300	4	CAT	D399				ARCO	Tract 444	1983
										Shell Oil	Tract 361	1983
JFP XI	JFP	jack-up	350	4	CAT	D-399				ARCO	Tract 208	1984
Key Singapore	Keydril	jack-up	300	3	EMD	16-E8				Chevron	Tract 318	1982
										Chevron	Tract 452	1983
										Chevron	Tract 337	1983
										Phillips	Tract 426	1983
										ARCO	Tract 437	1984
										Texaco	Tract 479	1984
Penrod 96	Penrod	jack-up	250	3	EMD	12-E8				Phillips	Tract 318	1983
Diamond M. Eagle	Diamond M	semisubmersible	2000	2	EMD	16-E9	1	EMD	16-E8	Chevron	Tract 446	1982
										Chevron	Tract 450	1984
										Phillips	Tract 408	1984

TABLE 3.4-1 (continued)
SURVEY OF DRILLING RIGS
CALIFORNIA OCS DEVELOPMENT

GENERAL RIG DESCRIPTION				MAIN POWER EQUIPMENT (Set 1)			MAIN POWER EQUIPMENT (Set 2)			CALIFORNIA OCS ACTIVITIES		
RIG NAME	OWNER	TYPE	MAXIMUM WATER DEPTH (feet)	QUANTITY	MANUFACTURER	MODEL	QUANTITY	MANUFACTURER	MODEL	OIL COMPANY	FIELD/ TRACT	YEAR
Diamond M. Falcon	Diamond M.	semisubmersible	2000	1	EMD	16-E8	2	EMD	16-E9B	ARCO Texaco	Tract 484 Tract 456	1985 1985
Diamond M. General	Diamond M	semisubmersible	1200	2	EMD	16-E9	1	EMD	16-E8	Union Texaco Union Texaco Gulf Reading & Bates	Tract 441 Tract 2206.1 Tract 2879 Tract 463 Tract 505 Tract 433	1982 1983 1983 1984 1985 1985
Jim Cunningham	Reading & Bates	semisubmersible	1500	4	EMD	16-8				Reading & Bates	Tract 415	1983
Ocean Odyssey	Odeco	semisubmersible	1500	6	ALCO	16V251F						
Penrod 73	Penrod	semisubmersible	1500	4	EMD	16-E9B				Ox. Petrol. Mobil Oil Ox. Petrol.	Tract 409 Tract 321 Tract 409	1982 1983 1983
Sedco 712	Sedco Forex	semisubmersible	1500	3	EMD	16-E9B						
Sedco 702	Sedco Forex	semisubmersible	1000	3	EMD	16-645-E9				Phillips Chevron	Point Sal Tract 450	1983 1984
Zapata Concord	Zapata	semisubmersible	2000	3	EMD	16-645-E8				Chevron Chevron Getty Oil Co.	Tract 450 Tract 452 Tract 395	1981 1983 1983

4.0 NO_X CONTROL TECHNIQUES FOR OFFSHORE OPERATIONS

4.1 Candidate NO_X Control Techniques

A number of emerging NO_X control technologies were identified from a literature search and review. In arriving at a list of candidate technologies, several criteria were established:

1) The technologies must be able to offer NO_X control above and beyond the level represented by current practice. For offshore gas turbines, the current practice is water injection. For medium speed diesel engines, current practice is turbocharging, timing retard, and enhanced intercooling. Thus, the technologies must be capable of generating emissions less than those represented by the current techniques, or they must be able to control the emissions which are presently produced.

2) The technologies must be described in the open technical literature. These developments have been reviewed by technical peers, thus providing a level of assurance to any proprietary claims.

The list of the NO_X control techniques which were considered for this program is shown in Table 4.1-1. These technologies are divided into four categories:

- Exhaust Gas Treatment,
- Gas Turbine Combustion Modifications,
- Diesel Engine Modifications, and
- Alternative Fuels.

A detailed descriptions and cost estimates for these techniques can be found in Appendices B and C of this report. Each of these techniques are summarized in the following sub-sections.

4.1.1 Exhaust Gas Treatment

The five exhaust gas treatment techniques analyzed in this study are:

Commercially Available SCR - A controlled amount of ammonia is added to the exhaust gases and the mixture is passed over a catalyst bed. SCR is in use on larger boilers, particularly in Japan and now in West Germany. In the past few

TABLE 4.1-1

NOX CONTROL TECHNOLOGIES EVALUATED IN THIS PROGRAM

Exhaust Gas Treatment	
	Selective Catalytic Reduction
	Selective Non-Catalytic Reduction
	RAPRENOx
	Electrochemical Cell Reduction
Gas Turbine Combustion	
	Dry Low-NOx Combustion
	Catalytic Combustion
	Zero Nitrogen
Diesel Engine Combustion	
	Tailored Injection
	Exhaust Gas Recirculation
	Water/Fuel Emulsion
	Charge Air Cooling
	Zero Nitrogen
Alternative Fuel	
	Duel-fuel (natural gas)
	Methanol
Others*	
	Nitrogen Plasma
	Ozone Injection
	Reburning
	Combined SOx/NOx Removal Techniques

---

* These were given initial consideration, but were dropped for a variety of reasons.

Dry Low NO_x Combustors - This concept has been under development for over a decade. Two techniques which have received research attention are lean pre-mixed combustors and staged, rich-lean combustors. In a lean pre-mixed set-up, combustion fuel and air are mixed at a ratio just above the lean extinction point. Combustion is then carried out uniformly at a lower temperature, thus reducing NO_x formation. In rich-lean combustors, the fuel is combusted stagewise, the first stage being rich, and the second lean, thus maintaining a low temperature profile throughout the combustion process. Mitsubishi has introduced a hybrid dry low NO_x combustors. Solar has been active in developing pre-mixed combustors, using swirl-stabilization to assist the combustion near the flameout region. G.E. will also soon be introducing a dry combustor for its turbine line. Solar has received sponsorship from GRI, EPRI, and Southern California Gas.

Catalytic Combustion - Catalytic combustion is commercially available for low temperature applications, such as space heating. In this technique, the fuel and the combustion air are premixed and passed over a catalyst bed. Combustion can take place both heterogeneously (on the catalyst surface) and homogeneously (in the catalyst interstices, being promoted by the formation of radicals on the catalyst surface). Catalytic combustors have been attempted for application on gas turbines, most recently in the United States in a program by Westinghouse and Englehard with funding by EPRI. The Japanese have also been actively involved in catalytic combustion research. This technique, when developed, would probably offer lower NO_x emission levels than would the lean premixed combustor. However, many more technical obstacles would need to be overcome in order for this technique to be effective.

Both of these gas turbine combustion modifications would displace water injection. They should be able to offer greater levels of NO_x control at a lower cost than water injection. As is the case with water injection, even greater levels of NO_x control could be achieved through treating the exhaust products with one of the exhaust gas treatment techniques described in the previous section.

In addition to the abovementioned four options to modify gas turbine combustion processes, another method for controlling NO_x from gas turbines is through the operation of the turbine on pure oxygen in a recycle scheme (the zero nitrogen concept). In the zero nitrogen concept, most of the exhaust gases are recycled and mixed with an appropriate amount of relatively pure (95 to 99 percent) oxygen. Since the levels of nitrogen are greatly reduced, NO_x formation is practically limited to that from fuel-bound nitrogen.

years, SCR has been applied on large gas turbines in California. About twelve licensors worldwide (and their regional representatives) offer SCR technology. Catalyst manufacturers, technology licensors, and researchers continue to improve their commercially available SCR technologies.

Selective Non-Catalytic Reduction (SNR) - A proprietary reagent (ammonia in the case of Exxon's Thermal DeNO$_X$, or Urea Solution in Fuel Tech's NO$_X$OUT) is interspersed throughout the exhaust gases in a time-temperature controlled reaction area. SNR has found over one hundred applications in the United States, primarily in large boilers and fired heaters.

RapReNO$_X$ - Exhaust products are mixed with isocyanic acid, which is formed from the controlled sublimation of solid cyanuric acid pellets. RapReNO$_X$ is an embryonic technology; it was discovered in 1986 at Sandia Livermore Laboratories. The initial research suggested great promise and development efforts geared towards diesel engine applications continue.

Electrochemical Cell Reduction - This is the only listed exhaust gas treatment technique which does not require a chemical reagent. Exhaust products are passed through a ceramic electrochemical reaction bed. This is also an embryonic technology. Although initial tests show that the operating requirements (hence operating costs) might be much less than that for the other techniques in this category, much research is needed before this process is considered proven.

All of the exhaust gas treatment technologies could be applied to either gas turbines or to diesel engines.

4.1.2 Gas Turbine Combustion Modifications

Water injection is the current practice for reducing NO$_X$ emissions from gas turbines in offshore applications. As a rule, water injection (at a rate of 0.8 pounds water per pound fuel) can reduce NO$_X$ emissions by 60 to 70 percent from their uncontrolled levels. While some manufacturers have been exploring the possibility of ultra-high water injection rates, it appears that such a practice would be detrimental to turbine life and efficiency. There are, however, two modifications to turbine combustors which appear to have potential promise to significantly reduce NO$_X$ emissions.

Charge Cooling - The air charge is reduced in temperature from about 110 to 60°F by a freon-based refrigeration process. Although the refrigeration unit would need to be run from either a power take off or the exhaust turbine, the lower inlet temperature could offset some of the turbocharger compression requirements by providing increased air density. A more moderate reduction in inlet air temperature could also be achieved through the use of a cooling tower for circulating cooling water in an isolated cooling loop.

In addition to the abovementioned four options to modify diesel engine combustion processes, another method for controlling NO_x from diesel engines could be through operation on pure oxygen in a recycle scheme (the zero nitrogen concept). In the zero nitrogen concept, most of the exhaust gases are recycled and mixed with an appropriate amount of pure (95 to 99 percent) oxygen. Since the levels of nitrogen are greatly reduced, NO_x formation is practically limited to that from fuel-bound nitrogen.

4.1.4 Alternative Fuels

Alternative fuels have been considered for diesel engines, but not for offshore gas turbines. The turbines are already burning platform gas, a clean fuel which is readily available on the platforms. For the diesel engines, the two alternative fuels which have been considered are natural gas and methanol.

Compressed Natural Gas (CNG) - Several methods for using CNG on offshore engines are possible, including optimized CNG engines and dual fueling. Optimized CNG engines could use one or more of several techniques to achieve low NO_x levels, including lean burn, spark ignition, torch ignition, fast burn and/or others. Research and Development is underway for highway engines to develop low NO_x CNG engines. In dual fueling a natural gas/air mixture, formed by a retrofit package of either a carburetor or a high pressure injector, is introduced. A diesel fuel pilot is injected through a separate port to ignite the mixture. The amount of diesel fuel used as a pilot is about 5 to 20 percent of total fuel energy at full load, but increases at lower loads. Substantial modifications to the cylinder heads and other engine components are required.

4.1.3 Diesel Engine Modifications

Some reciprocating engines which are used offshore have been fitted with selected techniques for reducing NO_x emissions, including turbocharging, injection timing retard, and enhanced intercooling (isolated from the jacket water cooling loop). Four engine modifications have been identified and analyzed in this effort. They are described below.

> Tailored Injection - The injection system and configuration is modified to reduce the portion of fuel consumed in the premixed combustion phase. To accomplish this, the initial rate of fuel injection is reduced. In this sense, the combustion is staged, resulting in a "lazy" burn during the first stage. Tailored injection has been developed by Bosch and other European engine manufacturers for truck engines. Several U.S. engine manufacturers are also conducting research and development programs on tailored combustion. The next generation of highway engines will feature tailored injection in combination with electronic control. The practicality of using these techniques suggest that existing engines would need to be replaced with advanced technology engines.
>
> Exhaust Gas Recirculation - A portion of the exhaust gas is cooled and recirculated to the engine, lowering flame temperatures and therefore, NO_x levels. The portion of the exhaust gases to be recirculated would be removed downstream of a turbocharger, cooled to the level of the manifold temperature via an intercooler, with condensed water being removed as necessary. The recycled exhaust gases would then be introduced into the intake manifold, ahead of the compressor, thus displacing part of the air flow. Some simple form of control system, such as proportional control, would be required during load changes.
>
> Water-Fuel Emulsion - Water is emulsified with the diesel fuel at a volume ratio of 40 to 60 percent. The emulsion can either be made off-line and stored or made on-line. Many manufacturers feel that the fuel and water should be emulsified as close as possible to the time in use, thus decreasing the chances of "slugging" the injector with a pocket of pure water. Modifications to the injection nozzles, one cam and the plungers, as well as installation of emulsifying equipment is necessary to convert an engine to water-fuel emulsion.

Methanol - Use of methanol in a diesel engine can be accomplished through one of several means:

- Compression ignition with diesel pilot,
- Spark-assisted ignition,
- Compression ignition with cetane-improver additive,
- Emulsion of 25 to 40 percent methanol in diesel fuel, or
- Compression ignition at elevated temperature.

Many of these methods for using methanol are presently under investigation by various researchers. Some of these methods are ammendable to retrofit on existing engines, whereas others would dictate engine replacement.

4.2 Screening Analysis

A screening analysis was carried out on the previously described technologies to select those with the greatest potential applicability to offshore sources. This analysis was based upon the technology profiles and the magnitude cost estimates shown in Appendices B and C.

The screening analysis considered a wide variety of factors, including:

- Expected NO_X removal efficiency,
- Cost,
- Technical hurdles to be overcome in development, and
- Other environmental and safety concerns.

While institutional hurdles are an important consideration in the adoption of new technologies, they were not addressed in the screening analysis.

4.2.1 Gas Turbines

A listing of the candidate technologies for reducing NO_X emissions from offshore gas turbines is shown in Table 4.2-1. Both exhaust gas treatment and gas turbine combustion techniques are listed in this table. The technologies are described in terms of their expected NO_X removal effectiveness, anticipated cost, and an estimated probability of a successful demonstration offshore in about five years. The expected NO_X reductions are relative to gas turbines equipped with water injection. The anticipated costs are all presented on a basis of

TABLE 4.2-1

CANDIDATE NO_x CONTROL TECHNOLOGIES FOR OFFSHORE GAS TURBINES

Candidate Technology	NO_x[1] Emission Reduction (%)	Annual Cost	Technology[2] Probability (%)	Key Development Considerations
Commercially Available SCR[3]	80	243,000	80	* Load Fluctuations * Temperature Control * Ammonia Storage and Handling
Commercially Available SNR[3]	60	580,000	50	* Reheat Control or Lower Temperature Reagents * Load Fluctuations
RapReNO$_x$[3]	60	660,000	35	* Temperature Window * Scale-Up/Residence Time
Electrochemical Cell Reduction[3]	60	97,000	5	* Oxygen Selectivity * Scale-Up/Residence Time
Dry Low-NO_x Combustor	40	38,000	80	* Load Fluctuations - Combustor Control * Flame-Out
Catalytic Combustor	80	63,000	30	* Load Fluctuations - Combustor Control * Catalytic Materials
Zero-Nitrogen Turbine	60	1,950,000	90	* Cost * Space Limitations

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[1] Percentage NO_x reduction from levels produced by gas turbine equipped with water injection.
[2] Estimated probability of a successful offshore demonstration within 5 years.
[3] Analysis based on this technology in combination with water injection.

Source: Arthur D. Little, Inc., Estimates comparing the technology to uncontrolled engines. Thus the costs of technologies which would be used in conjunction with current practice (water injection) represents a total cost of control.

The estimated probability of a successful demonstration offshore is based upon engineering judgement of the technologies' capabilities and the key requirements for offshore installations. These probabilities are generally lower than those which would be expected for most of these techniques in onshore applications. Some of the key distinguishing features between offshore applications and common onshore applications (such as cogeneration and prime mover duties) include:

- Load Following - Offshore gas turbines operate in an electric load following manner. Since the electric power requirements on platforms can vary frequently and sizeably, significant swings in load can be expected.

- Offshore Environment - Processing operations in an offshore environment are subject to rather severe space and weight limitations. Additionally, transport and storage of materials becomes complex when considering logistics and safety issues.

The probabilities of success have thus been estimated through qualitative consideration of the above issues, as well as the current status of the technologies and the hurdles to be overcome.

The anticipated NO_X performance levels and the total annual costs for the various combinations of NO_X control technologies for gas turbines are shown in Figure 4.2-1. The two techniques not considered for the final screening were zero-nitrogen gas turbines and electrochemical cell reduction. The former was not considered due to its very high annual cost; the latter portrays a very low probability of success, since the selectivity of the technique to reducing nitrogen oxides rather than oxygen has not been demonstrated.

Figure 4.2-1 shows the target NO_X emission value of 10 ppm. This target value represents a 60 to 75 percent decrease in NO_X emissions as compared to present levels (25 to 40 ppm). Also, through discussions with researchers and manufacturers, this level appears to be about the minimum value that can be expected through developments in the foreseeable future. The target value represents an emission rate which, on the basis of NO_X per unit output, is less than that achieved in a fossil fuel-fired power station equipped with low-NO_X combustion techniques.

FIGURE 4.2-1

NOx Control Technologies for Gas Turbines

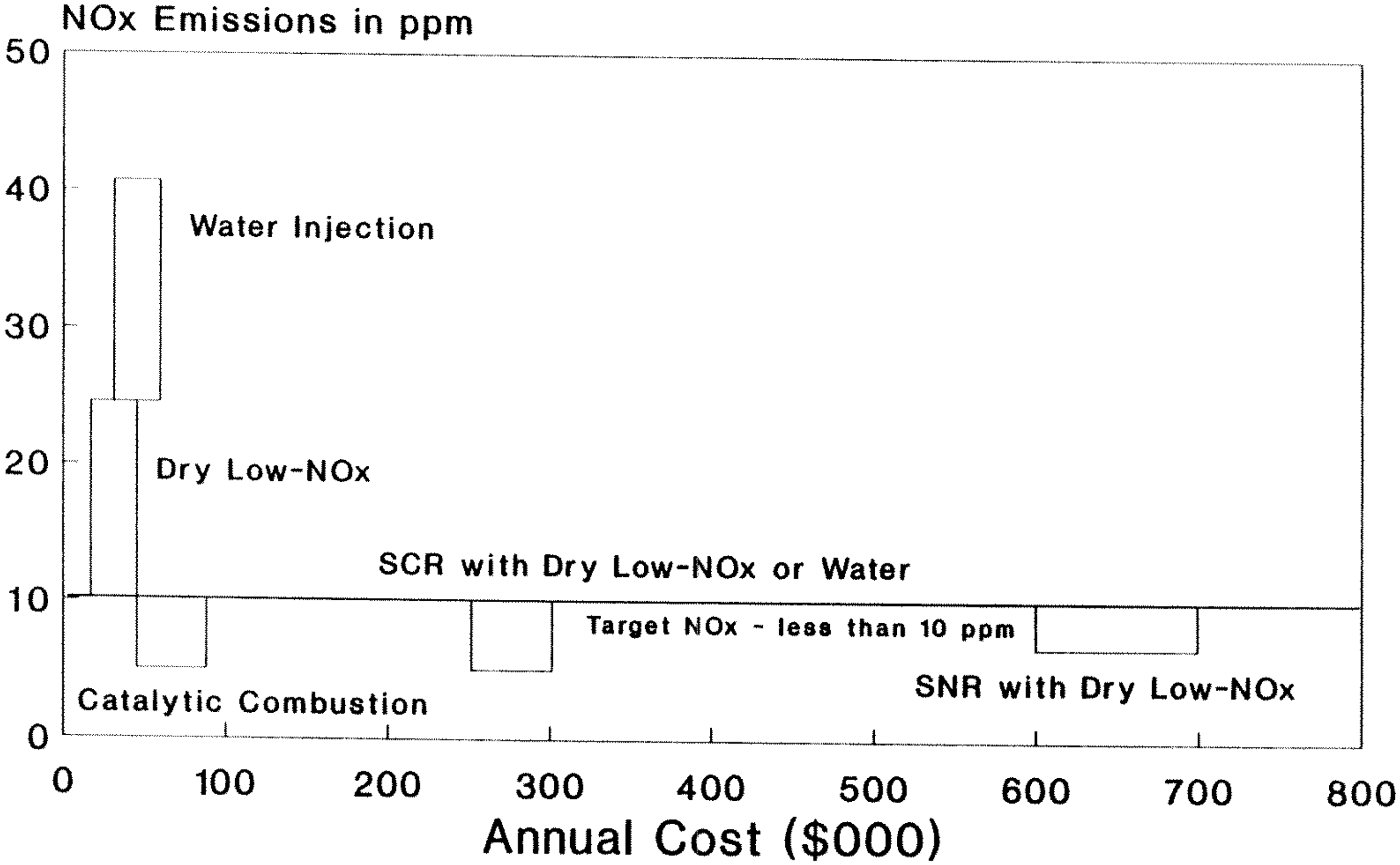

Figure 4.2-1 shows that there are several means of achieving the target performance of 10 ppm NO_X. The most attractive financially would be catalytic combustion. The other two means require exhaust gas treatment in conjunction with combustion modification: SCR plus water injection and SNR plus dry combustors. SNR plus dry combustors offers the benefit of easier integration with platform gas turbines, while SCR plus water injection has a greater likelihood for successful demonstration.

Implications for development are therefore assigned as follows:

Gas Turbine Combustors

Both techniques (dry low-NO_X combustors and catalytic combustors) show very favorable benefit to cost ratios compared to all other NO_X control options. Dry low-NO_X premixed combustors, however, may not offer reductions in NO_X levels much beyond that which is presently achievable through water injection. Catalytic combustors, on the other hand, would offer significant reductions not only in NO_X emissions, but also in emissions of carbon monoxide and hydrocarbons. The development path for catalytic combustors is probably much longer than that for dry low-NO_X combustors.

Many manufacturers are already showing strong interest in introducing dry low-NO_X combustors for their gas turbines. This technique should gain rapid acceptance by the offshore industry since it offers greater NO_X reduction while demonstrating favorable economics. From a technology development perspective, dry low-NO_X combustors should soon be available for onshore use; offshore use would follow once appropriate control techniques are developed to allow their use in load following duties.

Catalytic combustors will probably not be available for turbines until the mid to late 1990's. This technique shows great promise at providing cost effective control for all criteria pollutants, both offshore and onshore. A number of critical technical elements need to be resolved prior to the successful offshore demonstration of this technique.

Exhaust Gas Treatment

Exhaust Gas Treatment can be utilized for both diesel engines and gas turbines. Accordingly, recommendations on the development of these techniques are presented in Section 4.2.3, following the prioritization of techniques for diesel engines.

Priorities

Three techniques or combinations of techniques show the potential for achieving the target NO_X emission rate:

- Catalytic Combustion
- SCR With Water Injection or Dry Low-NO_X Combustors
- SNR With Dry Low-NO_X Combustors

Catalytic combustion, when available, should offer quite attractive economics, although its development path is quite long. Dry low-NO_X combustors, soon to be commercially available for new turbines, will offer greater control than that from water injection, although some development will be required for offshore applications. Both of these techniques are included in the long term program design. Both types of exhaust gas treatment, SNR and SCR could provide "polishing duty" service for offshore gas turbines. These techniques are compared in Section 4.2.3.

4.2.2 Diesel Engines

A listing of the candidate technologies for reducing NO_X emissions from offshore diesel engines is shown in Table 4.2-2. Exhaust gas treatment, engine modifications, and alternative fuels are listed in this table. The technologies are described in terms of their expected NO_X removal effectiveness, anticipated cost, and an estimated probability of a successful demonstration offshore in the reasonably near future.

The expected NO_X removal effectiveness and the anticipated cost are all presented on a basis of comparing the technology to current practice, which includes turbocharging, injection timing retard, and enhanced intercooling. As is the case for offshore gas turbines, the estimated probability of a successful demonstration offshore is based upon engineering judgement of the technologies' capabilities and the key requirements for offshore installations.

The anticipated NO_X performance levels and the total annual costs for the various combinations of NO_X control technologies for diesel engines are shown in Figure 4.2-1. Two techniques were not considered for the final screening: zero-nitrogen engine and electrochemical cell reduction. The former was not considered due to its very high annual cost; the latter portrays a very low probability of success, due to the lack of demonstration of selectivity of the technique to nitrogen oxides over oxygen.

TABLE 4.2-2

CANDIDATE NO_x CONTROL TECHNOLOGIES FOR OFFSHORE DIESEL ENGINES

Candidate Technology	NO_x Emission Level (g/hp-hr)	Annual Cost	Technology[1] Probability (%)	Key Development Considerations
Commercially Available SCR	2	176,000	50	* Load Fluctuations - Temperature Control * Ammonia Storage and Handling * Catalyst Failing
Commercially Available SNCR	3.5	171,000	60	* Reheat Control or Lower Temperature Reagents * Load Fluctuations * Reagent Storage and Handling
$RapReNO_x$	3.5	394,000	50	* Temperature Window * Scale-Up/Residence Time
Electrochemical Cell Reduction	3.5	72	5	* Oxygen Selectivity * Scale-Up/Residence Time
Tailored Injection	5	24,000	90	* Sophisticated Control
Exhaust Gas Recirculation	6	53,000	80	* Extensive Ductwork * Scrubber Retrofit
Water Fuel Emulsion	6	11,000	90	* Prevention of Water Slugs
Charge Air Refrigeration	8	13,000	90	* Space/Safety Considerations
Zero Nitrogen Engine	2	532,000	90	* Cost * Safety of Oxygen Use Offshore
Dual Fuel (Natural Gas)	5	46,000	90	* Storage of CNG * Space/Safety Considerations
Methanol	2	443,000	90	* Handling/Storage of Methanol * Other Emissions

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[1] Estimated probability of a successful offshore demonstration within 5 years.

Figure 4.2-2 also shows the target value of 2 grams per brake horsepower hour as the NO_x target for diesel engines. This level represents a 60 to 80 percent decrease in emissions over existing levels from typical offshore engines. Engine manufacturers believe that significant technology development efforts will be required to achieve this target emission level.

Figure 4.2-2 shows that there are several means of achieving the target emission level:

Methanol
Compressed Natural Gas (CNG)
Tailored Injection Plus Exhaust Gas Treatment (SCR or SNR)

SCR, although being advanced for onshore stationary engines, possesses a number of operational concerns for offshore applications, as described in Section 4.2.3. Therefore, the other two techniques have been selected for the long term development program.

Priorities for technology development are as follows:

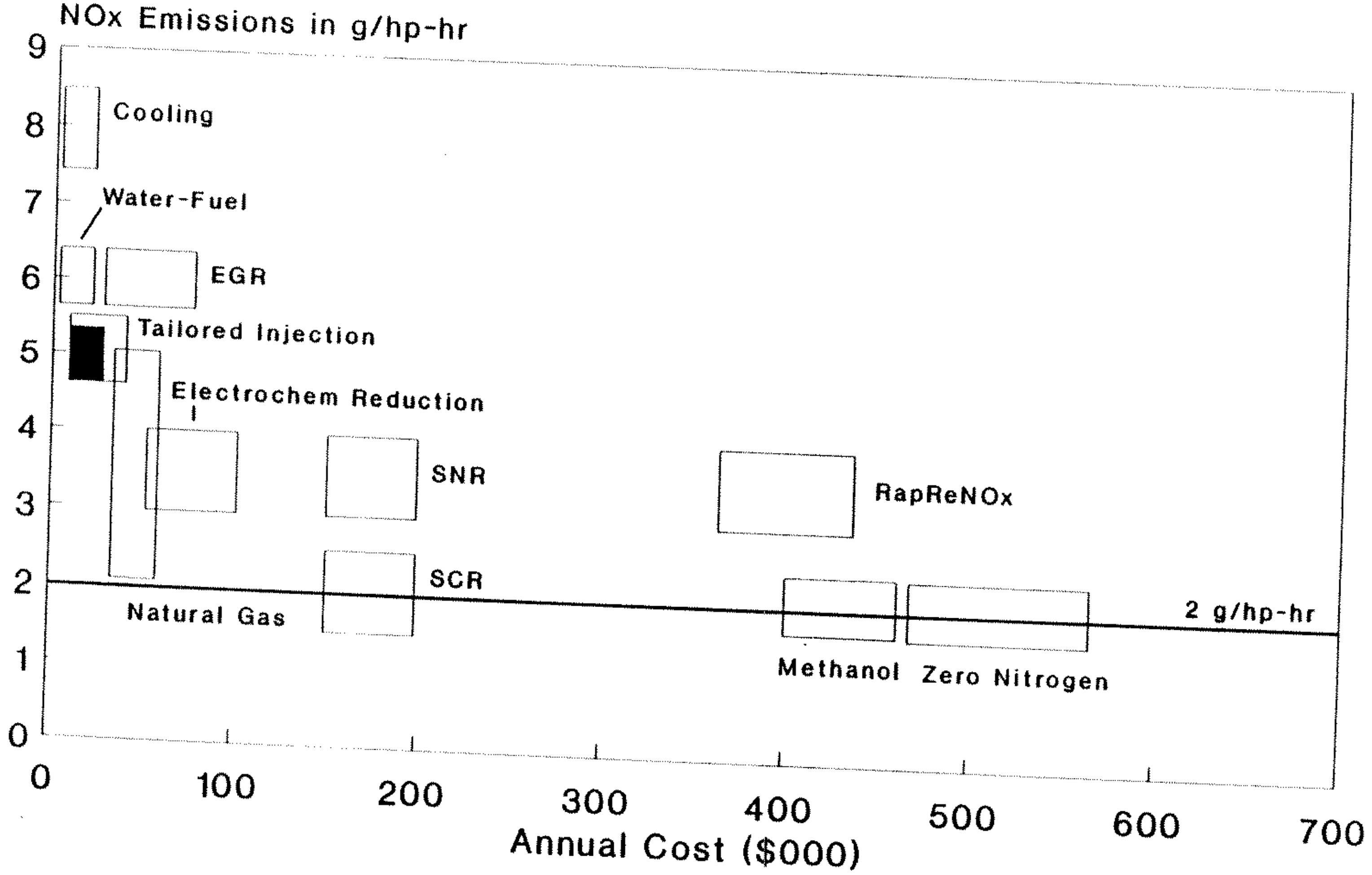
Methanol and CNG are presently being demonstrated for use onshore in high speed engines for bus applications in California and in other locations. Although the onshore experience is not directly transferable to offshore operations, much of the initial work has already taken place. Although engine modifications for using alternate fuels offshore need to be optimized, other considerations are also significant, including:

- Reduced cruising distance for vessels,
- Offshore safety of methanol or CNG fuel, and
- Available torque for emergency situations.

Should these considerations be resolved acceptably, alternate fuels could achieve the target emission rate rather quickly. The other technique for achieving the target is tailored injection in combination with exhaust gas treatment. The development program to advance these techniques for offshore applications is described in Section 5.2.

FIGURE 4.2-2

NOx CONTROL TECHNOLOGIES FOR DIESEL ENGINES



4.2.3 Exhaust Gas Treatment

All of the exhaust gas treatment techniques except electrochemical cell reduction demonstrate promise for offshore turbine applications. For diesel engines, exhaust gas treatment techniques are plagued by quite a number of problems specific to offshore applications, including:

- Space limitations on vessels,
- Low operating load factors on platform engines, and
- Hazards and difficulties in transporting reagents.

Other problems associated with engine applications of these various techniques are being addressed for onshore applications. Implications for selective catalytic reduction and selective non-catalytic reduction techniques are described below.

Selective Non-Catalytic Reduction

With currently available SNR reagents a significant cost debit is associated with reheating exhaust gases to the required operating temperature. Developers such as Technor (RapReNO$_X$), Exxon (DeNO$_X$), and Fuel Tech (NO$_X$-OUT) are continuing their efforts in developing reagents and techniques for SNR. While many of the new developments have not yet been commercially tested, initial results are promising. It is possible that, within the next several years, new SNR techniques with lower temperature windows and possibly even higher NO$_X$ removal efficiencies will become available. Many SNR techniques also offer the benefit of easy-to-handle, non-toxic reagents. Thus, with the development of low temperature reagents SNR could offer significant benefits over SCR for offshore applications.

Selective Catalytic Reduction

SCR is already gaining acceptance for use on onshore gas turbines in California. Development of SCR catalysts for diesel engines are continuing, aimed at engines with steady loads. Due to the duty cycle of offshore turbines, use of improved catalysts and SCR control systems is suggested for offshore turbines. Use of aqueous ammonia as a reagent should also be advanced to alleviate safety concerns. Due to operational difficulties on boats, development of SCR for offshore diesel engines should be focused on exploratory drill rig applications. For these rigs, SCR could serve as a "polishing" process for NO$_X$ removal, after the bulk of the NO$_X$ is eliminated through combustion modifications.

Process improvements for both SCR and SNR techniques for removing NO_x from exhaust gases can be expected to continue. Considering the requirements of offshore operations, SNR holds several advantages over SCR: lower initial cost, lower weight, and space requirement. On the other hand, advantages of SCR over SNR include greater effectiveness at reducing NO_x, a more proven commercial status, and a reduced or nil exhaust gas reheat requirement.

This report recommends pursuing development efforts of both SCR and SNR processes as part of the long term program. SCR enhancements should be actively developed and then demonstrated, as soon as practical. However, a significant research breakthrough is required in SNR technology for this process to be effective over the engine load range of interest without reheating exhaust gases. Therefore, a moderate level of effort, involving monitoring of research progress and selective funding of promising technologies is recommended. Should the required breakthrough occur, program emphasis can be shifted toward the SNR process.

5.0 LONG-TERM TECHNOLOGY DEVELOPMENT PROGRAM

This section describes two separate technology development programs: one for offshore gas turbines and another for offshore diesel engines. Suggestions for program management are also presented.

5.1 Offshore Gas Turbine Program

The offshore gas turbine program includes efforts for developing four technologies:

- Dry Low-NO_X Combustors
- Catalytic Combustors
- Selective Catalytic Reduction
- Selective Non-Catalytic Reduction

As was described in Section 4.2, the combinations of water injection or dry low-NO_X combustors plus SCR should achieve the target of 10 ppm NO_X within a reasonable period of time. SNR technology in combination with dry low-NO_X combustors may also reach this goal and would be preferable for offshore application due to advantages in space requirement and possibly cost. However, since no reagents have yet been found to be effective at gas turbine exhaust temperature levels, the probability of successfully applying this combination is lower. Consequently both SCR and SNR technologies should be included in the development program. Selection of best exhaust gas treatment process would take place prior to the offshore demonstration.

Catalytic combustors should be capable of achieving the 10 ppm goal with significantly less cost; however, it is unlikely that this technology could be made commercial within the timeframe of this program. Therefore, catalytic combustion receives a relatively low level of effort, intended only to keep abreast of the developments in the field. If significant breakthroughs occur in ongoing catalytic combustion research, then more attention should be focused on its development.

5.1.1 Duty Cycle and Baseline Emission Characterization

The first component of the offshore gas turbine program is to develop an adequate technical database on the duty cycle and emission characteristics of platform turbines. This information will be essential in evaluating: 1) the potential application of dry low-NO_X

combustors; 2) in developing the design criteria for a catalytic combustor; and 3) in designing test programs for exhaust gas treatment technologies.

Testing of the gas turbines should occur over a period of one to two months, where the following parameters should be monitored continuously.

- Exhaust gas bulk constituents: O_2, CO_2 (nitrogen and water by material balance),
- Criteria pollutants: CO, NO_x, ROC
- Fuel composition,
- Turbine operating conditions: output, fuel flow, temperatures, exhaust flow, water injection flow, etc, and
- Ambient conditions.

The data should be analyzed while this test period is being conducted. Prior experience suggests that after turbine emissions are fully characterized, only a few measurements need to be taken to monitor turbine performance over a longer period of time. We believe that turbine inlet and exhaust temperatures, ambient temperature and humidity, turbine output, fuel input and water injection rate will be adequate to characterize the turbine duty cycle over a longer period of time. Therefore, after the one or two months initial characterization has been completed, a longer period (4 to 6 months) of turbine monitoring would provide significant additional data on the turbines.

All testing should be done in accordance with accepted methods, such as those endorsed by the EPA or the California Air Resources Board. Additionally, quality assurance/quality control should be performed by an independent party. Test results should be compared to previously collected data on identical turbines, so that discrepancies can be verified during the actual testing.

5.1.2 Dry Low-NO_x Combustors

Gas turbine manufacturers are presently developing dry low-NO_x combustors stationary, onshore applications. Major programs are underway at Solar, Allison and G.E., the three largest suppliers of gas turbines to offshore projects in California. The two techniques being explored and developed in these ongoing programs are lean premixed combustors and rich-lean staged combustors. Although these concepts are being explored by several manufacturers, the exact hardware requirements are quite specific to each manufacturer and model.

The major impetus for the development of dry low-NO_X combustors is the ever more stringent NO_X emission regulations for onshore gas turbines. Due to the nature of these combustion techniques, they are more readily applied to turbines with steady full-load duty as opposed to offshore turbines with a load-following duty cycle. However, the offshore NO_X control program can benefit from the substantial research and development efforts already being invested by manufacturers in dry low-NO_X combustion technology. Development efforts should focus on modifications to proven combustor concepts that will extend their operation to accommodate offshore duty cycle requirements.

The recommended program for developing dry low-NO_X combustors for offshore applications includes the three areas below:

1) Design a study to examine changing the load profiles of individual turbines, yet maintaining present platform load.

2) Hardware modifications (if required) to enable turbines to perform optimally given their duty cycles as developed from number 1 above.

3) Offshore demonstration.

Each of these three areas are further described below.

Engineering Design Evaluation

In general, the dry low-NO_X combustors under development are designed for steady full load applications. Some combustors, in fact, have several operating modes, depending on the turbine load, and portray very low-NO_X performance only within a narrow full load range. Offshore turbines, on the other hand, have significant load swings. Thus the purpose of this engineering design evaluation is to identify how offshore turbine operation could be modified to more readily take advantage of the behavior of the low-NO_X combustors currently being developed.

The evaluation should focus on techniques to reduce load fluctuations and practices which would allow some turbines to operate near full load. Developments from all manufacturers that are active in supplying turbines to offshore platforms should be considered. Aspects of this analysis should include:

- Review of the duty cycle data (see Section 5.1.1),
- Platform load modelling,
- Load allocation among turbines,
- Consideration of other techniques to handle load swings (including turbines with water injection or rich burn engines with non-selective catalysts), and
- Load management to reduce load variations.

The results of this evaluation should also identify changes in performance, if any, that would be required of dry low-NO_x combustors for their use offshore. The turbine manufacturers will have to provide significant input in evaluating the scope of necessary hardware modifications.

Hardware Modifications

Depending on the results of the engineering evaluation, hardware modifications might or might not be required prior to demonstrating dry low-NO_x combustors offshore. Thus the scope or nature of this aspect of the program cannot be well-defined in advance.

Should modifications be required, the turbine manufacturer must be involved in conducting the development. Modifications would be quite dependent on individual manufacturer's turbines and their combustors.

As an example of the nature of hardware development for dry low-NO_x combustors, a recent report by Solar lists the additional development activities which are required for their Centaur Type H low-NO_x combustor:

- Optimize the pilot injector and fueling schedule to provide adequate combustor operating range and improved part load combustion efficiency.

- Augment the liner cooling near the combustor upstream end to drop wall temperature to the 1144K (1,600°F) target temperature.

- Develop a secondary air injection port configuration to yield the necessary turbine inlet temperature and pattern factor.

- Control system development to allow acceptable combustion system operation during engine transient as well as steady state operation.

- Development of a reliable ignition system for a multi-can ultra-low NO_X combustion system.

- Development of transition ducting to direct the combustor exhaust flow to the turbine nozzle.

- Engine design modifications to allow integration of the low emissions burner system into the gas turbine.

Some of the design criteria for these ongoing developments might not be compatible with the requirements of offshore turbines. Specific hardware modifications would thus be identified through the evaluation of offshore turbine suitability with appropriate input from the manufacturers and their research staff. Any modifications should be tested in controlled situations prior to full-scale demonstrations.

Offshore Demonstration

After any necessary modifications are made to a dry low-NO_X combustor, the turbine should be ready for an offshore demonstration. Should the hardware modifications be extensive, however, an onshore demonstration might be warranted prior to an offshore demonstration. The most important criteria in determining whether an onshore demonstration is first required are safety and reliability of any hardware modifications.

An offshore demonstration would include the following activities:

- Onshore preparation of the test turbine,
- Changeout of one platform turbine with the test turbine and preparation of a test monitoring unit (complete exhaust gas analysis, monitoring of all turbine operating parameters, etc.),

- Test program design and execution,
- Hardware design modifications (if required), and
- Performance analysis.

Once any operation problems discovered from the demonstration are resolved, and durability/longevity of the combustor components are proven, the technology should be considered as available for offshore applications.

5.1.3 Catalytic Combustion

Catalytic combustion for gas turbines is a technique which is still some years away from the commercial demonstration phase. Yet, when catalytic combustion does become available for offshore gas turbines, it could reduce NO_x emissions, as well as those of hydrocarbons and carbon monoxide, to practically insignificant levels. Thus, while other techniques show more short term promise for reducing emissions from offshore gas turbines, catalytic combustion provides a long term answer. Therefore, this report suggests following the developments in catalytic combustion, and recommends that the development of this technology be greatly pushed once the necessary research breakthroughs have occurred.

Many aspects of catalytic combustion technology need to be developed prior to the commercialization of this technology. These can be divided into two broad areas:

1) Catalyst Material Research

2) Prototype Development

The major participant players in the first area are catalyst suppliers and basic researchers in large laboratories and academia. The major projects in the second area are being carried out by consortiums of engine manufacturers and other parties, often being co-sponsored by several research organizations.

Catalyst Material Research

At this point, we believe the most important development required for successful use of catalytic combustion on gas turbines is a suitable catalyst material displaying the following properties:

- Thermal resistance to operating temperature,
- Constant activity over prolonged use at operating conditions,
- Resistance to thermal shocks from load cycling, and
- Resistance to physical deterioration from mechanical vibration.

The first step in this process will be to identify viable catalyst substrates or support materials. The second step will be to identify appropriate combinations of active catalytic ingredients and wash coats. In general, the development of catalytic materials is still considered to be more of an art than a science. While efforts are being made to better relate the structure of catalysts to the molecular activity, most of the research in developing new catalysts is being conducted on a trial and error type basis.

Prototype Development

After viable catalyst materials have been developed, they will need to be incorporated into prototype combustors. Research and development issues here include:

- Combustor shape, size, and configuration,
- Fuel and air premixing,
- Combustor control, and
- Integration into existing turbine engines.

While efforts into some of these areas have already been initiated, much of this work will be quite specific to an individual catalyst material and to an individual turbine engine. Other aspects, such as combustor control and fuel/air premixing, will have already been developed for the lean premixed family of combustors.

Since the timeframe for development of the catalytic combustor is most likely longer than the timeframe for the Offshore Operations NO_x Control Development Program, we recommend that a somewhat low level of effort be directed toward this technology. This effort should focus on staying abreast of all important developments in this area, so that any breakthroughs can be acted upon quickly. Should significant breakthroughs occur, it might be desirable to redirect efforts from other gas turbine techniques to catalytic combustion.

To follow developments in this field, the program should conduct an annual survey of developments in catalyst material research and in prototype developments efforts. As a part of this annual survey, researchers in the field should be made aware that this program would actively foster the full-scale development of catalytic combustors for gas turbines, once the likelihood for success appears high enough.

5.1.4 Selective Catalytic Reduction (SCR)

SCR systems have been successfully applied to onshore gas-fueled turbines in cogeneration service. However, the demands of offshore use (significant load variations, space restrictions, and safety considerations) require the development of enhanced SCR systems. The program's emphasis should be placed on improved feed forward/feed back control systems, catalysts that require less space and operate over wider temperature ranges, and use of aqueous ammonia as the reagent.

The recommended program for SCR technology is divided into three segments as follows:

1) Development of enhanced SCR system components.

2) Testing of SCR systems in a slip stream development unit.

3) Full scale field demonstration, if successful concepts are borne out through laboratory and slip stream testing.

Each of these development efforts is further describes below.

<u>Development of Enhanced SCR System Components</u>

To successfully apply SCR systems on offshore gas turbines, improvements to commercially available technology are required in several areas. The most challenging of these is load following capability. Platform turbines can experience rapid swings of significant magnitude in load, especially during drilling operations. These swings will produce significant variations in the amount of NO_x entering an SCR reactor. For effective SCR performance the ammonia injection rate must be controlled to yield a constant molar ratio of NH_3 to NO_x entering the catalyst bed. Advanced feed forward/feed back SCR control systems must be developed to track these load swings.

Most commercial SCR systems use anhydrous ammonia as a reagent. Safety concerns regarding the possible release of a toxic vapor cloud may preclude use of ammonia in this form on platforms. Ammonia-water solutions would resolve this problem. Although some commercial SCR systems have employed this reagent, development of improved injection systems will likely be required. These injection systems must be capable of providing a uniform distribution of ammonia across the exhaust duct over a wide load range.

Improved SCR catalysts may be required for offshore applications. Operation over a relatively wide temperature range is needed to accommodate variations in exhaust temperature due to load changes. Additional enhancements could include an increase in space velocity to reduce the volume of catalyst required, use of catalysts that "store" ammonia and may therefore be able to better accommodate load swings, and the ability to tolerate firing of liquid fuel in the turbines without degradation in performance due to poisoning or particulate deposition.

This portion of the development program should be conducted by selected SCR system manufacturers and control system specialists. It would involve laboratory or pilot scale testing of proposed concepts. Duty cycle and emission information collected from that portion of the program outlined in Section 5.1.1 would be used to develop test conditions that would simulate transient conditions experienced in platform gas turbine applications.

Parameters which should be investigated in these studies include the following:

- Temperature window of activity,
- Reagent stoichiometry,
- Side or by-product emissions, and
- Space velocity requirement.

Slip Stream Demonstration Unit

A slip stream demonstration unit will be designed to test SCR technologies on actual turbine exhaust gas. A portion of the exhaust gases from a platform gas turbine would be diverted to this unit to provide realistic test condition. The purpose of the unit is to develop all engineering and performance data that are required for designing a full-scale unit. This unit must be sufficiently flexible to allow for testing of various reagents (both liquid and gaseous) and various catalyst configurations.

Principle components of the slip stream unit should include:

- Reactor vessel (possibly interchangeable vessel sections with various reagent feed configurations, vessel internals, etc.),
- Reagent feed systems, liquid and gaseous,
- Reagent storage and handling systems,
- Gas sampling and analysis train (NO_x and O_2; other constituents, such as CO, CO_2, ROC, PM, by-product emissions etc., might only need to be analyzed intermittently),
- Data acquisition system (PC-based), and
- Skid mounted design so it can be easily transportable.

Since a primary function of the unit is to develop full-scale design parameters, much attention should be placed on instrumentation and data acquisition.

The slip stream demonstration unit should be used to conduct in-field testing of promising SCR systems after they are fully explored in a controlled laboratory or pilot plant setting. While the bulk gas composition will be fixed by the turbines themselves, the other key variables which need to be explored are the same as those identified for laboratory testing. Detailed test matrices and data reduction procedures should be established prior to conducting test programs so that the desired results can be achieved through the testing program.

Full-Scale Demonstration

Following tests in the slip stream demonstration unit of SCR technologies, the most successful process should be selected for full scale demonstration. For SCR, it is envisioned that laboratory experiments and the slip stream demonstration tests will define the unit performance reasonably well prior to a full-scale demonstration. However, some process optimization will be required for the scale up, particularly in the reagent injection system.

The size and configuration of the full-scale unit will strongly depend on the result of prior development work. Therefore, it its probably too early to describe the exact arrangement of the equipment although some of the system components would be roughly analogous to those required for the slip stream unit. Unlike the slip stream unit, the full-scale unit will probably be designed for only one SCR system; flexibility in handling several catalyst types is not a design criteria for the full scale unit.

Another important aspect of the full-scale demonstration program is to resolve issues related to the operability and longevity of the selected process. It is anticipated that certain critical components will be identified, and suitable design alterations made to achieve performance goals. After a successful demonstration, the technology should be considered available for operations.

5.1.5 Selective Non-Catalytic Reduction (SNR)

Two of the new concepts in SNR, (Technor's RapReNO$_X$ and Fuel Tech's work on lower temperature reagents for their NO$_X$OUT process) may prove to be effective for offshore applications. However, a considerable amount of research and development is still required in order to bring these techniques to a level of commercialization for offshore use. The suggested program for SNR development contains the following three components. Only the first is currently included in the Offshore Operations NO$_X$ Control Development Program. The remaining components could be activated if the research breakthroughs required to make SNR a viable offshore technology are achieved.

1) Continuous monitoring of SNR research and laboratory testing of promising new reagents.

2) Testing of SNR technologies in a slip stream development unit (if the required research breakthroughs are achieved).

3) Full-scale field demonstration (if concepts are successfully borne out through laboratory and slip stream testing).

The first component is designed to continuously monitor SNR research and, when appropriate, fund key research activities that may lead to the breakthroughs required for application of SNR on offshore gas turbines. If a promising technology is identified through this work, the remaining components could carry the concept through the required development stages to a full scale offshore demonstration. Each of these development efforts is further described below.

Monitoring of SNR Research and Laboratory Tests of Promising Reagents

The Offshore Operations NO_X Control Development Program should continuously monitor SNR research activities and should include, when appropriate, limited laboratory testing of promising SNR techniques. Presently, the MMS is sponsoring such work on the $RapReNO_X$ technology. Parameters which should be investigated in these studies include:

- Temperature window of activity,
- Reagent Stoichiometry
- Side or by-product emissions,
- Residence time requirements,
- Reagent feed techniques, and
- Influence of exhaust gas components.

Other tests might be dictated depending on the results of initial efforts. For example, a recent research report on the $RapReNO_X$ process by Sandia Laboratories suggests that isocyanic acid reduction of NO_X is greatly catalyzed by iron oxide. These results suggest that the surface effects in the $RapReNO_X$ process should be further investigated. This example demonstrates that all laboratory efforts in the development process should remain responsive to new process knowledge as it develops.

From the overall program perspective, it is also important to keep abreast of new SNR techniques as they are discovered. In this manner, promising new processes can be investigated in the laboratory for their potential applicability to offshore sources. Once the key process parameters are well-defined in the laboratory, the techniques should be tested on actual turbine exhaust gas.

Slip Stream Demonstration Unit

A slip stream demonstration unit (similar to the SCR unit described in Section 5.1.4) may be used to conduct in-field testing of promising SNR reagents if the required research breakthroughs are achieved and after they are fully explored in a controlled laboratory setting. While the bulk gas composition will be fixed by the turbines themselves, the other key variables which need to be explored are the same as those identified for laboratory testing. Detailed test matrices and data reduction procedures should be established prior to conducting test programs so that the desired results can be achieved through the testing program.

Full-Scale Demonstration

Following successful tests in the slip stream demonstration unit of SNR technologies, the most successful process would be selected for full scale demonstration. For SNR it is envisioned that laboratory experiments and the slip stream demonstration unit will test a variety of reagents at various temperatures, stoichiometries, etc., leaving the unit performance reasonably well-defined prior to testing a full-scale demonstration unit. Some process optimization will be required for the scale up, particularly in the reagent feed system/residence time requirements.

The size and configuration of the full-scale unit will strongly depend on the results of prior development work. Therefore, it is probably too early to describe the exact arrangement of the equipment. Although some of the system components would be roughly analogous to those required for the slip stream unit. Unlike the slip stream unit, the full-scale unit will probably be designed for only one technology (reagent); flexibility in handling several reagent types is not a design criteria for the full scale unit.

Another important aspect of the full-scale demonstration program is to resolve issues related to the operability and longevity of the selected process. It is anticipated that certain critical components will be identified, and suitable design alterations made to achieve the performance goals. After a successful demonstration, the technology should be considered available for offshore operations.

5.1.6 Schedule and Cost

A six year schedule for the gas turbine program is shown in Figure 5.1-1. This schedule shows activity in all five areas:

- Duty Cycle and Baseline Emission Characterization
- Dry Low-NO_X Combustors
- Catalytic Combustors
- Selective Catalytic Reduction
- Selective Non-Catalytic Reduction

Within these areas, the schedule is further broken down by major project effort.

The schedule which is shown is based upon what we believe to be realistic assumptions about the research components. Research and development cannot be clearly charted in advance; rather, some areas, such as hardware development, require trial and error efforts until an adequate solution or component is created. To assist in this process, research managers need to be aware of long term objectives as well as short term goals. Thus the schedule can be considered as representative of the program, but cannot by nature be rigid.

In accordance with the schedule, a representative cost estimate has been developed for the gas turbine program. This estimate is presented in Table 5.1-1. The cost estimate shows an approximate expenditure of $14.0 Million over the six year time frame. The cost is distributed among the five program areas as follows:

Duty Cycle and Emission	$1.1	Million
Dry Low-NO_X Combustor	6.8	
Catalytic Combustor	0.3	
SCR	4.8	
SNR	0.9	
TOTAL	$13.9	Million

If significant breakthroughs occur in catalytic combustion or SNR research and development, program emphasis and funding would be shifted towards these technologies. Potential sources of funding are described in Section 5.3.

FIGURE 5.1-1

GAS TURBINE NOx CONTROL PROGRAM

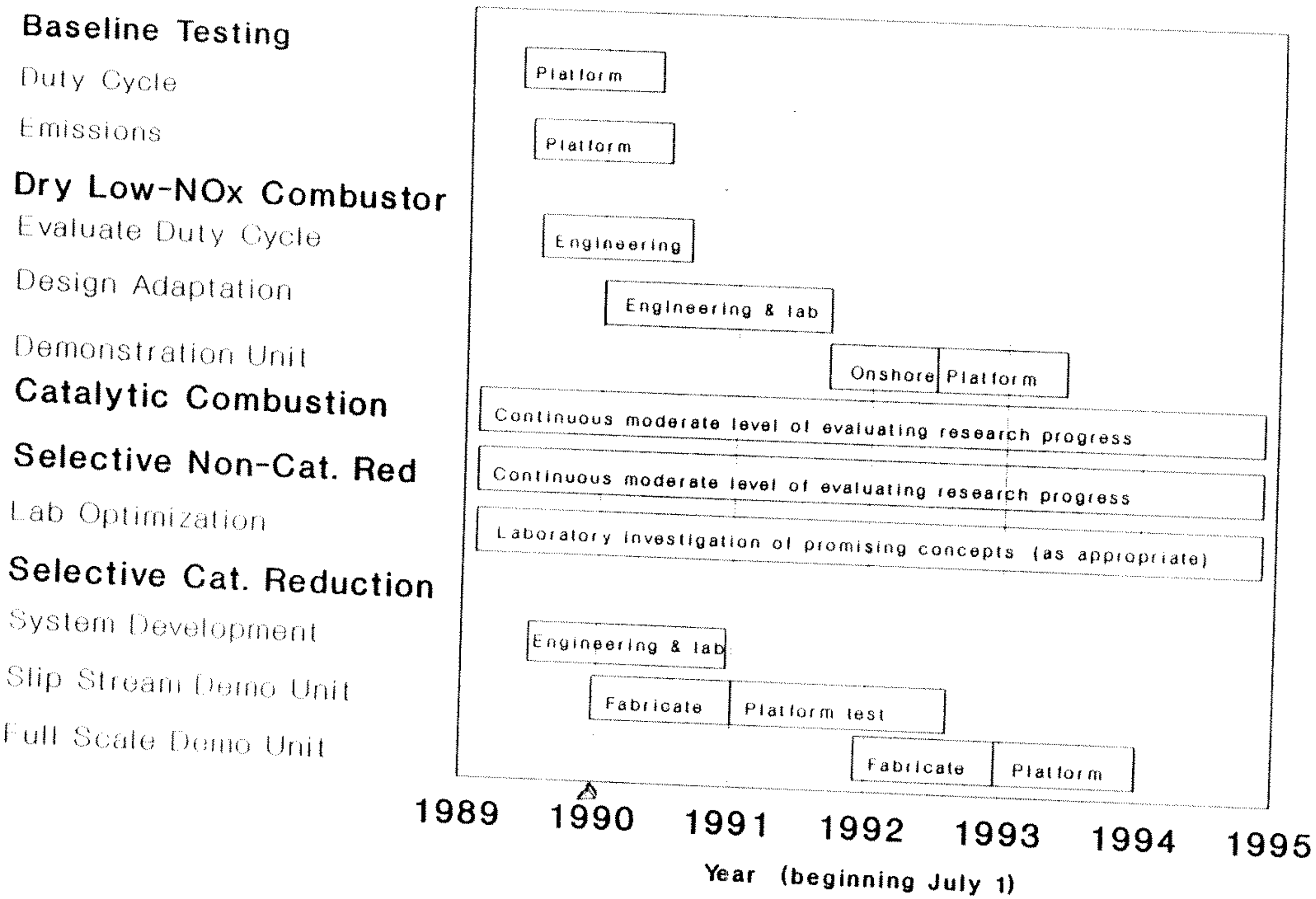


TABLE 5.1-1

GAS TURBINE PROGRAM COST ESTIMATE
($1,000's)

PROFESSIONAL SERVICES

	1989	1990	1991	1992	1993	1994	TOTAL
Baseline Testing							
Duty Cycle	150	100					**250**
Emissions	200	100					**300**
Dry low-NO_x Combustion							
Design Studies	100	200					**300**
Development		500	700				**1200**
Demonstration			400	600	400		**1400**
Catalytic Combustion	50	50	50	50	50	50	**300**
SCR							
Development	150	250	250	150	50	50	**900**
Slip Stream		400	400	200			**1000**
Full Scale				400	300	100	**800**
SNR	50	150	150	50	50	50	**500**
TOTAL	**700**	**1750**	**1950**	**1450**	**850**	**250**	**6950**

FACILITIES AND EXPENSES

	1989	1990	1991	1992	1993	1994	TOTAL
Baseline Testing							
Duty Cycle	150	100					**250**
Emissions	200	100					**300**
Dry Low-NO_x Combustion							
Evaluate							
Design		800	800				**1600**
Demonstration			800	1000	500		**2300**
Catalytic Combustion							
SCR							
Development	150	250	250	150	50	50	**900**
Slip Stream		400	100	100			**600**
Full Scale				500	100		**600**
SNR	50	150	150	50			**400**
TOTAL	**550**	**1800**	**2100**	**1800**	**650**	**50**	**6950**

TOTAL

	1989	1990	1991	1992	1993	1994	TOTAL
Baseline Testing							
Duty Cycle	300	200					**500**
Emissions	400	200					**600**
Dry Low-NO_x Combustion							
Evaluate	100	200					**300**
Design		1300	1500				**2800**
Demonstration			1200	1600	900		**3700**
Catalytic Combustion	50	50	50	50	50	50	**300**>
SCR							
Development	300	500	500	300	100	100	**1800**
Slip Stream		800	500	300			**1600**
Full Scale				900	400	100	**1400**
SNR	100	300	300	100	50	50	**900**
TOTAL	**1250**	**3550**	**4050**	**3250**	**1500**	**300**	**13900**

5.2 Diesel Engine Program

The offshore diesel engine program should emphasize alternative fuels, either methanol or natural gas, as the most attractive route to achieving the 2 g/hp-hr NO_x target. Conversion to alternative fuels can be effected in a variety of ways, some of which involve rather simple retrofits, characterized by lower initial costs, but higher operating costs. These should be more suitable for equipment which is present in the area for only short periods of time. Other methods of conversion involve the development of engines that are optimized for a particular fuel. These should be more suitable for the dedicated west coast fleet of offshore equipment.

Although technical hurdles to the development of alternative fueled engines for offshore operations do exist, the largest barriers to adopting alternative fuels are institutional limitations, which can include fuel supply, safety and health concerns, and impacts on host equipment. These institutional limitations should be explored prior to any significant technical efforts. If the institutional hurdles can be overcome through technology development and regulatory resolution, then alternative fuels would become the preferred path of the program. If alternate fuels cannot be utilized offshore, then the program should focus on a combination of combustion modifications and exhaust gas treatment to achieve the 2 g/hp-hr NO_x target.

5.2.1 Duty Cycle and Baseline Emission Characterization

Prior to demonstrating any of the technologies on an individual engine or vessel, the baseline emissions and duty cycle should be carefully monitored. From a recent study on crew and supply boats, excellent data is available on the duty cycle of a few boats serving offshore activities. But duty cycle data needs to be collected for cranes, exploratory drilling rigs and construction tugs.

Parameters to be collected during the duty cycle evaluation include:

- Fuel input,
- Generator output (for engine gensets),
- Engine speed,
- Exhaust and intake manifold temperatures,
- Ambient conditions,
- Exhaust gas bulk constituents, and
- Fuel composition.

While emission testing is being conducted, the exhaust should be monitored for NO_x, CO, CO_2, O_2, hydrocarbons and particulates.

The data should be analyzed, while this test period is being conducted. Prior experience suggests that, after engine emissions are fully characterized, only a few measurements need to be taken to characterize engine performance over a longer period of time. We believe that engine speed, exhaust temperature, injector rack position, and ambient conditions should adequately characterize engine duty over a longer period of time. After the one or two months initial characterization has been completed, a longer term program (4 to 6 months) of engine monitoring would provide significant additional data on the engines.

All testing should be done in accordance with accepted methods, such as those endorsed by the EPA or the California Air Resources Board. Additionally, quality assurance/quality control should be performed by an independent party. Test results should be compared to previously collected data on identical engines, so that discrepancies can be verified during the actual testing.

5.2.2 Feasibility of Alternative Fuels

The use of alternative fuels in place of diesel fuel could generate institutional and regulatory concerns, including:

- Availability of fuel,
- Acceptability of alternative fuels to marine vessel regulators,
- Cruising distance of vessels,
- Health effects of other emissions,
- Fuel supply infrastructure, and
- Safety concerns associated with the storage and handling of alternative fuels offshore.

In addition to these concerns, there are technical hurdles which need to be overcome prior to the development of commercially available alternative fuels for reciprocating engines. Many techniques are available for firing methanol or CNG, including spark ignition, diesel fuel pilot ignition, lean burn, cetane improvers, etc. The feasibility study should evaluate these institutional and regulatory concerns, as well as technical concerns, in a program which includes;

- Interviews and meetings with senior officials at the American Bureau of Shipping (ABS), the Coast Guard, and other concerned agencies to identify the basis of regulatory barriers, and safety issues related to the use of methanol or CNG on work boats and drill rigs.
- Review existing methanol and CNG demonstration projects in California (California Energy Commission and South Coast Air Quality Management District) in terms of technical gains which could be translated to offshore operations, and in terms of the potential for synergism between the ongoing efforts in this area and the Offshore Operations NO_X Control Development Program.
- Review recent technical developments in firing methanol and CNG in reciprocating engines to identify the most promising technique(s) for using these fuels in offshore engines.

The results of this feasibility study should lead to the diesel engine program decision point on whether to proceed with alternative fuels or another course.

5.2.3 Alternative Fuels Technology

As shown in Section 4.0 and Appendix B, there are a variety of techniques that are being explored for utilizing alternative fuels in diesel engines. For offshore operations, these techniques have been divided into two categories:

Retrofits - techniques which can be applied to existing engines to achieve alternative fuel firing and significant NO_X reduction. These techniques would be appropriate for equipment which is deployed for shorter periods of time. Use of retrofit techniques, although providing substantial emission reductions, would probably not achieve the 2 g/hp-hr target.

Optimized Engines - techniques which involve replacement of existing engines with new alternate fueled engines. These techniques would be more appropriate for equipment which is part of the dedicated fleet or permanent installations.

Methanol and CNG techniques and their technical challenges in both of these categories are described below.

Retrofit Techniques

Simple retrofit techniques such as dual fuel conversion kits for CNG with a diesel pilot and methanol fuel with a cetane enhancer have been demonstrated for heavy duty truck and bus engines. Some of these techniques are beginning to be demonstrated on larger medium-speed diesel engines in stationary applications. Engine modifications that are required to carry out these retrofits do not necessarily require the collaboration of engine manufacturers.

Fuel storage, fuel delivery, injectors, injection timing and engine rating could all be affected through the use of one of these simple retrofit techniques. Many of these areas are unique for each type of engine, thus several demonstrations would be required before these techniques could be considered as truly available for offshore operations. Offshore engines that could be targeted for these demonstrations include:

- Tug boat main engines,
- Exploratory drill rig engines and engine generators, and
- Construction equipment engines.

All of these equipment types are deployed for only short periods of time for individual projects. Thus the simpler retrofits with lower investment requirements become the most appealing way of controlling emissions.

Optimized Engines

Optimized engines involve the use of spark ignition, compression ignition, torch ignition, lean burn, etc., to efficiently combust methanol or CNG in an engine. These modifications are so extensive that replacement of an existing engine with a new one would be the most feasible method of conversion. Close collaboration with the engine manufacturers would be required for this element of the program to be successful.

Research and development efforts are underway to use methanol and/or CNG for many of the diesel engines commonly used on trucks and buses. Similar efforts have not yet been initiated for the larger engines that are typically found offshore. Three engine manufacturers account for nearly all of the engines being used offshore California: Electromotive Division (EMD), Detroit Diesel, and Caterpillar.

Hardware modifications will vary depending on the system(s) that are considered most appropriate for specific engines. Some of the important offshore engine manufacturers have been working on methanol fuel for other engines in their product line. DDA, for example, has been developing methanol technology using elevated compression temperature, with a compression ratio of 19 to 1. Caterpillar, on the other hand, has been developing methanol technology from spark assisted ignition. It is quite likely that individual manufacturers would wish to maintain their basic alternative fuel techniques while translating results from other engines to those used offshore. At this point in time, it is not appropriate to identify specific requirements of this phase of the methanol program. Much of the development work will be trial and error testing of components for engines on test stands in manufacturers research centers.

All of the engine developments will be unique for each type of engine, thus a number of demonstrations would be required before these techniques could be considered as truly available for offshore operations. Offshore engines that could be targeted for these demonstrations include:

- Crew and supply boat main engines and generators, and
- Pedestal crane engines.

These equipment types are permanently installed or are deployed for long term service. Thus replacement with optimized engines with lower operating costs becomes the most appealing way of controlling emissions.

Offshore Demonstrations

An offshore demonstration would include the following activities:

- Onshore preparation of a test engine (assuming engine owners would not desire extensive modifications to their own engines),
- Engine changeout (offshore or drydock),
- Test program design and execution, including emission monitoring,
- Hardware modification testing (if required), and
- Performance analysis.

5.2.4 Advanced Diesel Technology with Exhaust Gas Treatment

As previously described, alternative fuels technology are recommended as the preferred route for achieving the 2 g/hp-hr target for the diesel engine program. Should alternative fuels be institutionally unacceptable, then the 2 g/hp-hr NO_x target would need to be achieved through advanced diesel technology combined with exhaust gas treatment. Efforts that would be required for both of these areas are described below.

Advanced Diesel Technology

Advanced diesel technology would involve replacement of existing engines with advanced low emission engines. To achieve low emissions would require a combination of tailored injection and electronic control.

Low emission technology requires rather extensive research and development efforts on each engine for which it is developed. Systems that can be modified include injectors, timing control, piston shape, and others. These modifications are very specific to each engine design and model. Thus, most of the development work needs to be conducted by the engine manufacturers. Many of the manufacturers have already been testing and developing various tailored injection modifications for their truck and bus engine lines. It is highly probable that the individual manufacturers would want to utilize the methods and results from this work for their product lines used in offshore applications.

The first phase of the program would involve reviewing of individual manufacturers success in various modifications which have been completed for other engines. Although collaboration among manufacturers is not anticipated, there are quite a few development results that are available in the technical literature which might also be reviewed. Based upon these reviews, many possible modifications could be identified. An engineering evaluation should then be carried out to select those with the greatest promise for individual engines and their offshore applications.

A priority list of modifications and tests should result from the concept evaluation. This listing will recognize, of course, that the developments required will probably be "trial and error" by nature. The research efforts cannot be precisely planned, rather they will be oriented towards performance targets and criteria for evaluation.

A program for developing new systems and components will arise from the engineering evaluation. Systems which might need developing include:

- Dual injection for two stage injection,
- Advanced injection control and rate timing, and
- Enhanced injection spray effects.

Advanced control systems would also be demonstrated on engines in controlled laboratory settings, where a simulated offshore duty cycle could be tested. Single cylinder tests will be used extensively during the initial stages of development. Once components have been proven in single cylinder engines, full size engines on test stands should be utilized for testing overall performance and to improve component and system durability.

Exhaust Gas Treatment

The second component of this program would involve the development of exhaust gas treatment techniques for the offshore diesel engines. New developments are continuously occurring in catalytic and non-catalytic NO_X removal processes. At this point in time, catalytic processes using ammonia have been demonstrated on stationary diesel engines with continuous duty in West Germany and Japan. Various techniques have been utilized to overcome fouling of the catalyst with the particulate in diesel exhaust. Although SCR with ammonia is presently the most developed technique, other concepts are being developed. If exhaust gas treatment is deemed appropriate for the offshore diesel engines, it would be most constructive to re-evaluate the status of various techniques at that time. A general description of the suggested approach is presented here. This suggested program is quite similar to that shown in Sections 5.1.4 and 5.1.5 for the gas turbine exhaust gas treatment development effort.

Exhaust gas treatment techniques should be selected for offshore demonstration on the basis of successful laboratory results and engineering evaluation. The first step in trying one or more techniques offshore should be a slip stream demonstration unit, that allows for optimization of process operating parameters over the duty cycle of host equipment items. Detailed test matrices and data reduction procedures should be established to conduct test programs so that the desired results can be achieved through the testing program.

Slip stream demonstration should allow for testing of a wide variety of operating conditions for one or more process. Full scale demonstration should then focus on longevity and operability. While some process optimization would be required, the ranges of many operating parameter should be established during the slip stream demonstration phase.

5.2.5 Schedule and Cost

A six year schedule for the diesel engine program is shown in Figure 5.2-1. This schedule shows activities in all areas:

- Alternative Fuels Feasibility
- Methanol
- CNG
- Advanced Diesel Technology
- Exhaust Gas Treatment

Within these areas, the schedule is further broken down by major project effort. The schedule shows these developments by the combinations of techniques which would eventually result. Additionally, the schedule shows program I (alternate fuels) versus program II (advanced diesel technology plus exhaust gas treatment). Key decision points are also shown.

The schedule which is shown is based upon what we believe to be realistic assumptions about the research components. Research and development cannot be clearly charted in advance; rather, most areas require trial and error efforts until an adequate solution or component is created. To assist in this process, research managers need to be aware of long term objectives as well as short term goals. Thus the schedule can be considered as representative of the program, but cannot by nature be rigid.

In accordance with the schedule, a representative cost estimate has been developed for the diesel engine program. This estimate is presented in Tables 5.2-1 and 5.2-2. The cost estimate shows an approximate expenditure of about $13 Million over the 6 year time frame. These tables show the cost for both the alternative fuels program (preferred rate) and the advanced diesel program (alternate rate).

5.3 Program Management

Many organizations have interest in part or all of the Offshore Operations NO_x Control Development Program. Due to the magnitude of the research and development work required, the entire program will be comprised of a number of individual programs. Each individual program will focus on certain applications and certain technologies.

FIGURE 5.2-1
DIESEL ENGINE NOx CONTROL PROGRAM

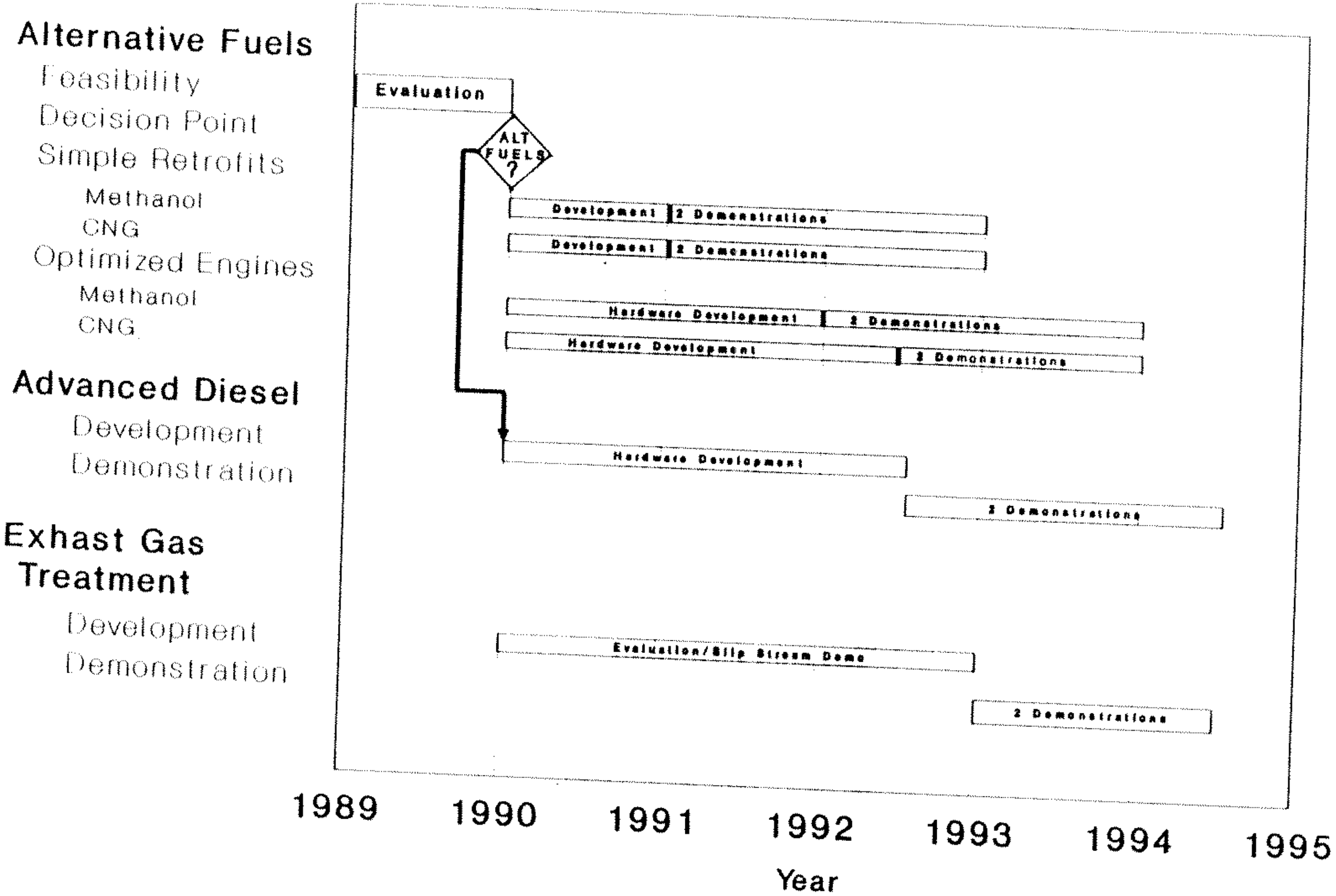


TABLE 5.2-1

DIESEL ENGINE PROGRAM

COST ESTIMATE

ALTERNATE FUELS PROGRAM
($1,000's)

PROFESSIONAL SERVICES

	1989	1990	1991	1992	1993	1994	TOTAL
Baseline Testing							
Duty Cycle	150	100					250
Emissions	200	100					300
Feasibility Determination	100						100
Simple Retrofits							
Methanol Demonstration		300	300	300			900
CNG Demonstration		300	300	300			900
Optimized Engines							
Methanol Development		400	400				800
Methanol Demonstration				500	500		1000
CNG Development		400	400	200			1000
CNG Demonstration				250	500	250	1000
TOTAL	**450**	**1600**	**1400**	**1550**	**1000**	**250**	**6250**

FACILITIES AND EXPENSES

	1989	1990	1991	1992	1993	1994	TOTAL
Baseline Testing							
Duty Cycle	150	100					250
Emissions	200	100					300
Feasibility Determination							
Simple Retrofits							
Methanol Demonstration		300	300	300			900
CNG Demonstration		300	300	300			900
Optimized Engines							
Methanol Development		500	500				1000
Methanol Demonstration				600	600		1200
CNG Development		500	500	250			1250
CNG Demonstration				300	600	300	1200
TOTAL	**350**	**1800**	**1600**	**1750**	**1200**	**300**	**7000**

TOTAL

	1989	1990	1991	1992	1993	1994	TOTAL
Baseline Testing							
Duty Cycle	300	200					500
Emissions	400	200					600
Feasibility Determination	100						100
Simple Retrofits							
Methanol Demonstration		600	600	600			1800
CNG Demonstration		600	600	600			1800
Optimized Engines							
Methanol Development		900	900				1800
Methanol Demonstration				1100	1100		2200
CNG Development		900	900	450			2250
CNG Demonstration				550	1100	550	2200
TOTAL	**800**	**3400**	**3000**	**3300**	**2200**	**550**	**13250**

TABLE 5.2-2

DIESEL ENGINE PROGRAM

COST ESTIMATE

ADVANCED DIESEL WITH EXHAUST GAS TREATMENT PROGRAM

($1,000's)

PROFESSIONAL SERVICES

	1989	1990	1991	1992	1993	1994	TOTAL
Baseline Testing							
Duty Cycle	150	100					**250**
Emissions	200	100					**300**
Alternate Fuels Feasibility	100						**100**
Advanced Diesel Technology							
Engine Development		600	600	300			**1500**
Demonstrations				250	500	250	**1000**
Exhaust Gas Treatment							
Engineering Evaluation		150					**150**
Slip Stream Demonstration			750	750			**1500**
Demonstration					600	600	**1200**
TOTAL	**450**	**950**	**1350**	**1300**	**1100**	**850**	**6000**

FACILITIES AND EXPENSES

	1989	1990	1991	1992	1993	1994	TOTAL
Baseline Testing							
Duty Cycle	150	100					**250**
Emissions	200	100					**300**
Alternate Fuels Feasibility							
Advanced Diesel Technology							
Engine Development		600	600	300			**1500**
Demonstrations				300	600	300	**1200**
Exhaust Gas Treatment							
Engineering Evaluation		50					**50**
Slip Stream Demonstration			1000	750			**1750**
Demonstration					750	750	**1500**
TOTAL	**350**	**850**	**1600**	**1350**	**1350**	**1050**	**6550**

TOTAL

	1989	1990	1991	1992	1993	1994	TOTAL
Baseline Testing							
Duty Cycle	300	200					**500**
Emissions	400	200					**600**
Alternate Fuels Feasibility	100						**100**
Advanced Diesel Technology							
Engine Development		1200	1200	600			**3000**
Demonstrations				550	1100	550	**2200**
Exhaust Gas Treatment							
Engineering Evaluation		200					**200**
Slip Stream Demonstration			1750	1500			**3250**
Demonstration					1350	1350	**2700**
TOTAL	**800**	**1800**	**2950**	**2650**	**2450**	**1900**	**12550**

Individual programs have already begun towards offshore operations NO_x control. Two programs which are just now getting underway are the investigation of RapReNO_x for offshore applications (Minerals Management Service, sponsor) and the development of advanced NO_x control technology for Solar Centaur Turbines in offshore applications (Chevron, sponsor; Santa Barbara County, manager). Each individual program will have different participants, sponsors, and structure.

Program management for the entire program thus includes management of the various individual efforts, as well as overall coordination. Important aspects of managing the individual efforts include sponsorship, technical review, and participants. Overall coordination, since the program is not centrally controlled, emphasizes technology management and technology transfer.

Management of Individual Programs

The structure of each individual program element will be unique. Structure of these elements should be formed based upon the parties involved in management, sponsorship, development efforts, and review. Furthermore, the structure must depend on the technology(ies) which are being developed.

Overall Coordination

Overall coordination of the program will emphasize technology transfer and information dissemination. Since many organizations will be involved in managing, sponsoring and conducting individual programs, it is important to have effective and complete communication among all participants.

Most of the individual efforts will probably establish technology advisory panels. Thus one important objective of overall coordination is to ensure comprehensive availability of all relevant information to these advisory panels. At the present time, Santa Barbara County and the Minerals Management Service are planning to jointly sponsor a workshop on NO_x control for offshore operations. This type of forum is well-suited for the information exchange that should be stemming from overall coordination.

A final aspect of overall coordination is ensuring that no large opportunity is overlooked. For example, should a breakthrough occur in catalytic combustion, the opportunities and challenges faced in its development should be disseminated to all concerned in the individual efforts for gas turbines.

Principal Participants

The likely roles of the principal participants in this program are described below. Each of these groups would play a key role on any technical advisory committee.

Minerals Management Service - The Minerals Management Service will serve the role of overall coordination, focusing on technology transfer and information dissemination. The Minerals Management Service will also continue to support focused laboratory and bench scale programs designed toward "proof of concept" testing of various innovations. The Minerals Management Service would also be responsible for assuring that new technologies comply with all applicable federal regulations.

State and Local Agencies - These organizations will often serve as managers for various development and demonstration programs. For example, the Santa Barbara County Air Pollution Control District will be managing a program to develop low-NO_X techniques for Solar Centaur gas turbines. These agencies will also play a large role in fostering the implementation of new technologies, once they are developed.

Oil Companies - These companies will be the major source of funding for most of the efforts. Funding will result from agreements made in the permitting process, and for those OCS operators who must offset emissions since advanced NO_X control can lead to reduced offset costs. The research and development arms of these companies will also play a significant role in technology development and technical review.

Equipment Manufacturers - These firms will conduct much of the hardware development that will be required. Some of this work will be partly sponsored from other sources, with the manufacturer providing cost-shared research and development. Other efforts might be entirely self-sponsored, when individual manufacturers see competitive gains to be achieved.

Platform Designers - This group would include the architectural and engineering firms who design offshore platforms. Their role would be as a technical advisor to assure that any new technology would be compatible with platform designs and that appropriate safety measures are being incorporated.

Others - A host of other participants will be involved to various degrees in the Offshore Operations NO_X Control Development Program, including:

- Research Organizations
- Other Regulatory Authorities
- Owners of leased equipment
- Professional Societies
- Concerned Public

Since OCS development receives significant political attention, the involvement and interest of a large number of parties can be anticipated.

Bibliography by Technology

Selective Catalytic Reduction

Ando, J. and C.B. Sedman, "FGD, SCR Gain Coal - Fired - Boiler Experience in Japan", Power, Feb. 1987.

Bartz, D.R., "Catalyzed Ammonia Reduction of NO_X Emissions from Oil Fired Utility Boilers," Paper P-195, NO_X Control Technology Workshop, Asilomar, California, Oct. 1977.

Cichanowitz, E. and G. Offen, "Applicability of European SCR Experience to U.S. Utility Operations", 1987 Symposium on Stationary Combustion Nitrogen Oxide Control.

Damon, Ireland and Giovanni, "Updated Technical and Economic Review of Selective Catalytic NO_X Reduction Systems", 1987 Symposium on Stationary Combustion Nitrogen Oxide Control, Vol II, Article 32, 1987.

Dupaski, R.B. and Pader, F., "NO_X Reduction on large Bore SI Engines Using Catalytic Converters", ASME Paper, DGP Division, Houston, Jan. 1981.

Gas Turbine World, "37 MW Cogeneration Plant for Berry Powered by Frame 6 with SCR", April 1988.

Harrison, B., Diwell, A.F. and Wyatt, M., "Controllng NO_X Emissions from Industrial Sources - An Application for SCR", Platinum Metals Review, Vol. 24, pp. 50, 1985.

Heck, R.M. et. al., "Catalytic Air Pollution Controls - Commercial Development of Selective Catalytic Reduction for NO_X", 1987 APCA Meeting.

Jarvis, P. M. et. al., "Catalytic $DeNO_X$ Systems for Utility and Industrial Combined Cycle Power Plants", 1985 American Power Conference.

Kobayashi, N. et. al., "Operating Experience of SCR Systems for Steam Generators", 1987 APCA Meeting.

Nakabayashi, Y. and R. Abe, "Current Status of SCR in Japan", 1987 Symposium on Stationary Combustion Nitrogen Oxide Control.

Nishimoto, Y., et. al. "Update Technology of Selective Catalytic Five Gas NO_X Removal Systems", Mitsubishi Heavy Industries, 1987.

Radin, M.G., and B. Boyles, "Turbine Exhaust DeNO$_x$ Using Selective Catalytic Reduction", 1987 American Power Conference.

Suyama, K., "The Improvement of NH$_3$ Injection Control System for a Selective Catalytic NO$_x$ Removal System", 1987 Symposium on Stationary Nitrogen Oxide Control.

Wasser, J.H and Perry, R. B., "Diesel Engine NO$_x$ Control with SCR", Stationary Source NO$_x$ Symposium, EPA and EPRI, 1984.

Williams, J. L. et. al., "Extruded Honeycombs as Catalytic Substrates for Stationary Emissions Control of NO$_x$", 1987 APCA Meeting.

Wilson, R.P., "Emission Control Methods for Large Stationary Engines: Part III - Catalytic NO$_x$ Reduction by Ammonia", Stationary Source NO$_x$ Symposium, EPA and EPRI, 1984.

Selective Non-Catalytic Reduction

Epperly, W.R. and Broderick, R.G., "Control of Nitrogen Oxides Emissions from Stationary Sources", Fuel Tech Inc., Stamford, Connecticut, 1987.

Exxon Res. and Eng. Co., "Improved Thermal DeNO$_x$ Process", 1987.

Fuel Tech Inc., "NO$_x$OUT Process for Post-Combustion NO$_x$ Reduction", 1987.

Hishinuma, Y. et.al., "NO$_x$ Removal Process by Injection of NH$_3$ and H$_2$O$_2$ in Gas Turbine Exhaust Gas", Hitachi Limited, 1979.

Hurst, B.E., "Thermal DeNO$_x$ Technology Update", 1985 Joint Symposium on Stationary Combustion NO$_x$ Control.

Lyon, R.K. and Longwell, J.P., "Selective Non-Catalytic Reduction of NO$_x$ by NH$_3$", NO$_x$ Control Technology Semiar, Paper SR.-39, Electric Power Research Institute, Palo Alto, California, Feb. 1976.

Lyon, R.K., U.S. Patent 3900554, Aug. 19, 1975

Lyon, R.K., "Thermal DeNO$_x$", Environ. Sci. Technol., Vol. 21, No. 3, 1987.

Makansic, J., Article on DeNO$_X$ NH$_3$ Injection System as applied to Woodwaste-Fuel Boiler, Power, Oct. 1987. pp. 97.

Quartucy, G. C., M. N. Mansour, and J. H. Nylander, "Full Scale Urea Injection Evaluation", 1987 APCA Meeting.

RAPRENO$_X$

Canton, J. A., and D.L. Siebers, "Comparison of Nitric Oxide Removal by Cyanuric Acid and by Ammonia", 1988 Fall Meeting - Western States Section of The Combustion Institute.

Perry and Siebers, "Rapid Reduction of Nitrogen Oxides in Exhaust Gas Streams", Nature, Vol. 324, pp. 657, Dec 1986.

Perry, R.A., "NO$_X$ Reduction using Cyanuric Acid: Pilot Scale Testing", 1988 Fall Meeting - Western States Section of The Combustion Institute, .

Siebers, D. L., Canton, J.A., "Removal of Nitric Oxide from Exhaust Gas with Cyanuric Acid", 1988 Fall Meeting - Western State Section of The Combustion Institute.

Siebers, D. L.; Canton, J.A. "Reduction of Nitrogen Oxides by the RapReNO$_X$ Process", Sandia National Laboratories, 1988.

Technor Inc., "RapReNO$_X$: A Solution to NO$_X$ Emissions", 1988.

ElectroChemical Reduction

Hossain, Neyman, Cook and Gordon, "IGR Solid-State Electrochemical NO$_X$ Control for Natural Gas Combustion Exhaust Gas", ASME Energy-Sources Tech. Conference, Environmental Session, Jan. 1988.

Dry Low-NO$_X$ Combustors

Aerni, A. and R. Kehlhofer, "Repowering of a Reheat Steam Turbine with a 70MW Gas Turbine", Brown Boveri Corp., 1987.

Anonymous, "GM Gas Turbine Get New Combustor", 1981.

Furman, Edward R. et. al., "Critical Research and Advanced Technology Support Project Summary Report", NASA Lewis, February 1983.

General Electric, "Lean Premixed-Prevaporized Combustor Conceptual Design Study", 1979

Hashizume, Yasuo et. al., "Development of High Performance Large Capacity Gas Turbine and Low NO_x Combustor, and Their Operation Results at 1090MW Combined Cycle Power Plant", Mitsubishi Heavy Industries, 1984.

Johnson, S.M. et. al., "Experimental Investigation of the Low NO_x Vortex Airblast Annular Combustor", NASA Lewis, June 1984.

Krockow W., "Burner Development for Large Industrial Gas Turbine Combustors", Kraftwerk Union AG, 1981.

Kuroda, M. et. al., "Development of Dry Two-Stage Low-NO_x Combustor for a Gas Turbine" Hitachi Works, Hitachi Ltd.

Lewis G. D. and Holladay, T.E. "Design of a Successful Low Emissions Burner", United Technologies, 1980.

McVey, J.B. and Kennedy, J.B. "Lean Stability Augmentation Study", UTC, May 1979.

Novick, A.S. and Troth, D.L. "Multifuel Evaluation of Rich/Quench/Lean Combustor", Detroit Diesel Allison, 1982.

Odgers J., "Problems in Future Gas-Turbine Combustors", 1982.

Peters, J.E., "Current Gas Turbine Combustion and Fuels Research and Development", University of Illinois, 1987.

Pierce, R.M. et al., "Advanced Combustion Systems for Stationary Gas Turbine Engines: Combustor Verification Testing", Pratt and Whitney Aircraft Group, Jan. 1980.

Roffe, Gerald and Venkataramani, K.S. "Experimental Study of the Effect of Cycle pressure on Lean Combustion Emissions", General Applied Science Laboratories, July 1978.

Roffe, Gerald and Venkataramani, K.S. "Experimental Study of the Effects of Secondary Air on the Emissions and Stability of a Lean Premixed Combustor", General Applied Science Laboratories, 1981.

Roffe, Gerald and Venkataramani, K.S. "Experimental Study of the Effects of Flameholder Geometry on Emissions and Performance of Lean Premixed Combustors", 1978

Roberts, Peter and Kubasco, Al, "Investigation of a Low NO_X Full-Scale Annular Combustor", Solar Turbines Inc., February 1982.

Smith, Ken, Solar Turbines, Leonard Angello, EPRI, F.R. Kurynske, GRI, "Preliminary Development of an Ultra-low NO_X Gas Turbine Combustor", 1986.

Smith, Ken, "Ultra-Low NO_X Gas Turbine Combustion System", Solar Turbines, October 1986.

Smith, Ken et. al., "Experimental Evaluation of Fuel Injection Configurations for a Lean Premixed Low NO_X Gas Turbine Combustor", Solar Turbines, 1987.

Smith, Angello and Kurzynske, "Design and Testing of an Ultra-Low NO_X Gas Turbine Combustor", ASME No.86-GT-263, June, 1986.

Smith, K.O., "Ultra-Low NO_X Gas Turbine Combustion System", Solar Turbines, Inc. report No. GRI-86/0255, Sept. 1986.

Sudo, Y. et. al., "Construction and Operation of Gas-Steam Combined Cycle Plant for Higashi Niigata Thermal Power Station No. 3", Tohoku Electric Power Co. Inc.

Toqan, Majed A., J. Derek Teare and Beer, Janos "Reduction of NO_X by Fuel Staging", MIT, 1988.

Catalytic Combustion

Dodds, W. J., "Advanced Catalytic Combustors for Low Pollutant Emissions", General Electric Co., 1979.

Furman, Edward R. et. al., "Gas-Turbine Critical Research and Advanced Technology Support", Project FY 1980 Annual Report, July 1982.

Furuya, Tomiaki et. al., "Hybrid Catalytic Combustion for Stationary Gas Turbine--Concept and Small Scale Test Results", Toshiba Corp., May 1987.

Hoshino, A., et. al., "Preliminary Tests of Catalytic Combustion in a Small Gas Turbine", Kawasaki Heavy Industries, May 1987.

Kesserling, J. P. et. al., "Design Criteria for Stationary Source Catalytic Combustion Systems", Acurex Corp., Aug. 1979.

Kesserling, J. P. and W. V. Krill, "Catalytic Combustion Component and System Prototype Development", Acurex Corporation, May 1986.

Krill and Martin, "Two Stage Catalytic Combustion Process and Apparatus Patent", Acurex Corp., Feb. 1979.

Pfefferle, L.D. and Pfefferle, W.C., "Catalysis in Combustion", Catalysis Reviews - Science and Engineering, Vol. 29, Nos. 2 and 3, pp. 219-267, 1987

Pillsbury, P.W., "Critical Component Technologies for Stationary Gas Turbine Catalytic Combustors", EPRI Research project AP4063, 1657-3, Aug. 1985.

Pillsbury, Rieke, Toof and Wisniewski, "Stationary Gas Turbine Catalytic Combustor Development Program", EPI Research Project AP-2584, 1657-1, Oct. 1982.

Prasad, Ravi "Catalytic Combustion" Catalyst Reviews - Science and Engineering, Vol. 26, No. 1, pp. 1-58, 1984.

Proceedings of Workshop on Catalytic Combustion (5th) Held at San Antonio, Texas, Sept. 1981. NTIS-PB84-145580, Jan. 1984.

Szaniszlo, Andrew J., "The Advanced Low-Emissions Catalytic-Combustor Program Phase I - Description and Status", NASA Lewis, March 1979.

Trimm, D.L. "Catalytic Combustion (review)" Applied Catalysis, Vol. 7, pp. 249-282, 1983.

Tailored Injection

Bettodo, R., T. W. E. Downes, I. D. Middlemiss, and F. Brear, "Development of the Perkins 'Squish Lip' Combustion System," Air Pollut. Symp. Low Pollut. Power Syst. Dev., NATO/CCMS Air Pollut., 39, pp. 13-14, 1974.

Campbell, J., J. Scholl, F. Hibbler, S. Bagley, D. Leddy, D. Abata, J. Johnson, "The Effect of Fuel Injection Rate and Timing on the Physical, Chemical, and Biological Character of Particulate Emissions from a Direct Injection Diesel", SAE Spec. Publ. SP-495, Diesel Combust. Emiss., Pt. 3, pp. 71-108, 1981.

Gibbons, Robert A., and B. A. Wolf, "Optimizing Diesel Combustion: Improving Fuel Economy, Engine Life, and Reducing Particulate and Nitrogen Oxide (NO_X) Emissions with Electrostatic Fluid Processors", U.S. EPA, Off. Res. Dev., Proc. Int. Symp., PB81 - 173809, pp. 210-24, 1980.

Gill, Alan P., "Design Choices for 1990's Low Emission Diesel Engines", SAE Technical Paper Series 880350, presented at the International Congress and Exposition, Detroit, Michigan, February 29 - March 4, 1988.

Goto, Shinichi, and Kazuo Kontani, "Dual Fuel Injector for Diesel Engines", Kikai Gijutsu Dendyusho Shoho/Journal of Mechanical Engineering Laboratory, v. 39 n. 6, Tokyo, Japan, pp. 265-271, Nov. 1985.

Grone, Ole, "Marine Propulsion Diesel Engine Progress", SAE Technical Paper Series 881162, presented at the Future Transportation Technology Conference and Exposition, San Francisco, California, August 8-11, 1988.

Hamamoto, Yoshisuke, T. Wakisaka, and S. Tanabe, "Effects of Air Swirl on Diesel Combustion, Investigation by Exhaust Gas Analysis", Nippon Hakuyo Kikan Gakkaishi, 15(11), pp. 880-888, 1980.

Ikeda, Hirokazu, S. Hirano, T. Kawasaki, K. Mizushima, and M. Nagai, "Experimental Studies on Specific Fuel Consumption and NO_X Emission of Diesel Engine (2nd Report); Effects of Fuel Injection and Combustion", Hitachi Zosen Tech. Rev., v. 46 n. 3, pp. 137-144, Sept. 1985.

Kasel, E. A., C. L. Newton, and R. A. Walter, "Field Tests of In-Service Modifications to Improve Performance of an Icebreaker Main Diesel Engine", U.S. NTIS, AD Rep., AD-A046241, p. 109, 1977.

Malov, R. V., "Effect of Film Injection on Diesel Engine Toxicity", Avto. Prom., 37(9), pp. 9-10, 1971.

Malov, R. V., V. S. Nos, E. E. Bozhenok, Ya. Ya. Vlasov, and E. A. Ermolov, "Reduction of Nitrogen Oxides and Soot in Diesel Exhaust", Dvigateli Vnutr. Sgoraniya (Kharkov), 18, pp. 166-74, 1973.

Morimatsu, T., T. Okazake, T. Furuya, and H. Furukawa, "Improvement of Emissions from Diesel Engines", presented at the New Engine Technology for Cogeneration Conference, ASME, Intern Combust Engine Div Publ ICE, v. 2, pp. 53-59, Kansas City, MO., 1987.

Richards, R.R., and J. E. Sibley, "Diesel Engine Emissions Control for the 1990's", SAE Technical Paper Series 880346, presented at the International Congress and Exposition, Detroit, Michigan, February 29 - March 4, 1988.

Sawa N., and S. Hori, "Experimental Study on Exhaust Gas of the Precombustion Chamber 4-Stroke Cycle Diesel Engine", Ibaraki Daigaku Kogakubu Kenkyu Shuho, 20, pp. 39-55, 1972.

Tanaka, Toshiake, K. Sugihara, and Takamasa, Ueda, "Improvement of IDI Diesel Engine Combustion Through Dual-Throat Jet Swirl Chamber", presented at the Combustion, Heat Transfer and Analysis Conference, Proceedings - Society of Automotive Engineers, Milwaukee, WI., pp. 182, Sept. 8-11, 1986.

V. A. Zvonov, E. I. Bozhenok, and L. S. Zaigraev, "Study of the Possibilities of Reducing the Emission of Nitrogen Oxides by Diesel Engines", Dvigateli Vnutr. Sgoraniya (Kharkov), 23, pp. 95-101, 1976.

Exhaust Gas Recirculation

Bachelder, D., Faibanks Morse Division, Private Communication, Dec. 1978.

Wasser, J.H and Perry, R. B., "Diesel Engine NO_x Control with SCR", Stationary Source NO_x Symposium, EPA and EPRI, 1984.

Wilson, R.P., "Emission Control Methods for Large Stationary Engines: Part III - Catalytic NO_x Reduction by Ammonia", Stationary Source NO_x Symposium, EPA and EPRI, 1984.

Water-Fuel Emulsion

Cook. D.H., and Law, C.K., "A Preliminary Study on the Utilization of Water-In-Oil Emulsions in Diesel Engines," Combustion Science and Technology, 1978.

Greeves, G., Khan, I.M. and Onion, G., "Effects of Water Introduction on Diesel Engine Combustion and Emissions", 16th Symposium on Combustion, pp. 321, Combustion Institute, 1976.

Genot, A., S.E.M.T., "Tests of Water-Fuel Emulsion", Private Communication, Nov. 1978.

Hamid, A., "Water-Fuel Emulsions for Reduction of Engine Pollution", Ph.D. Thesis, University Curie, Paris, June 1976.

Lebedev, O.N., "Special Characteristics of the Combustion of Drops of Water-Fuel Emulsions in Diesels", Fizika Goreniya i Vzryva 14, pp. 142, 1978.

Lestz, S.J., Melton, R.B., and Rambi, E.J., "Feasibility of Cooling Diesel Engines by Introducing Water into the Combustion Chamber", SAE Paper 750129, 1975.

Murayama, T., Tsukahara, M., Morishina, Y., and Miyamoto, N., "Experimental Reduction of NO_X, Smoke and BSFC in a Diesel Engine Using Uniquely-Produced Water (0-80%) to Fuel Emulsion", SAE Paper 780224, 1978.

Storment, J.O. and Coon, C.W., "Single-Cylinder Diesel Engine Tests with Unstabilized Water-In-Fuel Emulsions", DOT Report CG-D-13-78, Aug. 1978.

Thompson, R.V., "Application of Emulsified Fuels to Diesel and Boiler Plant", Trans. I. Mar. Eng. 91, pp. 83, 1979.

Charge Cooling

Helmich, M.J., "Development of Combustion Air Refrigeration System for a Large 4-Cycle SI Gas Engine", ASME 66-DGEP-7, 1966.

Natural Gas

Alson, J. A. "The Emission Characteristics of Methanol and Compressed Natural Gas in Light Vehicles", presented at the APCA Annual Meeting & Exhibition, p. 98, Jun. 19-24, 1988.

Bergmann, H., and B. Busenthur, "Facts Concerning the Utilization of Gaseous Fuels in Heavy Duty Vehicles", Gaseous Fuels For Transportation, Chicago, Illinois, 1986.

Ding, Xianhua, and Philip G. Hill, "Emissions and Fuel Economy of a Prechamber Diesel Engine with Natural Gas Dual Fuelling", SAE Technical Paper Series 860069, Detroit, Michigan, February 24-28, 1986.

Hull, R. W., "Environmental Benefits of CNG-Fueled Vehicles", November 1966-May 1987.

W. A. Goetz, D. Petherick and T. Topaloglu, "Performance and Emissions of Propane, Natural Gas, and Methanol Fuelled Bus Engines", SAE Technical Paper Series 880494, Detroit, Michigan, February 29-March 4, 1988.

Karim, G. A., and K. S. Burn, "The Combustion of Gaseous Fuels in a Dual Fuel Engine of the Compression Ignition Type with Particular Reference to Cold Intake Temperature Conditions", SAE Tech. Pap. Ser., 800263, p. 11, 1980.

Karim, G. A., and I. Wierzba, "Comparative Studies of Methane and Propane as Fuels for Spark Ignition and Compression Ignition Engines", SAE Technical Paper Series 831196, Warrendale, PA., 1983.

Milkins, Eric, "CNG-Dual Fuel Operation of An Urban Bus.", Conference, Motor Vehicle Technology: Progress and Harmony, Nov. 7-10, 1983.

Springer, K. J., "Diesel Emission Control Through Retrofits", presented by the Automotive Engineering Congress & Exposition, Detroit, Michigan, Feb. 24-28, 1975.

Tesarek, Herbert, "Employment Possibilities of the Diesel-Gas Process for Reducing Exhaust Emissions, Especially Soot (Particulate Matters)", SAE Tech. Paper, 750158, p. 9, 1975.

Trifunovic, R., M. Menjic, and V. Semibratov, "Driving and Performance Quality of Diesel Engines Using a Mixture of Liquied and Gasious Fuel", Goriva Maziva, 15(4), pp. 3-15, 1976.

Methanol

Dietrich, W. and Schonbeck, A., "The MWM Pilot Injection Alcohol Combustion Process", MTZ43, 1982.

Jones, R., "Characterization of a Heavy Duty Diesel Modified for Operation on Neat Methanol", EPA AASDSB 82-12, 1982.

Lawson, A., et al, "Heavy Duty Truck Diesel Engine Operation On Unstabilized Methanol/Diessel Fuel Emulsion", SAE 810346, 1981.

Nietz, A. and Chmeia, F., "Results of MAN-FM Diesel Engine Operating on Straight Alcohol Fuels", IV Symp. Alcohol Fuels, Vol. II, No. B-56, 1980.

Phatak, R.G. and Komiyama, K., "Spark Assisted Diesel", SAE 830588, 1983.

Wood, C.D. and Storment, J.O., "Direct Injected Methanol Fueling of Two-Stroke Locomotive Engines", SAE 800328, 1980.

General

Air Pollution Control District, County of Santa Barbara, technical assistance from Arthur D. Little, Inc., "Crew and Supply Boat NO_x Control Development Program", June 1987.

Ellison, W., "Assessment of SO_2 and NO_x Emission Control Technology in Europe", EPA/600/2-88/013, 1988.

Larkin R. et. al., "Combustion Modification Control for Stationary Gas Turbine", Acurex Corp., July 1981.

Makansi, J., "Gas Turbines", Power Magazine, March 1988.

Mobley, J. D., and Jones, G. D. "Review of U. S. NO_x Abatement Technology", EPA/600/D-85/105, 1985.

Mueller R. et. al., "ACT (Available Control Technology) for Stationary NO_x Sources", Acurex Corp., Dec. 1979.

Sedman, C. B., and Ando, J. "Japanese Activities in SO_2 and NO_x Control", EPA/600/D-87/368, 1987.

Thring R. H. and Hull, R. W. "NO_x Control Technology Database For Gas-Fueled Prime Movers, Phase I", Southwest Research Institute, April 1988.

Urban, C., "Evaluation of NO_x Reduction Technology for Natural Gas Industry Prime Movers", Southwest Research Institute, 1987.

Waterland L. R. et. al., "Environmental Assessment of Stationary Source NO_x Control Technologies", Acurex Corp., 1982.

APPENDIX B

NO_x CONTROL TECHNOLOGY SUMMARIES

APPENDIX B

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APPENDIX B.1

COMMERCIALLY AVAILABLE SELECTIVE CATALYTIC REDUCTION

B.1.1 DESCRIPTION

In any typical engine exhaust, the NO_x concentrations greatly exceeds the equilibrium levels which would be predicted for exhaust manifold conditions. That is, the NO_x is out of equilibrium since the reaction paths to N_2 and O_2 are relatively slow. It is therefore possible to reduce the NO by stimulating reactions which chemically convert the NO to N_2 and O_2. In the SCR process, ammonia reduces exhaust gas NO_x within a catalyst bed. Homogeneous reaction of ammonia with NO_x occurs rapidly at gas temperatures above about 1,500°F. However, at the lower temperatures typical of engine exhaust, the reaction rates are too slow. Introduction of appropriate noble metal, base metal or zeolite catalysts allow this process to proceed at lower temperatures (450-850°F). The overall reactions involved in the SCR process are as follows:

$$NH_3 + NO + 1/4\ O_2 \dashrightarrow N_2 + 3/2\ H_2O$$
$$NH_3 + 1/2\ NO_2 + 1/4\ O_2 \dashrightarrow 3/4\ N_2 + 3/2\ H_2O$$
$$NH_3 + 3/2\ NO \dashrightarrow 5/4\ N_2 + 3/2\ H_2O$$
$$NH_3 + 3/4\ NO_2 \dashrightarrow 7/8\ N_2 + 3/2\ H_2O$$

A complete SCR system consists of an anhydrous ammonia storage tank, an ammonia vaporizer, carrier gas (air or steam) supply, ammonia injection grid, catalyst bed, and instrumentation/controls. Integration of these system components is shown in Figure B.1-1.

The SCR reactors are usually constructed of modular sections to facilitate replacement of the catalyst. To minimize the gas pressure drop, parallel flow "honeycomb" catalyst configurations are often used. Although a wide range of catalysts have been employed, most systems now use titanium oxide, vanadium pentoxide or zeolites. Integration of an SCR reactor with a gas turbine waste heat recovery unit is shown if Figure B.1-2. Ammonia is injected upstream of the reactor at a rate that provides a molar ratio of NH_3/NO of about 0.8-1.5.

Figure B.1-3 is a schematic of SCR applied to a diesel engine. Ammonia, from a storage tank, is injected upstream of a catalytic reactor comparable in size with the muffler now used on these engines.

B.1.2 NO_x REDUCTION POTENTIAL

Wasser and Perry, et. al., and Wilson, et. al., have reported two sets of test results of SCR systems retrofitted to diesel engines. In both cases, catalyst contamination by diesel soot had a significant impact on NO_x removal efficiency.

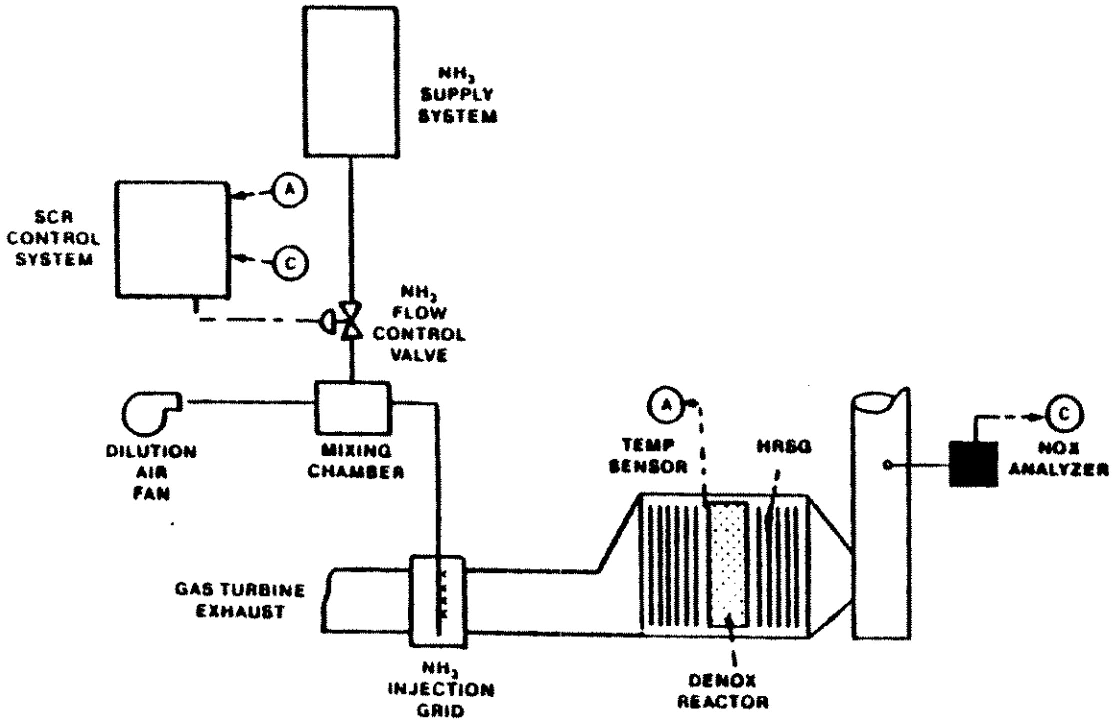


FIGURE B.1-1

SCR SYSTEM COMPONENTS

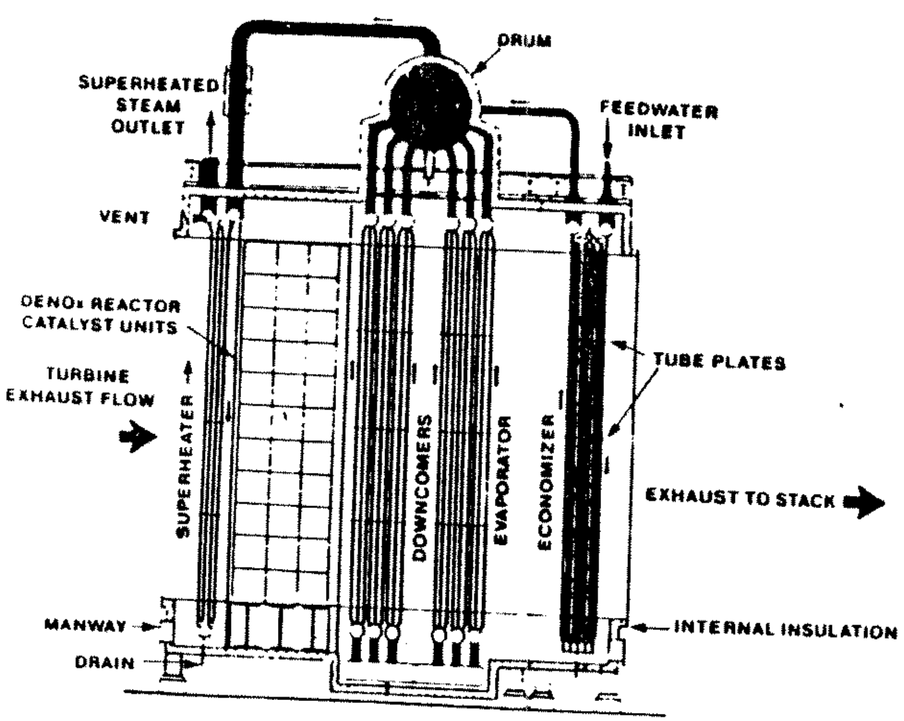
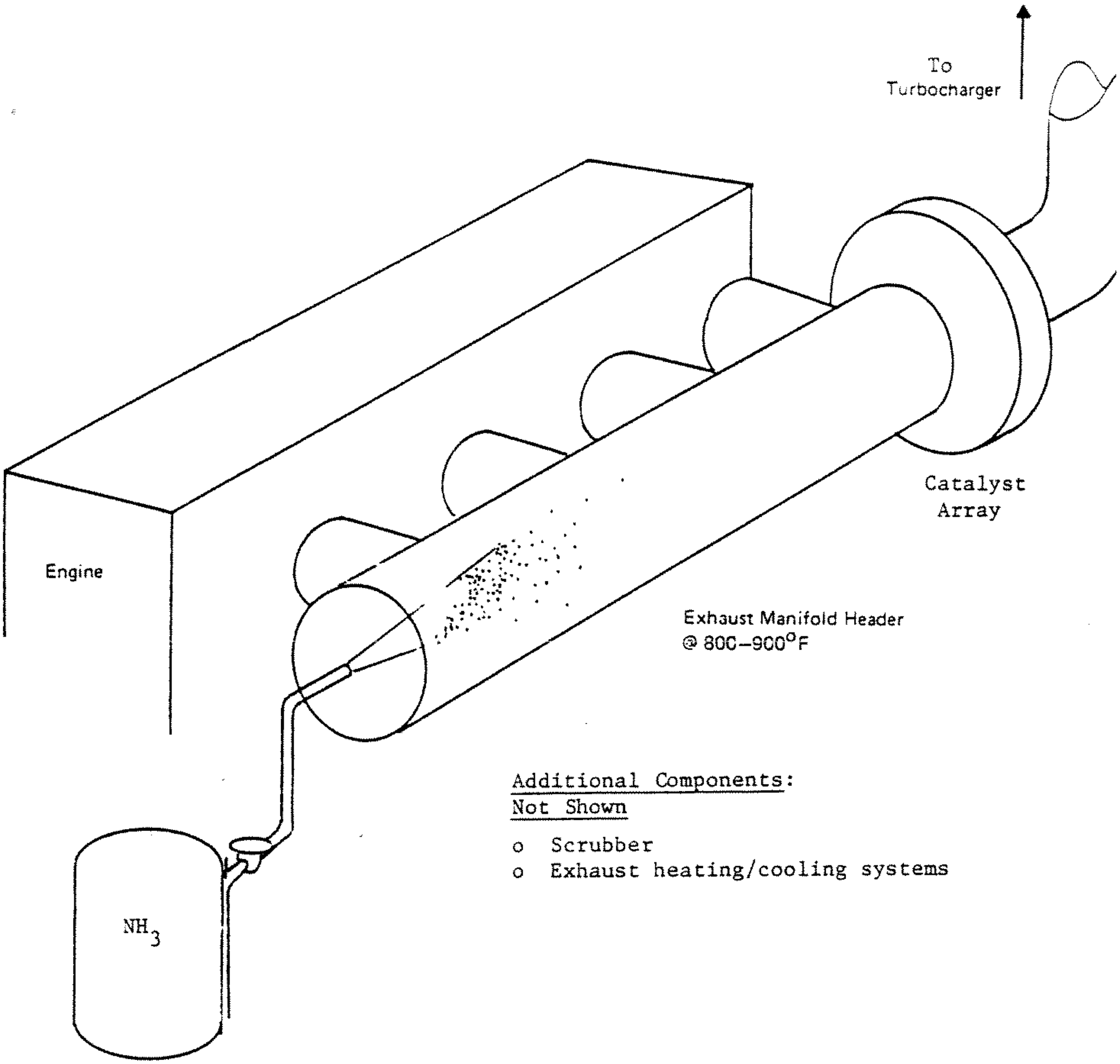


FIGURE B.1-2

SCR CATALYST POSITION



<u>Additional Components:</u>
<u>Not Shown</u>

- o Scrubber
- o Exhaust heating/cooling systems

FIGURE B.1-3

Schematic of SCR Applied to a Diesel Engine

The published results for lean-burning natural gas engines include Dupaski and Pader and unpublished tests in Japan by Engelhard. These tests indicate that the catalyst/NH_3 system is effective at high O_2 levels, with converter efficiencies ranging from 75-98 percent and optimum temperature from 240-400°C. EPRI reported 90 percent NO_x removal with an SCR system on a pilot scale coal boiler. Engelhard reported that industrial boiler tests gave 70-90 percent NO_x reduction, and that a commercial application at 0-12 percent O_2 gave 80 percent conversion for a five-year period. However, both installations were at relatively high pressure (75-90 psi). Engelhard also reports several retrofits on large natural gas engines in California, including engines made by Enterprise, Ingersol Rand, and Clark.

B.1.3 DEVELOPMENT STATUS

Research on Selective Catalytic Reduction of NO_x was initiated in the late 1960's in Japan. Subsequent developments by companies in the U.S., Germany and Japan have brought this technology to the point of commercial application. Currently, there are over 200 SCR systems operating in Japan, predominantly on boilers. In the U.S., at least ten SCR systems are operating in gas turbine cogeneration plants, with more scheduled for start-up over the next few years. While several of the cogeneration plants have experienced significant problem with their SCR systems, it appears that, with proper design and control, SCR units are currently a viable option for reducing NO_x emissions from stationary onshore gas turbines that burn natural gas and operate at relatively steady loads.

SCR experience on reciprocating engines has been less extensive and systems for diesel engines are not yet commercially viable. Although the technology can be said to be proven for stationary spark-ignition engines on gas fuel, it has not been used extensively on stationary engines because of the relatively high cost and other NO_x-control methods (such as "jet cell" ignition for lean burn engines) are readily available. For stationary diesel engines, there is the added handicap of catalyst soot deposition and engine oil poisoning.

B.1.4 IMPACT ON EFFICIENCY

Methods which chemically remove NO_x after the combustion process should have little effect on engine operation or fuel consumption. There will be a small power loss associated with the catalyst pressure drop and the ammonia injection system.

B.1.5 PRACTICAL CONSIDERATIONS

The most critical aspects of selective NO_x reduction systems are: (a) safe ammonia handling and transport, (b) control of reactor temperature and ammonia feed rate to avoid system upsets or excessive ammonia emissions, (c) catalyst contamination by diesel soot or catalyst poisoning when sulfur is present in the fuel or by lubricating oils, and (d) ammonium bisulfate particulates produced at lower temperatures from SO_3 and excess of ammonia.

For the catalyst-based system, the following technical requirements must be met:

- NH_3 must be injected so as to obtain uniform distribution.
- The reactor temperature must be maintained (heaters or coolers may be required) within optimum range.
- The NH_3/NO_x ratio must not be too large or NH_3 will be emitted, but not too small or NO_x will not be adequately reduced.
- The catalyst surface area must be sufficient for a given exhaust flow rate (i.e., the maximum space velocity must not be exceeded).
- Hydrogen cyanide and ammonia are potentially toxic by-products. Conditions must assure that any added nitrogen (in the form of NH_3, for example) is exhausted as N_2.
- SCR Control systems must be capable of following rapid changes in engine load.

APPENDIX B.2

SELECTIVE NON-CATALYTIC REDUCTION

B.2.1 DESCRIPTION

There are several NO_x control processes which inject a chemical agent into hot combustion products to reduce NO_x. The differences between these processes revolve around the selected gas temperature range and the specific agent. These processes for selective reduction of NO_x maintain overall lean stoichiometry, and therefore should not be confused with reburning where the combustion products pass through a fuel-rich zone followed by a lean burnout zone. Two commercial SNCR processes are described below:

Thermal $DeNO_x$: The SNR process was pioneered by Exxon Research and Engineering Company in the early 1970's. Their technique utilizes ammonia as the reagent and is characterized by the following overall reaction:

$$NO_x + NH_3 + O_2 + H_2O \text{--->} N_2 + H_2O$$

Within the temperature range of 1,600-2,200°F, this process is effective in reducing NO_x. Above this range, NO_x is produced, while below it, the reaction does not proceed at a rate that is fast enough for practical applications. To apply Thermal $DeNO_x$ to engines the exhaust temperature must be raised into the operating window through use of duct burners.

In the Thermal $DeNO_x$ process (Figure B.2-1), anhydrous ammonia is vaporized and mixed with a carrier gas (air or steam). The combined stream is supplied at a controlled rate to multiple nozzles located in the wall of the exhaust gas duct. These nozzles are positioned to provide adequate exhaust gas residence time within the prescribed temperature window. Figure B.2-2 shows the location of wall injectors for a commercial boiler application. In this case three injection zones were installed to obtain adequate NO_x reduction over the boilers operating load range. Mixing of the ammonia with exhaust gas is accomplished by proper size and location of the cross-flow jets produced by the nozzles. Ammonia flow rate is adjusted to yield and NH_3/NO_x molar ratio of about 1.2-2.0. Commercial applications of the Thermal $DeNO_x$ process in boilers have achieved NO_x reduction of 50-80 percent.

Enhancements to the Thermal $DeNO_x$ process are required for direct application to engine exhaust streams. Addition of other chemical species to ammonia can improve the NO_x reduction capabilities of this process at lower temperatures. Exxon has demonstrated that hydrogen can decrease the lower bound of the Thermal $DeNO_x$ operating window to about 1,300°F. However, this level is still not low enough for direct application to engines. Since Exxon is not actively conducting research in this area, it is unlikely that further methods for decreasing the Thermal $DeNO_x$ operating window will be found in the near future.

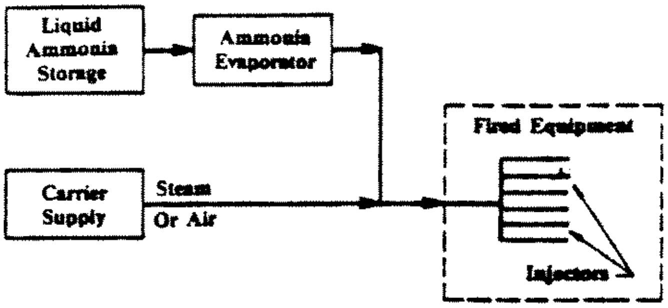


FIGURE B.2-1

SIMPLIFIED THERMAL DeNO$_x$ SUPPLY SYSTEM FLOW DIAGRAM

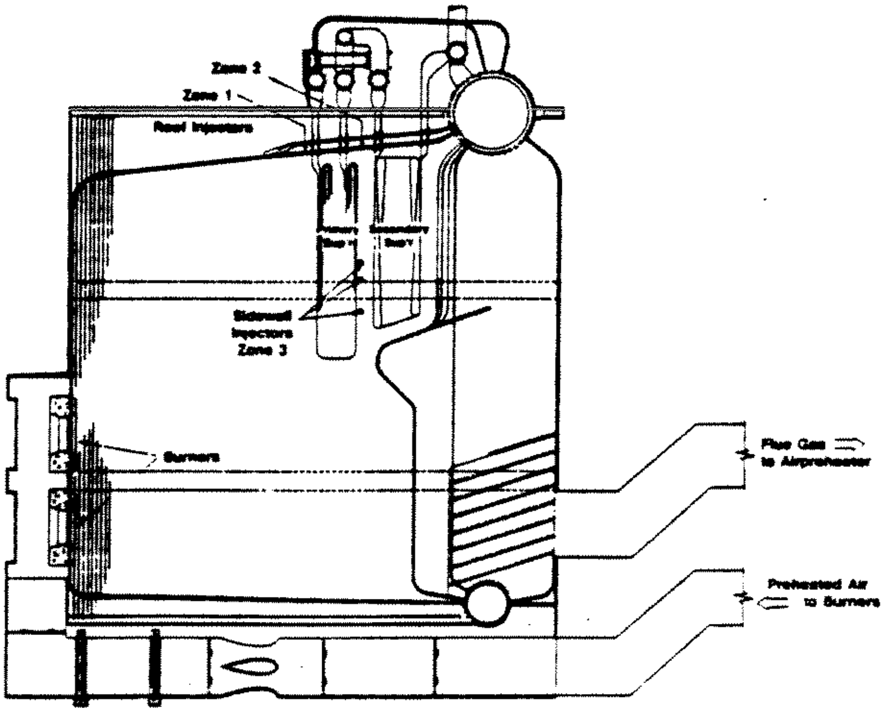


FIGURE B.2-2

200,000 KG/HR BOILER FITTED WITH THERMAL DeNO$_x$ KAWASAKI, JAPAN

$\underline{NO_x\ Out}$: Fuel Tech has licensed a SNR process that was developed in the mid-1970's under EPRI sponsorship. This technique uses urea as the reagent and is described by the following overall reaction.

$$CO(NH_2)_2 + 2NO + 1/2\,O_2 \text{--->} 2N_2 + CO_2 + 2H_2O$$

NO_x reduction is effective within an exhaust gas temperature window of about 1,700-1,900°F. However, with the use of proprietary chemical enhancers, Fuel Tech has extended this range to 1,500-2,100°F. Certain enhancing chemicals by themselves are claimed to be effective in reducing NO_x at temperature levels as low as 1,000°F.

A flow diagram of the NO_xOUT process is provided in Figure B.2-3. The reagents are mixed with water and then fed to atomizing nozzles located in the walls of the exhaust gas duct. Mixing of reagent with exhaust gas is achieved by control of the spray size, distribution, and penetration. The urea injection rate is controlled to provide a urea/NO_x molar ratio of about 0.5-1.0 (note that one mole of urea reacts with two moles of NO in the balanced reaction above). Commercial demonstrations for the NO_xOUT process in boilers and incinerators have attained NO_x reduction of 50-80 percent. However, all of these applications were at temperatures (1,300-2,000°F) well above gas turbine exhaust levels.

Further improvements to the NO_xOUT process are required for direct application to engine exhaust. Fuel Tech is actively screening reagents that may be effective in reducing NO_x at typical exhaust temperatures. To date about 150 chemicals have been evaluated. Some success has been achieved at temperatures as low as 850°F. Fuel Tech's plan for developing technology for gas turbines includes the demonstration of a reagent that is effective in the 900-950°F range on a commercial unit in the summer of 1989.

B.2.2 $\underline{NO_x\ \text{REDUCTION POTENTIAL}}$

Makansic reports that a recent Thermal DeNO_x application gave 50 to 60 percent NO_x reduction at a ratio of ammonia to NO_x of 2.0. Exxon has indicated that NO_x reductions as high as 80 percent are possible with improved ammonia injection technology. Fuel Tech targets 50 to 80 percent NO_x reduction for their NO_xOUT process. We estimate that 50-70 percent is a reasonable expectation for the entire set of SNCR processes.

B.2.3 DEVELOPMENT STATUS

Thermal DeNO_x is a commercially proven technology for units such as boilers, furnaces, and municipal waste incinerators. Over 60 installations are currently in service. NO_xOUT has been demonstrated in circulating fluidized beds, municipal wastes incinerators and boilers. The first two commercial applications are starting up this year.

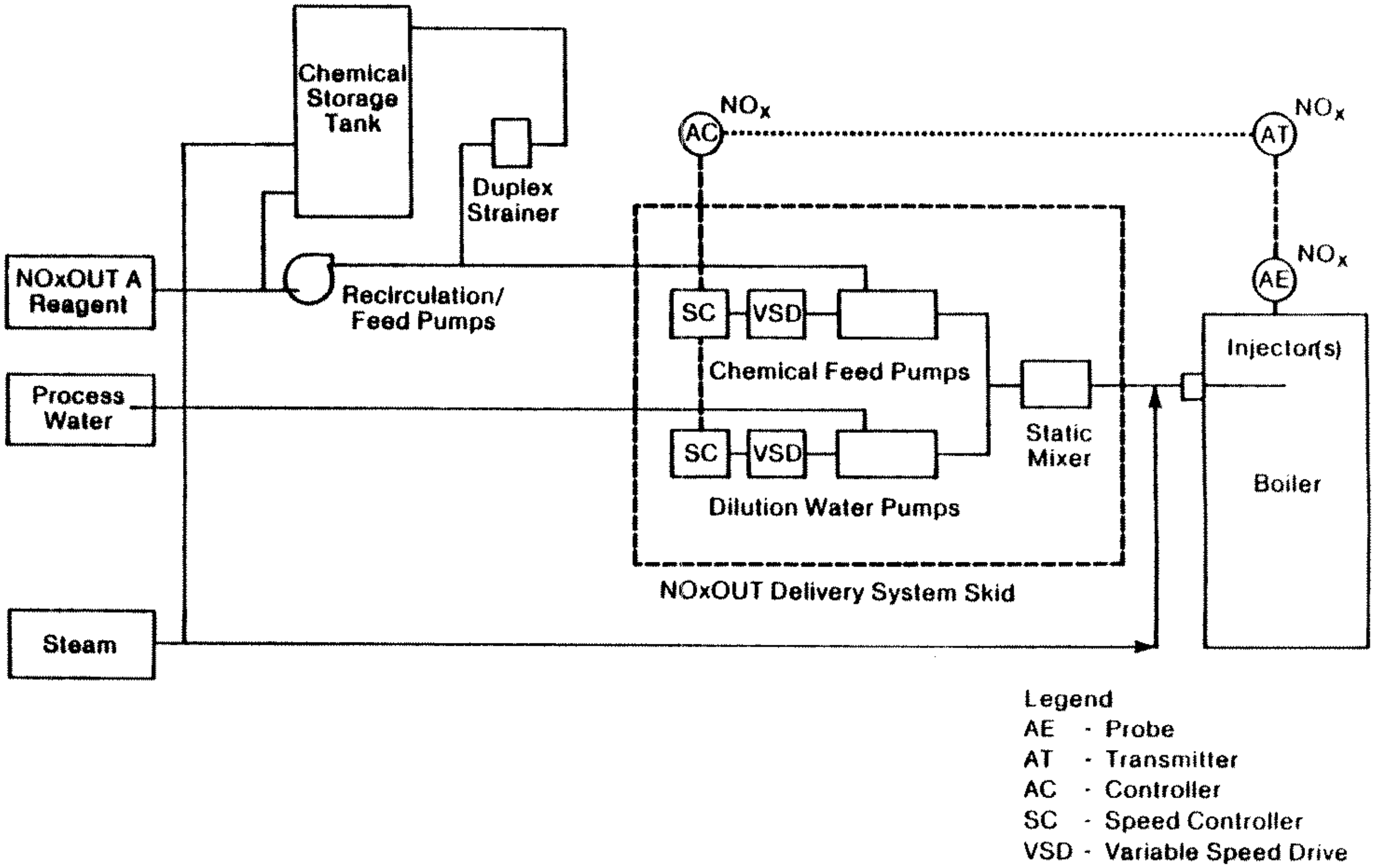


FIGURE B.2-3

NO_xOUT PROCESS FLOW DIAGRAM

None of the SNR processes have been commercially applied to engines. Exhaust temperatures are below the level where known reagents can effectively reduce NO_x without the use of a catalyst. (While exhaust temperatures can be raised into the required window through the use of a duct burner, this can create a significant economic penalty for the process.) However, both Fuel Tech and Exxon are pursuing situations that may allow use of their processes on gas turbines.

Over the past year, Fuel Tech has been developing reagents that they claim might prove to be effective in controlling NO_x at temperatures as low as 850°F. Preliminary tests in a combustion tunnel indicate that reductions in excess of 50 percent may be possible. Demonstration of their process on a gas turbine with exhaust temperature in the range of 900-950°F is being planned.

Exxon is investigating the injection of ammonia downstream of the gas turbine's combustor. Kinetic modelling of this process has shown that significant reductions in NO_x levels are possible. However, no experimental work has been conducted.

B.2.4 IMPACT ON EFFICIENCY

For installations where exhaust gas is reheated or otherwise available at temperatures greater than 1,400°F, there is no fuel penalty for $DeNO_x$ or NO_xOUT. The fuel penalty for reheating, if required, can be severe if there is no useful application for the heat.

B.2.5 PRACTICAL CONSIDERATIONS

- Non-uniform mixing of ammonia in the exhaust can release undesirable by-products such as HCN, $(CN)_2$, N_2O, etc. Operating with low ammonia slip is known to be a problem and sophisticated reagent injection techniques and control systems are required to minimize excess ammonia emissions.
- Residence time requirements need to be defined for engine exhaust applications.
- Temperature and flow non-uniformities in the engine exhaust may limit NO_x reduction.
- SNR Control Systems must be capable of following raping changes in engine load.

APPENDIX B.3

RAPRENO$_X$

B.3.1 DESCRIPTION

RapReNO$_x$ (Rapid Reduction of Nitrogen Oxides) is a selective non-catalytic reduction technique for NO$_x$ which was discovered in 1986 at Sandia Livermore. Unlike the commercially available SNCR processes (Exxon's Thermal DeNO$_x$ which uses gaseous ammonia and Fuel Tech's NO$_x$Out which uses liquid urea solution) RapReNO$_x$ uses a solid reagent, cyanuric acid, $C_3N_3(OH)_3$. At exhaust gas temperature, cyanuric acid decomposes to isocyanic acid (HNCO), which reduces NO$_x$ through a complex series of reactions. Although the details of this process are not fully understood, the following reaction scheme has been postulated:

$$\begin{array}{ll} \mathrm{HNCO} & \dashrightarrow \mathrm{NCO} + \mathrm{H} \\ \mathrm{H} + \mathrm{HNCO} & \dashrightarrow \mathrm{NH_2} + \mathrm{CO} \\ \mathrm{NH_2} + \mathrm{NO} & \dashrightarrow \mathrm{H} + \mathrm{OH} + \mathrm{N_2} \\ \mathrm{NH_2} + \mathrm{NO} & \dashrightarrow \mathrm{H_20} + \mathrm{N_2} \\ \mathrm{NCO} + \mathrm{NO} & \dashrightarrow \mathrm{N_2O} + \mathrm{CO} \end{array}$$

The initial experiments at Sandia appeared to show that significant reduction (over 80 percent) in NO$_x$ emissions were possible at relatively low gas temperatures (700-900^{o}F) without the use of a catalyst. However, follow-up tests revealed that catalytically active surfaces present in the initial tests were probably responsible for the excellent performance. Without a catalyst it appears that temperatures of about 1,500^{o}F are required for effective NO$_x$ control.

Since RapReNO$_x$ is a new NO$_x$ control technique, all system components are not yet fully developed. The basic system would probably include a cyanuric acid storage vessels, an injection system that would provide uniform mixing of the solid (or its by-product HNCO) with exhaust gas, a reaction chamber and monitoring/control instrumentation. Injection techniques may include use of steam, air or water as the carrier. Through ongoing research activities, the specifications for these and other system components should become more fully developed.

Experiments at Sandia and Technor have demonstrated that cyanuric acid can effectively control NO$_x$ emissions at temperatures characteristic of engine exhaust when catalytic surfaces are present. Further development work on the catalytic process has been conducted by a Japanese firm. Their work has shown that NO$_x$ reductions of about 80 percent can be achieved with an Fe_2O_3 based catalyst system. Potential advantages for this process relative to conventional SCR include the ability to reduce catalyst volume, use of non-toxic catalysts, and improved load following (catalyst stores HNCO).

B.3.2 NO_x REDUCTION POTENTIAL

Preliminary test results from $RapReNO_x$ development have shown NO_x reductions as great as 80 percent. $RapReNO_x$ is based on a solid reagent. It is therefore susceptible to mass transfer limitations. Thus, we believe the probable NO_x reduction from $RapReNO_x$, once it is developed to a commercial status, will be 50 to 70 percent.

B.3.3 DEVELOPMENT STATUS

The initial announcement of $RapReNO_x$ technology was based upon process screening research in a laboratory flow reactor, followed by tests on a 7 hp Onan engine. At the present time, tests are being initiated on a Cummins engine under DOE sponsorship. A Japanese firm has been investigating the performance of the $RapReNO_x$ process at lower temperatures when different catalytic materials are used. These early tests are oriented towards defining NO_x removal as a function of key reaction and operating parameters. Future efforts would focus on performance optimization, operability, and any secondary or side-effects.

B.3.4 IMPACT ON EFFICIENCY

As is the case with other exhaust gas treatment technologies, a slight efficiency penalty would be expected due to the reactor chamber pressure drop and the power required for reagent feed.

B.3.5 PRACTICAL CONSIDERATIONS

A number of issues will need to be addressed during the $RapReNO_x$ development program, including:

- Complete characterization of performance as a function of time, temperature, etc.
- Evaluations of catalysts that may enhance the process at lower temperatures
- Mass transfer effects, limitations.
- Reagent stoichiometry.
- Production of side-emissions/by products, such as HNCO, NH_3, HCN, $(CN)_2$, N_2O, etc.
- Practical equipment configurations.
- Control system, response to engine load changes.

APPENDIX B.4

SOLID-STATE ELECTROCHEMICAL REDUCTION

B.4.1 DESCRIPTION

The exhaust gas is passed through a solid-state, porous foam, ceramic electrolyte (zirconia, ceria, or Bismuth oxide) containing silver electrodes. NO_x is selectively reduced by electrochemical reactions. Figure B.4-1 shows electrochemical NO_x reduction in ceramic foam

B.4.2 NO_x REDUCTION POTENTIAL

The potential of this method is yet to be determined; 50-90 percent NO_x reduction is conceivable. To date there is no data on actual engine exhaust.

B.4.3 DEVELOPMENT STATUS

Solid-state electrochemical reduction is considered as an embryonic technology. Its history and critical research needs include:

- The process discovered at Stanford in 1974 by Puncharatnam.
- Further research by Mason lead to a patent in 1981.
- GRI sponsored research is underway; recent results were reported by Hossain et. al.
- Tests have been conducted on gases containing 20 percent to 100 percent NO. The effectiveness of the process with more realistic concentrations (250-2,500 ppm) has yet to be determined.
- O_2 selectivity/power drain by other species needs to be explored.
- Volumetric reaction rate is unknown at this time.

B.4.4 IMPACT ON EFFICIENCY

One to five percent penalty due to exhaust pressure drop, plus 1-2 percent penalty due to power for electrodes can be expected.

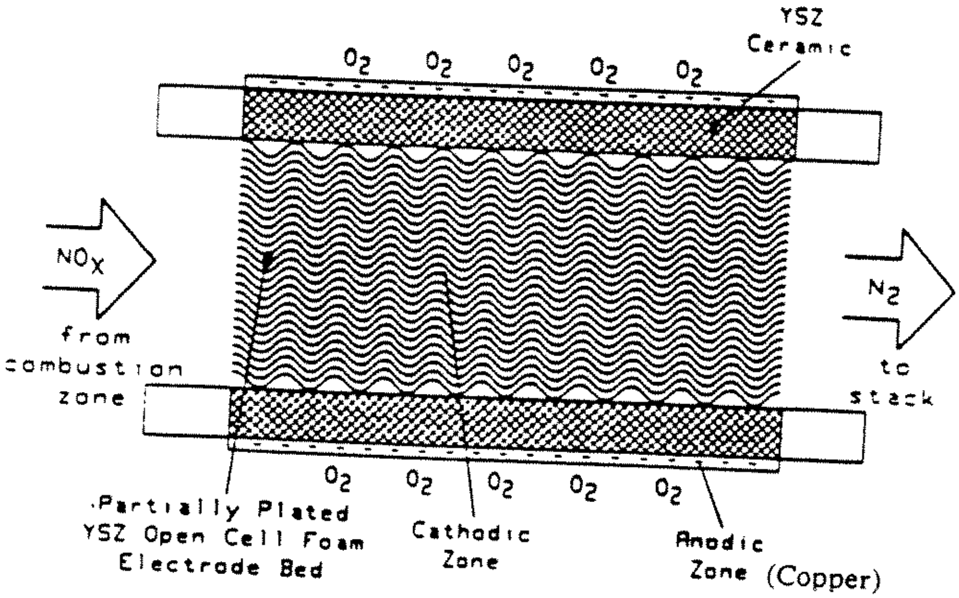


Figure B.4-1

Electrochemical Reduction in Ceramic Foam

B.4.5 PRACTICAL CONSIDERATIONS

While the process has not yet been attempted on actual exhaust, practical considerations which could emerge include:

- Fouling of foam electrolyte by diesel soot (soot removal needed?)
- Cracking of ceramic due to thermal stress.
- Pressure drop of porous foam reactor requires blower.

APPENDIX B.5

DRY LOW-NO_x COMBUSTORS

B.5.1 DESCRIPTION

Two types of dry low-NO_x combustors for gas turbine engines are under development: lean pre-mixed combustors and rich-lean combustors.

Lean pre-mixed combustors (Figure B.5-1) for turbines firing gaseous fuels can significantly reduce NO_x emissions by operating the burner primary zone at a lean fuel/air ratio. In addition, lean pre-mixed combustors also provide a uniform fuel/air mixture, thus reducing the occurrence of local hot zones in the combustor. Since NO_x formation is a strong function of temperature, NO_x emissions are substantially reduced by lowering the overall combustion temperature and by ensuring more even combustion throughout the chamber.

In the rich-lean concept (Figure B.5-2), two combustion zones are arranged in series: a fuel-rich primary zone and a fuel-lean secondary zone. These are separated by a reduced diameter "quick-quench" section. The air entering the primary zone is premixed with fuel to prevent formation of local stoichiometric mixtures. Minimum NO_x concentration level are obtained at primary zone equivalence ratios near 1.3. In the fuel-rich zone, both temperature and oxygen concentration are low to minimize NO_x formation. Quench air is then added to rapidly cool the fuel-rich products and produce the required lean stoichiometry for second stage. In this stage, low combustion temperatures limit NO_x formation.

B.5.2 NO_x POTENTIAL REDUCTION

For gas fired turbines the lean premixed concept is preferred due to its greater potential for NO_x control. NO_x emissions from laboratory-type lean pre-mixed combustors have been measured to be as low as 10 ppm (at 15 percent O_2) with corresponding low emissions of CO and hydrocarbon. Some industry sources suggest that this level will not be achievable in actual practices in the field. We believe that when this technology is fully developed, NO_x emissions at full load will range from 15 to 25 ppm (at 15 percent O_2) for turbines in the 3 to 4 MW size range.

B.5.3 DEVELOPMENT STATUS

Several manufacturers of gas turbines have been developing the lean premixed technique over the past decade. Solar has been very active in their development program, working in conjunction with EPRI, GRI, and Southern California Gas. A field demonstration of Solar's lean pre-mixed swirl-stabilized combustor on a small gas turbine is being planned. Solar's test unit is shown in Figure B.5-1.

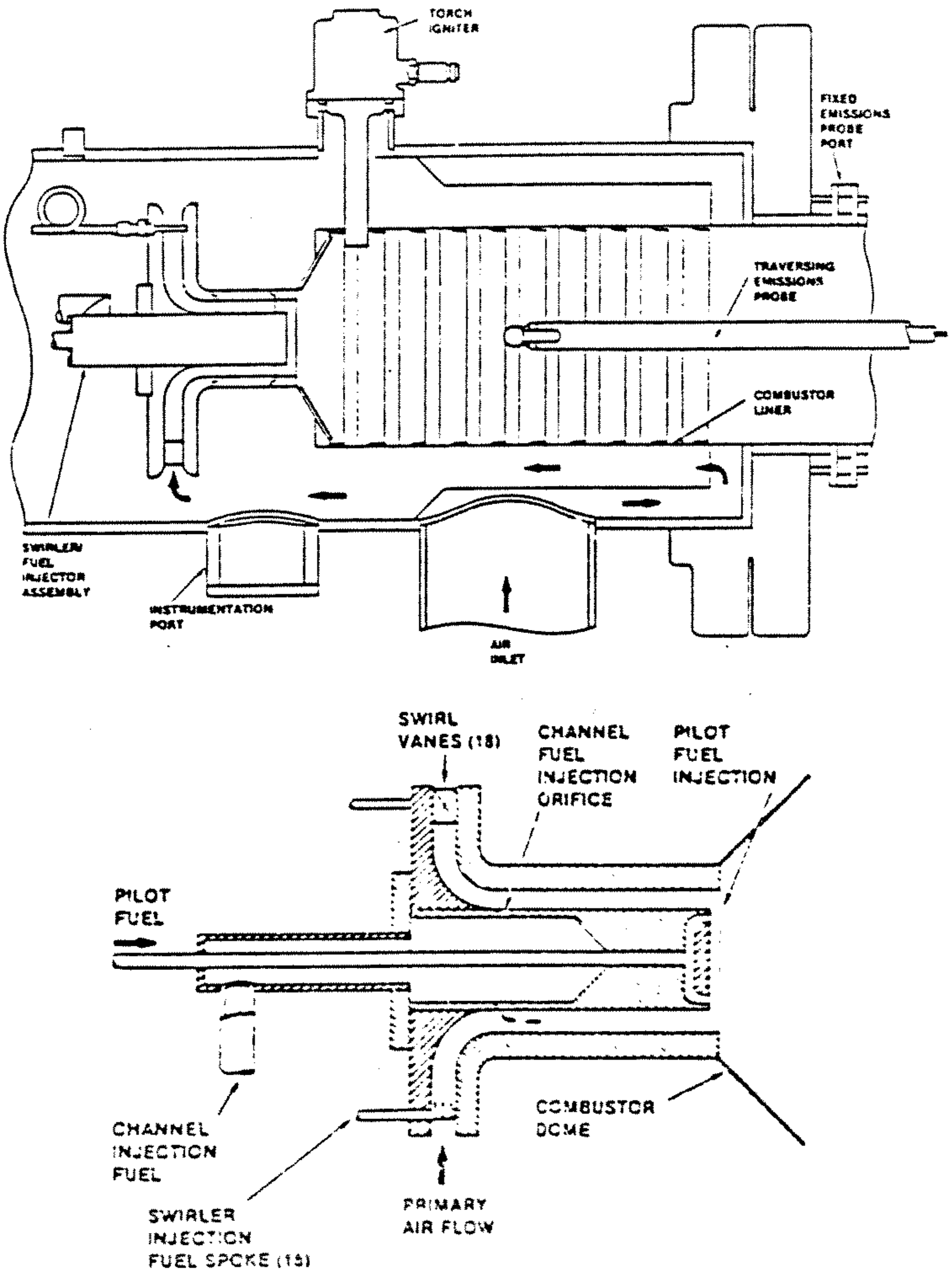


Figure B.5-1

Diagram of Solars Test Unit
for Lean Pre-mixed Combustors

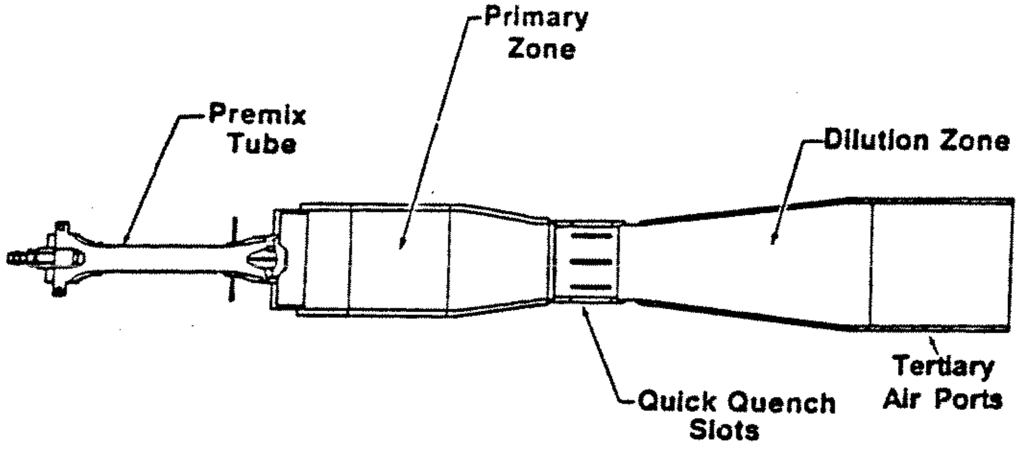


FIGURE B.5-2

RICH-LEAN STAGED COMBUSTOR

SOURCE: R. Larkia et. al. "Combustion Modification Controls for Stationary Gas Turbine, Volume 1" July 1981

B.5.4 IMPACT ON EFFICIENCY

The impact on fuel efficiency should be almost negligible compared to uncontrolled gas turbines. Since water injection decreases fuel efficiency by several percentage, a lean pre-mixed combustor should be more efficient than one operating with water injection.

B.5.5 PRACTICAL CONSIDERATIONS

Lean pre-mixed combustors portray a number of unique operating characteristics which are being addressed in the technology's developmental process. Since they operate near the lean extinction point, there is a chance of achieving incomplete combustion. Thus it is possible to produce a marked increase in CO emissions. Also, by operating close to the extinction point, a potential for flame-out exists, especially at reduced loads or during transient load changes. Development of this technique will require the use of fuel staging, variable geometry, and/or multiple combustion zones to ensure operability over the full range of operating conditions. Finally, since the combustion gases are pre-mixed, there is a potential for flashback or autoignition upstream of the primary zone.

In solving these issues defined above, a recent Solar report presents the following developments which will be required to commercialize this technology:

- Optimize the pilot injector and fueling schedule to provide adequate combustor operating range and improved part load combustion efficiency.
- Augment the liner cooling near the combustor upstream end to drop wall temperatures to the 1144K (1,600°F) target temperature.
- Develop a secondary air injection port configuration to yield the necessary turbine inlet temperature and pattern factor.

Of these three development areas, the dilution zone optimization represents the major activity. The lean pre-mixed burner has less dilution air available for exhaust temperature profile optimization relative to a production burner because of the large primary zone air flow needed for lean combustion. Consequently, the degree of mixing control may be reduced. The improvements required in wall cooling and pilot fuel injection appear relatively minor. Wall temperatures exceed target levels by small amounts in only a very localized region. Past development work on high turndown fuel injectors provides an excellent foundation for injector optimization.

In addition to the improvements mentioned above in terms of optimizing the ultra-low NO_X combustor as an engine component, issues must also be addressed to advance the entire combustion system. These system areas include:

- Control system development to allow acceptable combustion system operation during engine transient as well as steady state operation.
- Development of a reliable ignition system for a multi-can ultra-low NO_X combustion system.
- Development of transition ducting to direct the combustor exhaust flow to the turbine nozzle.
- Engine design modifications to allow integration of the low emissions burner system into the gas turbine.

With the possible exception of the control system strategy, the development effort required in each of the areas above will be a function of specific gas turbine engine design characteristics.

APPENDIX B.6

CATALYTIC COMBUSTOR FOR GAS TURBINES

B.6.1 DESCRIPTION

A catalytic combustor is used in place of the conventional diffusion flame combustor in a gas turbine. NO_X is reduced by carrying out the oxidation of the fuel at a relatively low temperature, promoted by the catalyst. Combustion occurs both on the catalyst surface and in the catalyst channels.

A schematic of the catalytic combustor is shown in Figure B.6-1. Various configurations are possible, all of which have a mechanism for preheating combustion air to catalyst ignition temperature and a method for providing start-up heat. Two main types of catalysts have been used in tests to date: precious metals (Pt or Pd) on alumina and supported metal oxides (Cobalt and Chromium being the most common). The catalyst is supported on a honeycomb monolith, often configured in a graded-cell design, where the monolith channels become more narrow with increasing distance through the bed.

B.6.2 NO_X REDUCTION POTENTIAL

Small-scale tests have shown NO_X emissions as low as 1-2 ppm. Accounting for less homogeneous oxidation in full scale hardware. NO_X emissions below 10 ppm could be expected.

B.6.3 DEVELOPMENT STATUS

Prior work has included small-scale demonstration, bench-scale development of prototype units, and laboratory investigation of various catalyst formulations and catalyst properties. U.S. participants in catalytic combustion programs include Westinghouse, General Electric, Englehard, DOE, EPA, EPRI, and NASA. Japanese investigators have also been active in this area. For example, Kawasaki Heavy Industries is nearing the end of a seven year development program. However, these research and demonstration efforts to date have not produced a commercially available gas turbine catalytic combustor.

B.6.4 IMPACT ON EFFICIENCY

A slight decrease in efficiency (1 to 2 percent) might be experienced due to pressure drop through the catalyst bed. However, lower CO and hydrocarbon emissions can offset a portion of this loss.

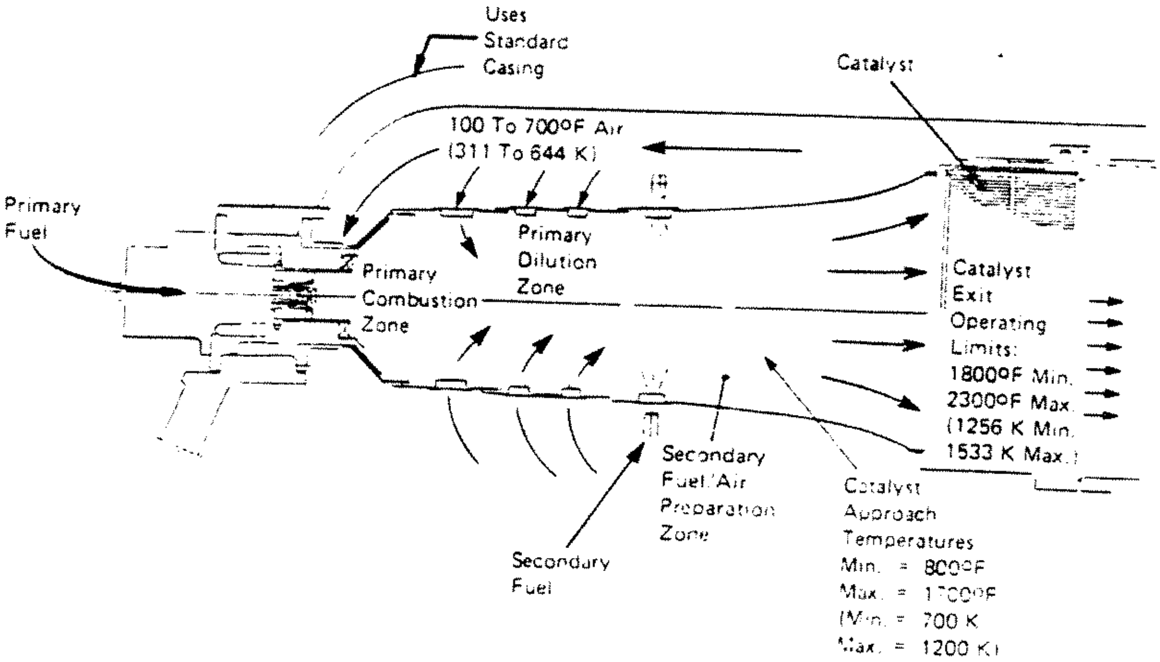


Figure B.6-1

Schematic of Catalytic Combustor

B.6.5 PRACTICAL CONSIDERATIONS

Laboratory tests on catalytic combustors show a decrease in emissions of NO_x and other pollutants. The ideal catalyst formulation/combustor design combination has not yet been identified. Criteria that needs to be met by this combination include:

- stable catalyst properties at operating temperature;
- resistance to thermal shock;
- sufficient preheat to ignition temperature; and
- uniform fuel-air premixing capability.

Poisoning by lead or sulfur compounds does not appear to be a problem, since these components are volatilized at catalyst operating temperature.

APPENDIX B.7

ZERO-NITROGEN GAS TURBINES

B.7.1 DESCRIPTION

A flow diagram for the zero-nitrogen gas turbine concept is shown in Figure B.7-1. A gas turbine is operated in an exhaust recycle mode, with most of the exhaust being cooled and recycled to the turbine inlet, and a small fraction being purged to the atmosphere. Rather high purity oxygen is added to the recycled exhaust products for the combustion. A material balance corresponding to the flow diagram is presented in Table B.7-1.

B.7.2 NO_x REDUCTION POTENTIAL

The NO_x emissions from a zero-nitrogen concept gas turbine could, in theory, be nil if absolutely pure oxygen were to be used. In reality, oxygen purity would not be 100 percent, but could be 95 percent or less. In general, NO_x emissions would increase with decreasing levels of oxygen purity. Preliminary kinetics calculations suggest that 95 percent oxygen purity would generate NO_x emissions of 5-10 ppm, whereas 99 percent oxygen purity would result in NO_x emissions of 2-5 ppm.

B.7.3 DEVELOPMENT STATUS

The zero-nitrogen concept has been employed on reciprocating engines for submarines. We are not aware of any applications of this technique on gas turbines. Although all system components for this technique have been demonstrated for various other applications, a development program would be required prior to field demonstration or implementation.

B.7.4 IMPACT ON EFFICIENCY

While the difference in combustion gases with the zero-nitrogen concept would not greatly impact turbine efficiency, the energy requirement for oxygen production would be very large. For example, the power required to produce 95 percent oxygen would be almost half the electrical output of a turbine-generator. Thus, when viewed as an entire system, the fuel efficiency would be roughly cut in half.

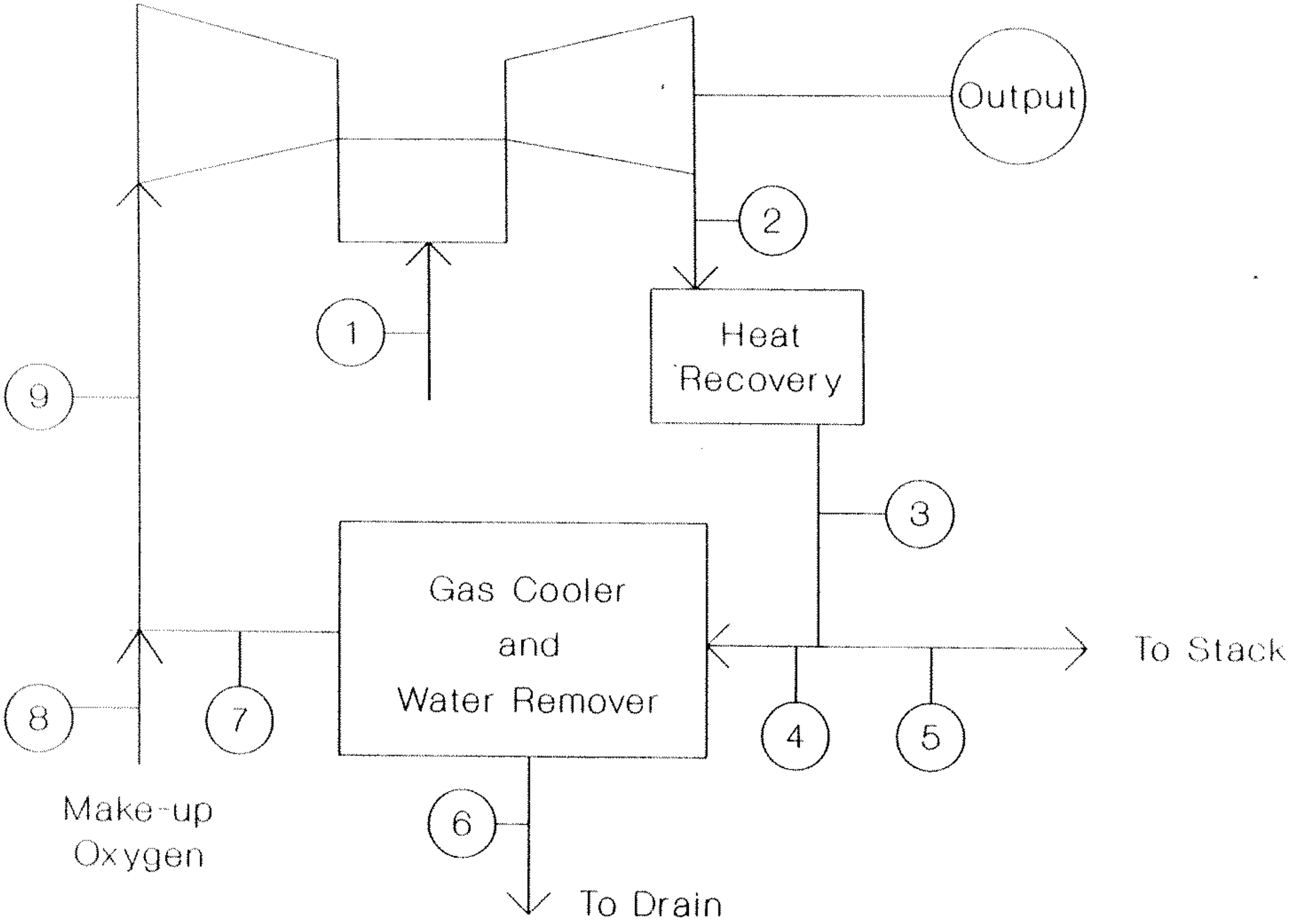


Figure B.7-1

Flow Diagram of Zero-Nitrogen Gas Turbine

TABLE B.7-1

MATERIAL BALANCE FOR ZERO NITROGEN GAS TURBINE SYSTEM
(in thousand pounds per hour)

Stream	1	2	3	4	5	6	7	8	9
CO_2	0	107	107	102	5	0	102	0	102
O_2	0	25	25	24	1	0	24	8	32
H_2O	0	5	5	5	0	4	1	0	1
N_2	0	2	2	2	0	0	2	0	2
CH_4	2	0	0	0	0	0	0	0	0
Total	2	139	139	133	6	4	129	8	137
Temp	60	840	400	400	400	60	60	60	60

B.7.5 PRACTICAL CONSIDERATIONS

In addition to the above mentioned severe impact on efficiency, there are a number of other practical considerations regarding the zero-nitrogen concept, including:

- Size/space/weight limitations for using the system in an offshore environment.
- Oxygen production technique vs. onshore production/pipeline transport.
- Oxygen storage capacity.
- Safety in storing/handling oxygen.

The cost estimations, shown in Appendix C, also show the zero-nitrogen concept to be a very expensive alternative.

APPENDIX B.8

TAILORED FUEL INJECTION

B.8.1 DESCRIPTION

The objective of tailored fuel injection is to limit the quantity of fuel that is consumed during the premixed combustion portion of the cycle. This is accomplished through reducing the ignition delay, and/or controlling the initial fuel injection rate. In addition, electronic control of fuel and timing can be used to optimize real time engine performance for both emissions and fuel economy.

Many specific modifications have been attempted by various researchers to achieve low NO_x emission available through tailored injection. These modifications are categorized as follows:

> *Optimizing Injection Nozzle Design Characteristics* - Efforts at controlling the dispersion and atomization of fuel have included using nozzles with numerous small orifices and controlling the pattern and angle of the fuel spray. In addition, zero sac nozzles have been tested.
>
> *Using Novel Injection Nozzle Designs* - Novel designs to achieve a staged combustion include slit, secondary or auxiliary injection systems. An example of such a system using two injectors is shown in Figure B.8-1. Another configuration is the coaxially oriented dual injection, using an outer throttle type valve and an inner needle type valve.
>
> *Selecting the Optimum Injection System* - Either pump-line-nozzle systems or unit injectors can be used. Either of these systems can be controlled mechanically or electronically.

B.8.2 NO_x REDUCTION POTENTIAL

For most engines, a trade-off exists between NO_x emissions versus those of particulate and hydrocarbon. For this reason, tailored injection might need to be accompanied by other modifications to reduce emissions of these other pollutants. We believe that 40 to 60 percent reduction in emissions is feasible using tailored injection. While tailored injection alone might be able to achieve greater NO_x emissions reduction, concern over emissions of other pollutants limits our estimate of the NO_x reduction potential from this method.

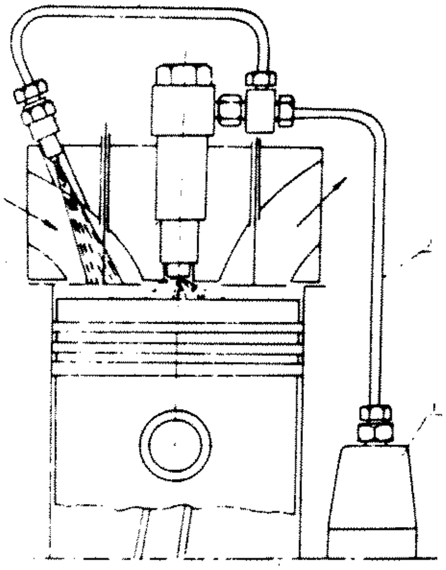


Figure B.8-1

Schematic of Second Injector for Staged Combustion

B.8.3 DEVELOPMENT STATUS

Bosch and other European diesel equipment manufacturers have been developing low-NO_x truck engines which embody tailored injection.

Most United States engine manufacturers have been developing one or more of the above mentioned fuel injection modifications to achieve lower NO_x levels.

The potential for tailored fuel injection has not yet been fully realized.

B.8.4 IMPACT ON EFFICIENCY

For most engines, a trade-off exists between NO_x emissions and fuel economy. The development of tailored fuel injection should clearly minimize the impact on fuel efficiency. We believe that a maximum fuel penalty of 2 percent would be a reasonable design goal for tailored injection.

B.8.5 PRACTICAL CONSIDERATIONS

Tailored injection requires a rather extensive research and development effort on each engine for which it is developed. General concerns which need to be addressed would include:

> Possible formation of smoke in local fuel rich zones,
>
> Combustion requires completion by about 50 degrees after top center or the fuel efficiency penalty becomes increasingly severe, and
>
> At low loads, the fuel flow is relatively small and spray conditions are marginal. Therefore, tailored injection is not likely to be as effective at low load as at rated load.

Depending on the specific duties and applications of a given engine, additional modifications might be required to improve engine performance or reduce emissions of other pollutants. Measures which might need to be developed in conjunction with tailored injection could include the following:

- combustion system: swirl versus quiescent
- increased injection pressure
- improved mixing
- reduced compression ratio
- troidal versus reentrant bowl
- decreased prechamber volume
- variable geometry electronically controlled turbocharging

APPENDIX B.9

EXHAUST GAS RECIRCULATION

B.9.1 DESCRIPTION

A portion of exhaust gas is cooled and recirculated to the engine, lowering flame temperatures and thereby NO_x. The portion of exhaust gas to be recirculated would be removed downstream of the turbocharger and cooled to the level of the manifold temperature using an intercooler with the condensed water removed as necessary. The EGR would then be introduced into the manifold displacing part of the air flow, ahead of the compressor. Proportional control or some form of simple EGR control will be required during load changes. Figure B.9-1 shows a typical EGR configuration.

B.9.2 NO_x REDUCTION POTENTIAL

We estimate that 33-55 percent NO_x reduction is feasible using EGR. For example, in tests of an 11-inch bore Pielstick diesel engine, Wilson, et. al., showed NO_x could be reduced 51 percent by 15 percent EGR with acceptable smoke (but 4 percent fuel penalty). In separate tests of a two-stroke diesel engine at 115 psi BMEP, NO_x was reduced 35 percent by 11 percent EGR with an associated increase in smoke (from Bosch 1.0 to 1.7) and a BSFC penalty of 1 percent (Bachelder). For a four-stroke diesel engine at 280 psi BMEP, SEMT found smoke acceptable at 10 percent EGR (with 30 percent NO_x reduction). At 20 percent EGR, 90 percent NO_x reduction was reported but smoke was unacceptable (Bacharach). These test results suggest that the optimum amount of EGR is about 15 percent of the intake airflow.

B.9.3 DEVELOPMENT STATUS

- EGR has been widely used on certain automotive spark-ignition engines since the late 1970's.
- EGR has been tested for truck and bus engines as part of manufacturers NO_x controls to meet the 1991 EPA standards.
- EGR technology has been widely tested on larger medium-speed engines for the past 15 years, but is not commercially proven. There are diesel demonstration sites, however.

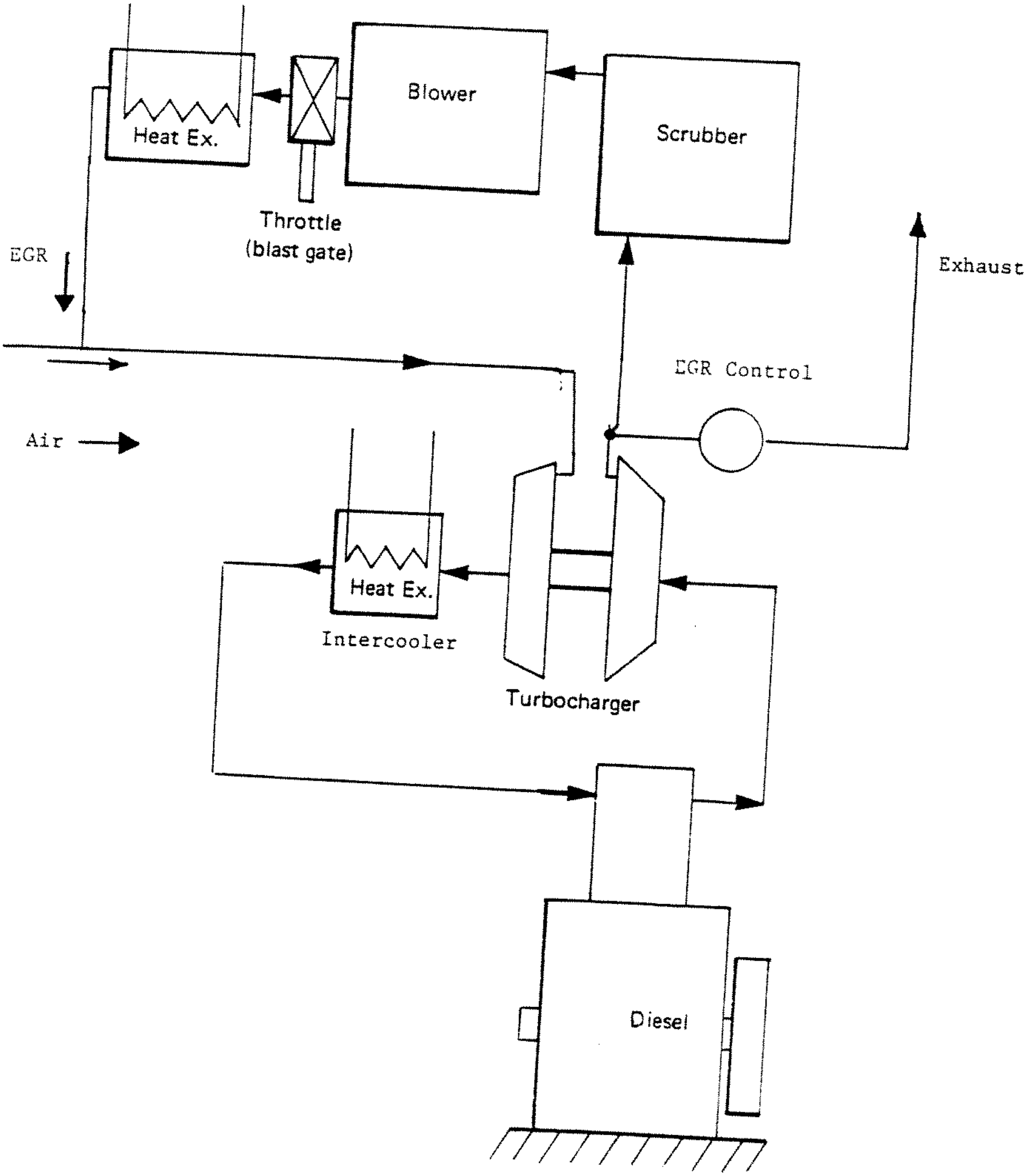


Figure B.9-1

EGR Configuration for Turbocharge Diesel Engine

B.9.4 IMPACT ON EFFICIENCY

We estimate that EGR results in a 2-4 percent penalty in fuel consumption. A slight degradation in efficiency is expected, based on the lower ratio of specific heats and lower peak pressure which result with EGR. Water-fuel emulsion can be utilized in conjunction with EGR in order to restore the fuel consumption to normal and eliminate smoke.

B.9.5 PRACTICAL CONSIDERATIONS

- Turbocharged engines require a separate blower to boost the exhaust up to the manifold pressure.
- Lube oil contamination by smoke could accelerate ring wear.
- Condensed water must be removed.
- Ductwork requires considerable space.
- Proportional control of EGR required as load and speed changes.
- The inlet system may require periodic cleaning to remove deposits.
- EGR is expected to be much more attractive for four-stroke engines than for two-stroke engines. The exhaust gas of a two-stroke engine is already highly diluted with scavenging air; therefore, high exhaust recirculation rates would be needed to achieve significant NO_X reduction.
- Each specific diesel model has a unique "breakpoint" for EGR, beyond which smoke is excessive. Increased smoke in certain diesel engines may limit the amount of EGR to a level too low to achieve substantial NO_X reduction.

APPENDIX B.10

WATER-FUEL EMULSION

B.10.1 DESCRIPTION

Water-fuel emulsions can be stabilized and stored or made on-line. Most manufacturers feel that the fuel and water should be emulsified as close as possible to the time of use in order to minimize the possibility of "slugging" the injector with a pocket of pure water. Manufacturers agree that an injector designed for a water/fuel emulsion would probably not be suitable for "cold" starting the engine.

A schematic for a typical emulsion system (Gaulin) is shown in Figure B.10-1. This unit continuously circulates the fuel/water mixture through a high pressure pump and orifice which produces the water-fuel emulsion, a portion of which is drawn off and used in the engine. Surfactants (such as Span and Tween) may be needed in these systems to maintain the emulsion, depending on the level of natural Surfactants in the fuel.

B.10.2 NO_x REDUCTION POTENTIAL

Figure B.10-2 shows the data on emulsions for large-bore engines. Greeves et. al., found that mixing the fuel and water prior to injection in the cylinder gave greater NO_x reduction than injection of the fuel and water through separate injectors. Based on Figure B.10-2, it appears that 40-50 percent NO_x reduction could be obtained if the water-fuel ratio were increased to 60 percent. Even greater NO_x reductions have been observed in small bore engines for a 60 percent water rate.

B.10.3 DEVELOPMENT STATUS

Water-fuel emulsion has been demonstrated on several stationary diesel engines but is not in widespread use. It cannot be considered off-the-shelf, commercial technology in that an R&D project would be required to resolve durability issues.

B.10.4 IMPACT ON EFFICIENCY

The optimum approach may be to combine 2 to 3 degrees of injection retard with 30/70 water-fuel emulsion, since this is expected to have significant NO_x reduction with no fuel penalty. The effect of water/fuel injection on the BSFC depends on the engine, but generally has been favorable in tests to date. Figure B.10-2 shows that the majority of medium speed engines tested show an improvement in BSFC ranging from 2 to 6 percent. A fraction of the BSFC improvements may be offset by any horsepower which the emulsor will require to produce the water-fuel emulsion.

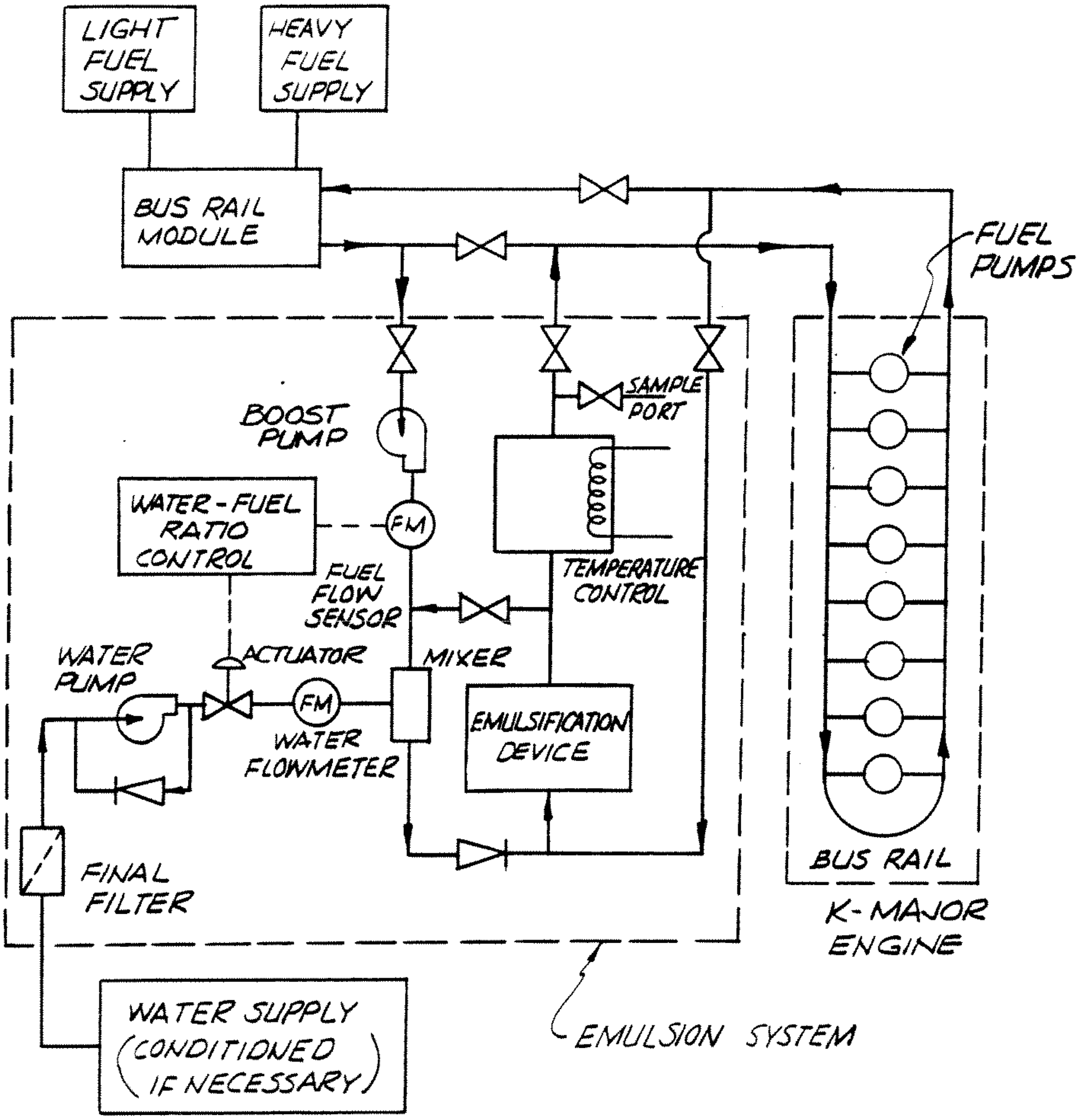


Figure B.10-1

Schematic of Typical Emulsion System

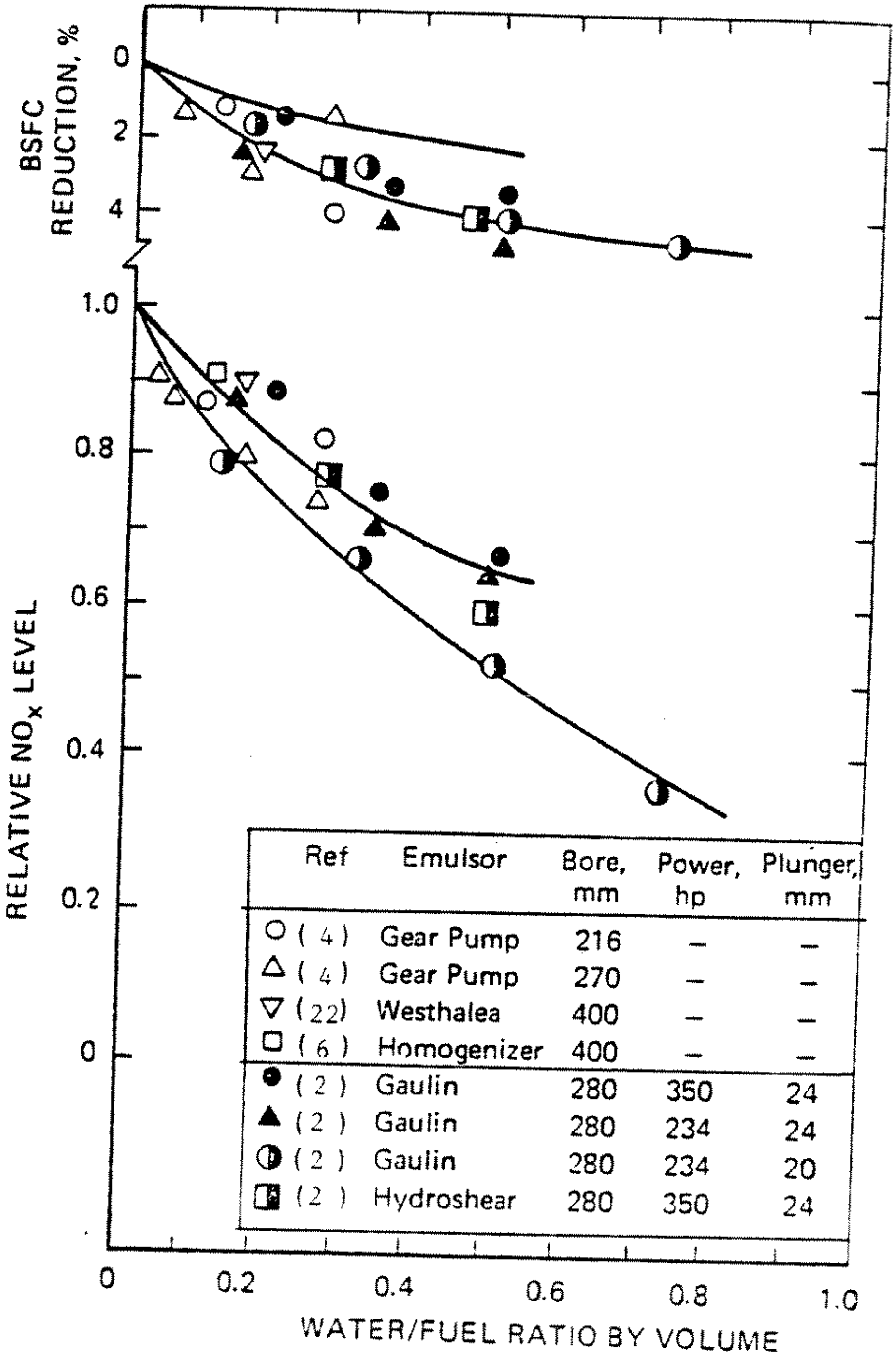


Figure B.10-2

Data on Emulsions for Large Bore Engines

B.10.5 PRACTICAL CONSIDERATIONS

The most critical aspect is preventing "slugs" of water from separating out of the emulsion. Non-emulsified water has been shown to produce severe damage to the fuel system components. Water slugging can be prevented with a control system which maintains proper ratio of water, fuel, and emulsifier (if any). The control system may be programmed to produce different water/fuel ratios at various engine loads land speeds, as is the case for EGR use in automotive engines. There is some risk of separation of fuel and water as a result of failure of the metering system during a load change. Therefore, the use of emulsions would be preferred for steady-state operating engines.

Another critical element in making emulsions effective will be optimized control of the injection timing for each water-fuel ratio, since ignition delay is known to be affected by emulsions. Proper timing will be required to optimize the reduction in NO_x while retaining the engine fuel economy.

A surfactant may be necessary to assure emulsification; if so, the choice of surfactant and quantity will be critical.

The effect of the fuel oil-water mixture on the durability of the engine and the availability of water which is relatively free of minerals are also important.

A reduction in particulates or smoke with water-fuel mixture ratios up to approximately 30 percent has been reported. For achieving particulate reduction with a minimum amount of water usage, an optimum of between 10 and 20 percent water to fuel ratio is recommended. The reduction in soot is attributed to a chemical effect (possible water-column reaction) near the burning droplets, because the soot reduction correlates with H/C ratio of the treated fuel.

APPENDIX B.11

CHARGE COOLING

B.11.1 DESCRIPTION

In this method, the air charge is reduced in temperature from about 110°F to 35-70°F by either a cooling tower or a freon refrigeration process.

A refrigeration unit or cooling tower, run either from the exhaust or a power take off, precools the inlet air by 50-70°F (one experimental system maintained the air temperature at 40°F year round). Configurations for diesel engines will depend on the level of turbocharging. The lower inlet temperature could offset some of the turbocharging requirement by providing increased air density.

Three configurations of the refrigeration approach are shown in Figure B.11-1. Option A, a refrigeration unit driven by the inlet air turbine, is preferred by many manufacturers. In order to achieve 40°F, some mechanical refrigeration system would be required.

If 40°F manifold air is not required (e.g., if 60°F is sufficient), then chilled water can be used instead of refrigeration (A, B, or C in Figure B.11-1).

The lower air temperature reduces NO_X by two mechanisms: first, the mixture can be leaned out because the engine can be charged with denser air. Second, after compression, just prior to ignition, the mixture has been cooled by 100-200°F, about twice the extent of intake air precooling. This substantially lowers NO_X formation rates during the ensuing combustion process. According to data on large-bore engines, a 50°F drop in manifold air temperature is estimated to reduce NO_X by 10-15 percent in diesel engines.

B.11.2 NO_X REDUCTION POTENTIAL

The NO_X reduction for large-bore diesel engines is about 10 to 15 percent for a 50°F decrease in charge air temperature. Small bore diesel engine measurements also suggest a 10 percent to 15 percent reduction in NO_X for 50°F decrease in air temperature.

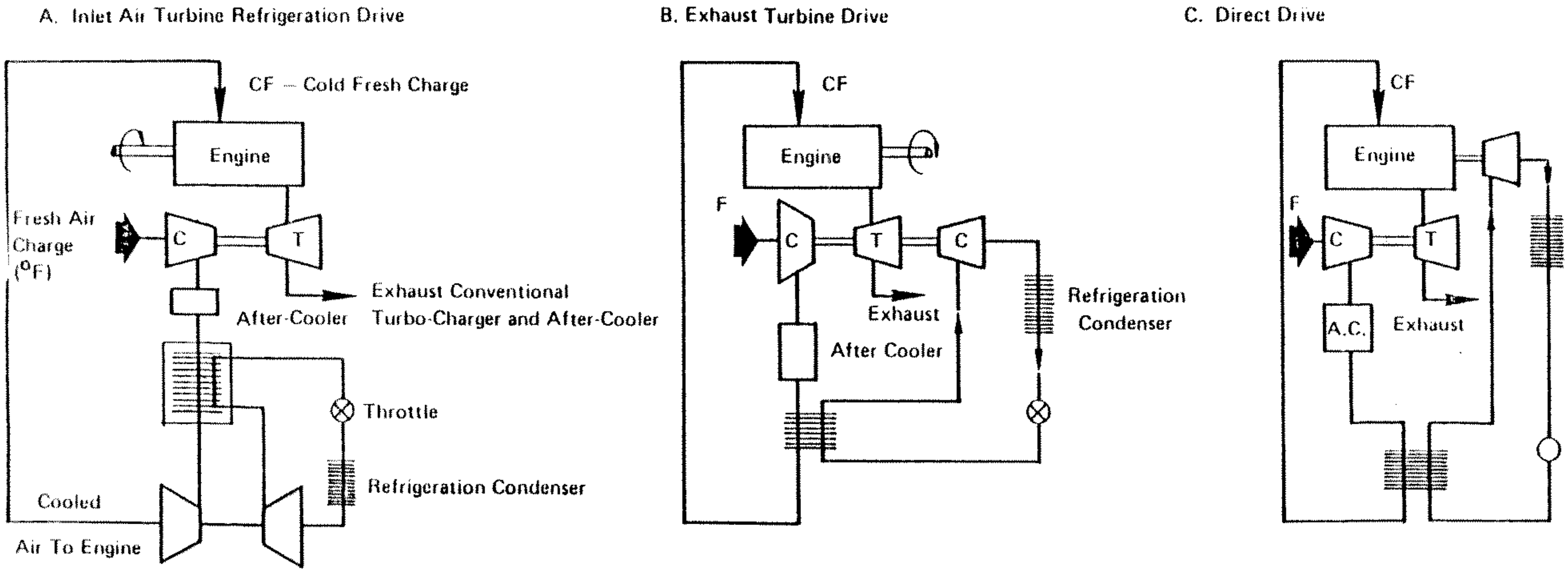


Figure B.II-1

Three Configurations of Refrigeration Approach to Charge Cooling

B.11.4 IMPACT ON EFFICIENCY

Some BSFC benefit might be expected, because of the efficiency advantage when the air density is increased. Also, the "spike" burning rate is increased for chilled intake air, and this improves efficiency. For example, Cooper successfully applied refrigeration to a four-stroke spark ignition engine and obtained 5 percent improvement in BSFC. However, part of the efficiency gain was due to a spark advance of 6°CA. In summary, the method appears very promising with respect to BSFC.

B.11.5 PRACTICAL CONSIDERATIONS

Balancing the refrigeration cycle and inlet/exhaust energy flows will be important. Difficulties with transient performance and start-up may be more pronounced with Configurations A and B, but less pronounced with C. The power drain of the compressor is also a factor. Additional considerations are as follows:

- Present intercooler systems are limited to 85°F inlet temperature, which results in relatively little NO_x reduction, so that either chilled water or refrigeration is advisable.
- Mechanical refrigeration systems may suffer from control system maintenance problems.
- To be most effective, the effective system must control air temperature as a function of load.
- An increase in condenser or cooling feedwater will be required for the refrigeration approach.

APPENDIX B.12

ZERO NITROGEN DIESEL ENGINE

B.12.1 DESCRIPTION

The zero-nitrogen engine operates on pure oxygen, using CO_2 from recycled exhaust as a diluent in place of N_2. There is no nitrogen and therefore no NO_x. Figure B.12-1 shows the schematic of recycled diesel engine.

B.12.2 NO_x REDUCTION POTENTIAL

100 percent, in theory.

B.12.3 DEVELOPMENT STATUS

This system has been developed and utilized for specialized diesel engines used in submarines and mining operations where air supply is limited. For example, systems have been demonstrated by:

- Hitachi
- Aerojet

Critical Unknowns/Needed Work

- Less expensive methods of on-site oxygen production, perhaps by electrolysis of water.
- Control system with rapid response.

B.12.4 IMPACT ON EFFICIENCY

Three to five percent penalty due to the relatively high CO_2 concentration, which lowers the ratio of specific heats of the hot gas.

B.12.5 PRACTICAL CONSIDERATIONS

- Any air leaks will produce NO_x.
- On-site oxygen storage and/or production requires additional space.
- Normal hazards associated with oxygen.

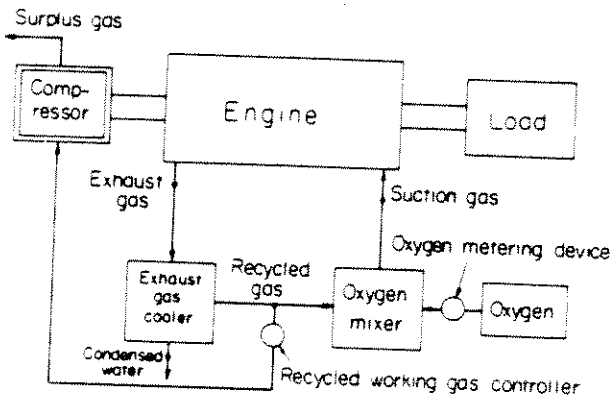


Figure B.12-1

Schematic of Zero-Nitrogen Diesel Engine

- Both O_2 and exhaust CO_2 must be modulated to respond to load and speed changes.
- High O_2 can degrade lube oil films on cylinder wall.

APPENDIX B.13

NATURAL GAS FUEL

B.13.1 DESCRIPTION

Natural gas fuel can be used in engines employing a variety of combustion techniques, including:

> *Dual-Fuel Operation* - a diesel fuel pilot is used to ignite a natural gas/air mixture formed by a retrofit package consisting of either a carburetor or a high pressure gas injector. The amount of diesel pilot can represent as low as 5 percent of the total fuel value at full load, with increasing proportions as load decreases. A cylinder head cross section showing dual-fuel operations is shown in Figure B.13-1. A prechamber dual-fueling technique is shown in Figure B.13-2.
>
> *Spark Ignition* - several diesel engine manufacturers offer spark ignited natural gas versions of their stationary engine generator product lines. These engines typically have lower compression ratios than those found for their diesel counterparts.
>
> *Advanced Natural Gas Engine Technology* - advancements in natural gas engine technology are being pursued to achieve high thermal efficiency with low emissions. Various techniques are being explored, including prechamber combustion with torch ignition and fast burn technology.

B.13.2 NO_X REDUCTION POTENTIAL

The use of natural gas alone does not ensure low NO_X emission; however, through modification and tuning, natural gas fueled engines can produce low NO_X emissions. In some tests, natural gas fueled engines have produced more than fifty percent greater NO_X emissions than their diesel counterparts (Goetz et. al.). In other tests, natural gas fuel has resulted in 80 percent reduction of NO_X emissions (Ding and Hill). We believe that optimizing engines for using natural gas should result in NO_X emission levels ranging from 2 to 6 grams per horsepower hour.

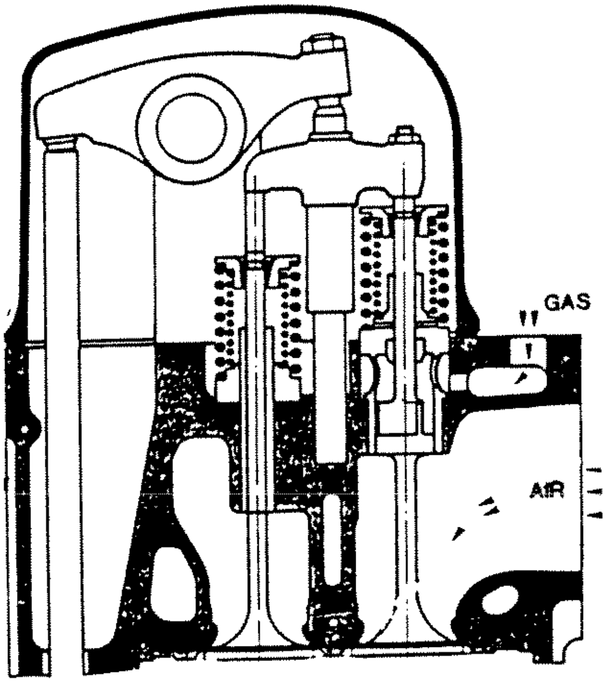
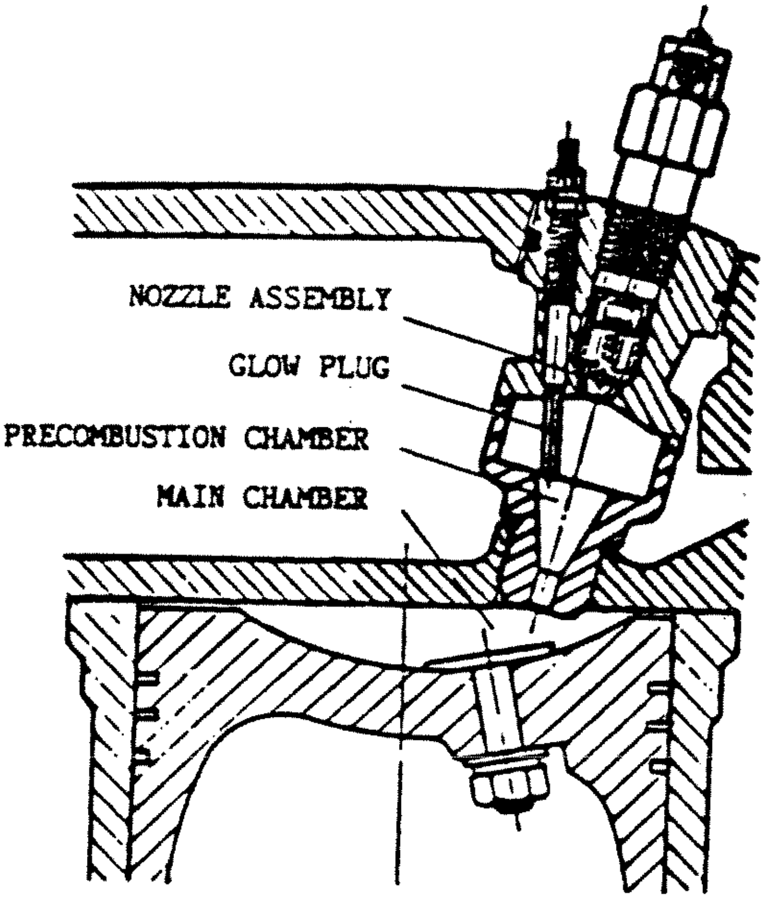


Figure B.13-1

Cylinder Head Cross Section
Showing Duel Fuel Operation



Combustion Chamber Geometry

Figure B.13-2

B.13.3 DEVELOPMENT STATUS

Many natural gas engine technologies are commercially available for some engine models. Research and development is continuing, emphasizing high efficiency and low emissions of all pollutants. Examples of the commercial status and present research include:

> Fairbacks Morse offers a low NO_x dual-fuel engine (Pielstick PC 2.5 model).
>
> Transit buses in many areas are demonstrating natural gas technology. Locales include Tacoma, Vancouver, Los Angeles and New York.
>
> Waukesha and Cooper Bessemer have engines with precombustion torch ignition which achieve NO_x levels less than 3 g/bhp-hr.
>
> Low NO_x techniques for various engines are being developed at Caterpillar and Southwest Research Institute with sponsorship from various organizations.
>
> University of Alabama has conducted LNG retrofit tests on Caterpillar 3406 and Perkins 4.236 engines in marine applications.

Critical Unknowns/Needed Work

To achieve low emissions in a dual fueled engine, the quantity of pilot fuel needs to be reduced while operating very lean.

Second generation natural gas engines, now under development, will require extensive research and development.

B.13.4 IMPACT ON EFFICIENCY

The efficiency of using natural gas will vary according to specific engine and natural gas technique. While some researchers have reported average losses in brake specific fuel consumption of as much as 5 percent, other researchers have reported regions of greater fuel efficiency. Losses in efficiency can be expected to be greater at lower loads.

B.13.5 PRACTICAL CONSIDERATIONS

Various practical considerations in using natural gas fuel can include the following:

Compression ratio must be limited to prevent detonation of the gas air mixture during compressions.

Explosion of the intake or exhaust manifolds is a potential hazard that exists in natural gas engines when they misfire.

The control system must be able to modulate both diesel fuel and natural gas for dual-fuel engines during changes in load and speed.

Natural gas fuel requires greater storage volume compared to diesel fuel.

Refueling requires high pressure systems and/or longer refueling times when compared to diesel fuel.

APPENDIX B.14

METHANOL

B.14.1 DESCRIPTION

In this method, the engine is modified to permit substitution of methanol for diesel fuel (DF2), using one of the following five approaches:

(a) Compression ignition of methanol spray with a separate DF2 pilot injector (5-10 percent of the fuel energy is DF2). This approach is shown in Figure B.14-1.

(b) "Spark-assisted" ignition of methanol spray (stratified charge) - this method is used by M.A.N. and Caterpilar.

(c) Compression ignition of methanol with cetane-improver additive. This approach is the subject of a current NYSERDA project at Cummins, O.R.F., and Daimler.

(d) Emulsion of approximately 25-40 percent methanol in DF2 - this approach does not lower NO_X as much as pure methanol.

(e) Elevated compression temperature; air must be raised to 1,600°F or above in order to ignite methanol - this approach is used by Detroit Diesel (CR = 19/1 with exhaust gas retention).

Lower NO_X results from the lower flame temperature of methanol-air mixtures. "Fumigation", or premixing with a carburetor, is not satisfactory for heavy duty diesels which see full load service, because methanol would preignite on the compression stroke at full load.

B.14.2 NO_X REDUCTION POTENTIAL

Many references describe methanol technology for diesel engines; the following data is typical:

- EPA tested a Volvo truck diesel engine retrofit with the DF2 pilot configuration (approach (a) above) and found 50 percent NO_X reduction.

- Golden Gate Transit tested the M.A.N. approach (approach (c) above); they observed 30-40 percent NO_X reduction.

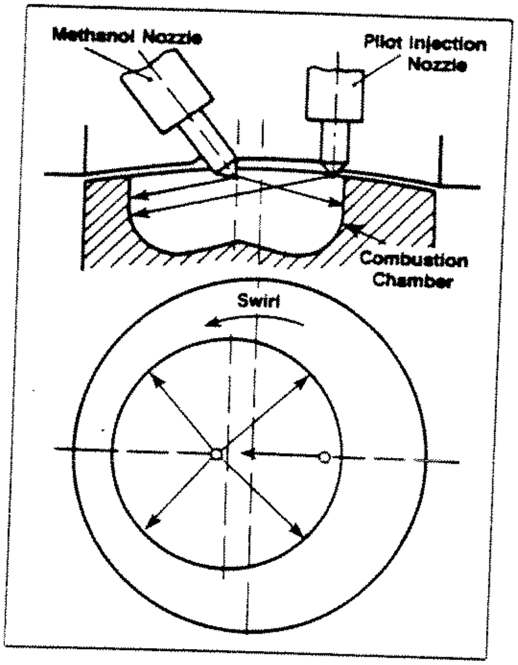


Figure B.14-1

Methanol Spray with seperate DF2 pilot injector

- Detroit Diesel (DDA) found 75 percent NO_x reduction for their methanol engine (approach (e) above) compared to their "advanced technology" diesels which exhibit 4-5 g/bhp-hr. For the 13-mode cycle, 0.92 g/bhp-hr was the NO_x level for the engine on methanol. At full load, 1,300 rpm the NO_x level was 0.9 g/bhp-hr. However, these test values were for methanol in conjunction with retard timing. When the DDA engine was retrofitted on a bus engine at standard timing, 2.2 g/bhp-hr was the result; this is probably a more realistic expectation for the NO_x level of other diesel engines converted to methanol.

The above test data suggests that 2 ± 1 g/hp-hr is readily achievable (70-80 percent reduction).

B.14.3 DEVELOPMENT STATUS

Certain methanol conversion methods (approaches (c) and (d)) have only been tested in the laboratory. Further technology development and special engine modifications are required for methanol to be used on specific diesel engines.

It is worthy to note that over 3,000 vehicles in Sao Paulo, Brazil have been converted to 100 percent alcohol since 1977 (CR = 12, spark-assisted) using approach (b).

The use of methanol as a substitute for gasoline was first tried by Lichty and Phelps in 1937 on a 1936 Chevy. Until the late 1970's, interest in methanol was directed toward gasoline engines. Only later when the automotive diesel became more popular, and NO_x and particulate emissions were recognized as problematic, did methanol substitution in diesel engines become of interest.

In the early 1980's, transit bus fleets were evaluated by Golden Gate Transit and in Germany (M.A.N. approach). DDA engines retrofit for methanol were also evaluated by Golden Gate.

B.14.4 IMPACT ON EFFICIENCY

Test data show that the overall bsfc impact is not significant; however, methanol may offer a small advantage. Some of the observed effects of methanol are as follows:

- Slower burn once ignited; timing advance may be needed.
- Lower peak cylinder pressure.
- Atomization and air-fuel mixing requires longer duration because the fuel volume doubles with methanol; this slightly lowers efficiency.
- Methanol flames have lower radiation heat flux; this boosts engine efficiency.

B.14.5 PRACTICAL CONSIDERATIONS

(1) Undesirable knock occurs with methanol for high compression engines (if CR = 20 or above), depending on the amount of residual gas.

(2) One potential side benefit of methanol vs. DF-2: Higher fuel energy can be injected and burned per engine cycle, because there is no smoke limit with methanol. That is, it may be possible to obtain more power from a given engine displacement.

(3) With methanol, aldehyde emissions may go up; perhaps this can be countered with an oxidizing catalyst other than lube oil.

(4) Polynuclear aromatic hydrocarbons are reduced by 90 percent with methanol.

(5) Fuel storage volume must increase or range decrease (approximately 2.2x).

(6) Injection nozzles and fuel-pumps-plungers must be enlarged.

(7) Cold start problem because of low vapor pressure (need glow plug or heated manifold).

(8) Separation of blends - prefer pure or low concentrations.

(9) Lubricity additives may be needed to protect fuel system (1,000 hour life).

(10) Storage tank ullage can be flammable.

(11) Increased wear on rings noticed by Volvo.

(12) Fuel wetted gaskets and metals must be coated with protective films because of the chemical effect of methanol.

APPENDIX C

NO_x CONTROL TECHNOLOGY COST ESTIMATES