DCN No.: 90-209-028-11

Note: This is a reference cited in *AP 42, Compilation of Air Pollutant Emission Factors, Volume I Stationary Point and Area Sources.* AP42 is located on the EPA web site at www.epa.gov/ttn/chief/ap42/

The file name refers to the reference number, the AP42 chapter and section. The file name "ref02_c01s02.pdf" would mean the reference is from AP42 chapter 1 section 2. The reference may be from a previous version of the section and no longer cited. The primary source should always be checked.

EVALUATION OF SCR NO_x CONTROLS FOR SMALL NATURAL GAS-FUELED PRIME MOVERS

PHASE I

Topical Report

Prepared by

G. S. Shareef and D. K. Stone
Radian Corporation
3200 East Chapel Hill Road
Research Triangle Park, NC 27709

for

Gas Research Institute

Contract No. 5089-254-1899

GRI Project Manager
Kathleen S. Locke
Air Quality

July 1990

GRI DISCLAIMER

LEGAL NOTICE: This report was prepared by Radian Corporation as an account of work sponsored by the Gas Research Institute (GRI). Neither GRI, members of GRI, nor any person acting on behalf of either:

a. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

b. Assumes any liability with respect to the use of, or for damages resulting from the use of, any information, apparatus, method, or process disclosed in this report.

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. GRI-90/0138	2.	3. Recipient's Accession No.

4. Title and Subtitle
Evaluation of SCR NO_x Controls for Small Natural Gas-Fueled Prime Movers

5. Report Date July 1990

6.

7. Author(s) Gunseli Sagun Shareef and Diana K. Stone

8. Performing Organization Rept. No

9. Performing Organization Name and Address
Radian Corporation
Progress Center
3200 E. Chapel Hill Rd./Nelson Hwy.
P. O. Box 13000
Research Triangle Park, North Carolina 27709

10. Project/Task/Work Unit No. 209-028

11. Contract(C) or Grant(G) No.
(C) 5089-254-1899
(G)

12. Sponsoring Organization Name and Address
Gas Research Institute
8600 West Bryn Mawr Avenue
Chicago, Illinois

13. Type of Report & Period Covered
Topical Report
December 1989-July 1990

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

The objective of the study was to develop a data base on selective catalytic reduction (SCR) applications on small natural gas-fired prime movers with emphasis on SCR system performance and costs. Major sources of information included telephone contacts with the SCR sites, SCR system suppliers, and engine/turbine manufacturers.

Eleven SCR units were identified as operational at seven sites on gas turbines. All were base load cogeneration facilities. On internal combustion (IC) engines, 13 SCR units at nine sites are operational (three cogeneration and ten gas compression/transmission/distribution). Nine of the units are variable load applications. Two principal SCR system problems identified include lack of reliability for continuous emission monitors (CEMs) and catalyst failures due to either structural integrity or poisoning.

Total installed capital costs for SCR systems on combustion turbines showed a smooth decrease from 140 to 40 $/hp for the 4,300 to 12,000 hp size range. Catalyst costs were about 30 to 40 percent of the total installed costs. IC engine SCR costs ranged from 30 to 250 $/hp, with no apparent correlation with engine size (350 to 6,710 hp).

17. Document Analysis a. Descriptors
selective catalytic reduction
SCR
prime movers
gas turbines
reciprocating engines

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

18. Availability Statement
Release unlimited

19. Security Class (This Report) Unclassified

20. Security Class (This Page)

21. No. of Pages 55

22. Price

(See ANSI-Z39.18) See Instructions on Reverse

OPTIONAL FORM 272 (4-77)
(Formerly NTIS-35)
Department of Commerce

RESEARCH SUMMARY

TITLE	Evaluation of SCR NO_x Controls for Small Natural Gas-Fueled Prime Movers - Phase I
CONTRACTOR	Radian Corporation
	GRI Contract Number: 5089-254-1899
PRINCIPAL INVESTIGATORS	G.S. Shareef D.K. Stone
REPORT PERIOD	December 1989 - July 1990 Topical Report
OBJECTIVE	To develop a data base for small natural gas-fired prime mover selective catalytic reduction (SCR) applications focusing on SCR system performance and costs
TECHNICAL PERSPECTIVE	The natural gas industry is presently without a current data base to evaluate the cost and operating characteristics of SCR under the conditions anticipated for small natural gas-fueled prime movers in compressor station and cogeneration applications. The application of SCR to small prime movers could likely increase due to existing and anticipated regulations to limit NO_x.
RESULTS	Eleven SCR units were identified as operational at seven sites on gas turbines. All were base load cogeneration facilities. On internal combustion (IC) engines, 13 SCR units at nine sites are operational (three cogeneration and ten gas compression/transmission/distribution). Nine of the units are variable load applications. Two principal SCR system problems identified include lack of reliability for continuous emission monitors (CEMs) and catalyst failures due to either structural integrity or poisoning. Total installed capital costs for SCR systems on combustion turbines showed a smooth decrease from 140 to 40 $/hp for the 4,300 to 12,000 hp size range. Catalyst costs were about 30 to 40 percent of the total installed costs. IC engine SCR costs ranged from 30 to 250 $/hp, with no apparent correlation with engine size (350 to 6,710 hp).
TECHNICAL APPROACH	The documentation focused on prime mover characterization, SCR system performance, and SCR system costs. Major sources of information included telephone contacts with SCR sites, SCR system suppliers, and engine/turbine manufacturers, as well as Radian in-house projects and the GRI co-sponsored EPRI project (Environmental and Economic Evaluation of Gas Turbine SCR NO_x Control). In-depth analysis of the performance/cost data was not conducted under this phase as it is within the scope of Phase II activities.

PROJECT IMPLICATIONS

Phase I of this contract established a data base of small gas-fueled engine SCR experience. These data, which were inaccessible in the past, are now available for the gas industry and others who use such engines to provide necessary facts in responding to regulatory concerns and policies. Analysis of the data base is planned for Phase II of this contract.

GRI Project Manager
Kathleen S. Locke
Air Quality

SUMMARY

The application of selective catalytic reduction (SCR) to small natural gas-fueled prime movers at cogeneration facilities and compressor stations could likely increase due to existing and anticipated regulations to limit NO_x emissions from such emission sources. The natural gas industry is presently without a current data base with which to evaluate the cost and operating characteristics of SCR under the conditions anticipated for small prime movers in compressor station and cogeneration applications. Although there have been field studies conducted by the South Coast Air Quality Management District (SCAQMD) and American Gas Association in the early 1980s, it is currently not possible to calculate the true economic, energy, and environmental impacts that would apply to such systems. Therefore, the current study was undertaken to collect and evaluate information on SCR control of NO_x emissions from small prime movers.

This report presents the findings from the Phase I effort. The specific objective of this effort was to document and develop a data base for all small, natural gas-fired prime mover SCR sites (reciprocating engines and turbines less than 20,000 hp in size) in the United States. The documentation focused on prime mover characterization, SCR system performance, and SCR system costs. Major sources of information included telephone contacts with SCR sites, SCR system suppliers, and engine/turbine manufacturers as well as Radian in-house projects and the GRI co-sponsored EPRI project (Environmental and Economic Evaluation of Gas Turbine SCR NO_x Control). In-depth analysis of the performance/cost data was not conducted under this phase as it is within the scope of Phase II activities.

Small Prime Mover SCR Site Identification

Gas Turbines -- All of the SCR applications on gas turbines are at cogeneration facilities, are located in California, and fire natural gas exclusively. Of the 26+ SCR units identified at 17 sites, only 11 SCR units at seven sites are operational. Construction of three SCR units is scheduled for 1991 at one site, one site was recently permitted, and a permit to construct is pending at yet another site. The seven remaining SCR projects are not operational due to project cancellations during the permitting process or due to bankruptcy.

Internal Combustion (IC) Engines -- Overall, 21 SCR applications on IC engines have been identified. Thirteen SCR units at nine sites are currently operational (two cogeneration and 11 gas compression/transmission/distribution SCR units) with all but two located in California. Only one of the operating

SCR units involves gas transmission. Two of the operating SCR units are on engines firing sewage digester gas, with another operating SCR unit on a dual fuel diesel engine.

Nine SCR units that were operational in the early 1980s are no longer in service. In most of these cases, the units have been replaced with clean burn engines or electric motors due to poor SCR performance or economics.

Small Prime Mover SCR System Characterization

Gas Turbines -- SCR design and operating information was obtained for seven sites. All of these applications are base load cogeneration facilities. With one exception, the SCR systems employ vanadium, titanium, and zeolite-based catalysts and operate in the 650-850°F range. The SCR unit that operates at 470°F employs a platinum catalyst. Space velocities range from 6,500 to 12,000 ft^3/hr of exhaust gas per ft^3 of catalyst for non-precious metal catalyst systems. Design NO_x reductions range from 65-85 percent while the actual percent NO_x removals are in the 59 to 92 range. Reported NH_3/NO_x ratios range from 0.9 to 1.2.

Permitted NO_x levels are in the 8-22 ppm (at 15% O_2) range. The 22 ppm limit for one unit is based on SCR only with no wet injection into the combustor. Applications with SCR and wet injection are characterized with a permit limit range of 8-15 ppm. Ammonia slip is limited to 20 ppm on two SCR units only. The other units have no permit restrictions and report ammonia slips in the 10 to 32 ppm range.

IC Engines -- The information identified for IC engines represents two cogeneration and seven gas compression/transmission/distribution facilities. The two cogeneration units and one gas transmission unit are base load applications, with the remaining gas compression/distribution units operating at variable load.

The SCR units in IC engine applications also employ vanadium, titanium, platinum, and zeolite catalysts and typically operate between 550-850°F except for two units. One of these two units operates at 900°F and employs a zeolite catalyst and the other unit operates at 850-900°F (catalyst type unspecified). Reported space velocities are in the 2,000 to 10,000 ft^3/hr of exhaust gas per ft^3 of catalyst. The design NO_x removal levels range from 80 to 95 percent while the actual NO_x removal levels show a wide variation, from 20 to 96 percent. Reported NH_3/NO_x ratios for the IC engine SCR applications range from 0.6 to 1.0.

The NO_x permit limits for the IC engines are based either on percent reduction across the catalyst, tons/yr, ppm, or g/Bhp-hr. There are no ammonia slip permit restrictions on IC engine SCR applications.

Small Prime Mover SCR Operating Experience

Two principal SCR system problems identified in this study include lack of reliability for continuous emission monitors (CEMs) and catalyst failures due to either structural integrity or poisoning.

Gas Turbines -- SCR units on gas turbines have been operational only since 1986, with the operating unit with the most experience having logged about 30,000 hours. Typical start-up problems have included flow stratification and control system performance. The main operational problem area has been the CEMs. To date, one unit has had the entire catalyst replaced and an additional layer of catalyst has been required in another. Except in one case, the operators are generally pleased with the operation of the SCR units.

IC Engines -- The IC engine SCR experience is more substantial than the gas turbine SCR experience in this size range since a number of units were installed in the early 1980s. Some SCR units have logged 30,000-40,000 operating hours. Start-up problems with these units have included control system and analyzer failures. In some cases, the automatic controls were converted to manual control. Other problems with the operation of the SCR units include overloading the engine and catalyst support failure. Catalyst has been replaced at three units and catalyst additions have been required at two units due to catalyst sintering.

A number of IC engine SCR units are no longer in operation. Some of these units were part of the SCR test programs conducted in the early 1980s and were taken out of service due to poor performance. Other engine/SCR systems have been replaced with clean burn engines, electric motors, or rich-burn engines with non-SCR. Currently, three operators have plans to remove the SCR units in the near future, with one of the plans directly related to dissatisfaction with the SCR unit performance reliability.

Small Prime Mover SCR Cost Data

Very limited data were available on capital and operating costs of SCR systems included in this study.

Capital Costs -- Very limited data were available on total installed capital costs and operating costs of SCR systems included in this study. Based on actual data from five sites, the total installed capital costs for SCR systems with automatic controls were less than $900,000 (1989 dollars) for gas turbines 12,000 hp or less in size. Catalyst costs were about 30 to 40 percent of the total installed costs. On a per unit output basis, the costs ranged from 140 to 40 $/hp for the size range 4,300 to 12,000 hp, and showed a smooth decrease with increasing turbine size.

The cost data for IC engine SCR systems were obtained from eight sites and cover the size range 350 to 6,710 hp. (The 6,710 hp engine is a dual fuel diesel engine). Excluding a low estimate due to the market forces at the time of purchase, the capital costs show an increase with engine size and range from $70,000 to $900,000. On a per unit output basis, these costs range from 30 to 250 $/hp, with no apparent correlation with engine size.

Overview of Current Regulatory and SCR NO_x Control Applications

Gas Turbines -- Three regulatory bodies, SCAQMD, New Jersey Department of Environmental Protection (NJDEP), and Northeastern States for Coordinated Air Use Management (NESCAUM) have proposed or adopted NO_x emission limits for gas-fired turbines. For example, the rule proposed by SCAQMD for turbines in the 0.3 to less than 2.9 MW (400 to 3,900 hp) range specifies 25 ppm at 15 percent O_2. For the 2.9 to less than 60 MW (3,900 to 80,400 hp) range, NO_x emission limits are 9 ppm with SCR; and 12 ppm without SCR. For the NJDEP and NESCAUM NO_x emission limits, the regulatory basis is the application of wet injection.

California has established BACT for NO_x at 9 ppm. Other areas of the country have adopted this NO_x level as BACT as well. In recent BACT analyses for NO_x, the U.S. Environmental Protection Agency is considering $3,000 to $6,500 per ton of NO_x removed as a reasonable range of costs for NO_x control.

IC Engines -- The SCAQMD is currently proposing a rule that would require engines over 50 Bhp to be replaced with electric motors or to achieve proposed engine NO_x emission limits (0.25 lb NO_x/MW-hr or 5 ppm of NO_x at 15 percent O_2 and 25 percent engine efficiency).

Most regulators in the early to mid-1980's permitted IC engines using the proposed New Source Performance Standards for stationary IC engines as a basis. As engine designs have improved, regulators have begun to require selection of the lowest NO_x emitting engine that is suitable for the application as BACT.

TABLE OF CONTENTS

Section			Page
Disclaimer			ii
Research Summary			iv
Summary			vi
Figures			xi
Tables			xii
1.0	INTRODUCTION		1-1
	1.1	Background	1-1
	1.2	Objectives and Approach	1-1
2.0	SMALL PRIME MOVER SCR SITE IDENTIFICATION		2-1
	2.1	Data Gathering	2-1
		2.1.1 Gas Turbines	2-2
		2.1.2 IC Engines	2-2
3.0	SMALL PRIME MOVER SCR SYSTEM CHARACTERIZATION		3-1
	3.1	SCR Technology Description	3-1
	3.2	Gas Turbines	3-6
	3.3	IC Engines	3-6
4.0	SMALL PRIME MOVER SCR SYSTEM OPERATING EXPERIENCE		4-1
	4.1	SCR Operating Experience - Gas Turbines	4-4
	4.2	SCR Operating Experience - IC Engines	4-5
5.0	SMALL PRIME MOVER SCR COST DATA		5-1
	5.1	Capital Costs	5-1
		5.1.1 Gas Turbines	5-1
		5.1.2 IC Engines	5-5
		5.1.3 Costs for Turbines and Engines	5-5
	5.2	Operating Cost Data	5-11
6.0	OVERVIEW OF CURRENT REGULATORY AND SCR NO_x CONTROL APPLICATIONS		6-1
	6.1	Gas Turbines	6-1
	6.2	IC Engines	6-2
7.0	REFERENCES		7-1

FIGURES

Number		Page
3-1	SCR System Block Diagram	3-4
5-1	SCR Capital Costs for Gas Turbines	5-3
5-2	SCR Capital Costs Per Unit Output for Gas Turbines . . .	5-4
5-3	SCR Capital Costs for IC Engines	5-7
5-4	SCR Capital Costs Per Unit Output for IC Engines	5-8
5-5	SCR Capital Costs for Gas Turbines and IC Engines	5-9
5-6	SCR Capital Costs Per Unit Output for Gas Turbines and IC Engines	5-10
5-7	SCR Operating Costs for IC Engines	5-12

TABLES

Number		Page
2-1	Small Prime Mover SCR Sites - Gas Turbines	2-3
2-2	Small Prime Mover SCR Sites - IC Engines	2-4
2-3	Operating SCR Units - Gas Turbines	2-5
2-4	Operating SCR Units - IC Engines	2-6
3-1	Small Prime Mover SCR System Characteristics - Gas Turbines	3-2
3-2	Small Prime Mover SCR System Characteristics - IC Engines	3-3
4-1	Small Prime Mover SCR Operating Experience - Gas Turbines	4-2
4-2	Small Prime Mover SCR Operating Experience - IC Engines	4-3
5-1	SCR System Capital Cost Data - Gas Turbines	5-2
5-2	SCR System Capital Cost Data - IC Engines	5-6
5-3	SCR System Operating Cost Data - Gas Turbines	5-13
5-4	SCR System Operating Cost Data - IC Engines	5-14

1.0 INTRODUCTION

1.1 BACKGROUND

The application of selective catalytic reduction (SCR) to small, natural gas-fueled prime movers at cogeneration facilities and compressor stations could likely increase due to existing and anticipated regulations to limit NO_x emissions from such emission sources. The regulatory driving forces at the State level include SCR requirements by air quality management/pollution control districts on gas turbine cogeneration applications in California and in a number of states in the New England area. Also, the Northeastern States for Coordinated Air Use Management (NESCAUM) have issued guidelines for combustion turbines which require the application of SCR unless it can be shown to be technically infeasible.

At the Federal level, the U.S. Environmental Protection Agency (EPA) has recently promulgated NO_x increments as part of the Prevention of Significant Deterioration program effective October 17, 1989. This will likely lead to increasingly stringent future NO_x control requirements in other areas of the U.S. as well. In addition, the U.S. EPA is developing a "top-down" policy for NO_x Best Available Control Technology (BACT) analysis. The top-down analysis is requiring a much more detailed evaluation of SCR and justification of its technical and economic infeasibility (if SCR is not selected as BACT).

The natural gas industry in the U.S. is presently without a current data base with which to evaluate the cost and operating characteristics of SCR under the operating conditions anticipated for small, natural gas-fueled prime movers in compressor station and cogeneration applications. Although field studies were conducted in the early 1980s by South Coast Air Quality Management District (SCAQMD) and American Gas Association on SCR systems applied to IC engines, it is currently not possible to calculate the true economic, energy, and environmental impacts that would apply to such systems. The gas industry must presently rely on information from SCR system suppliers regarding the specifications, performance, and costs for these systems, or on Japanese and German SCR experience which may not be directly translatable to U.S. applications. Therefore, Gas Research Institute (GRI) has contracted with Radian Corporation to conduct a study to collect and evaluate information on SCR control of NO_x emissions from small, natural gas-fueled prime movers.

1.2 OBJECTIVES AND APPROACH

The project is to be conducted in two phases over an approximately two-year period. The four primary objectives of the two-phase program are to:

- Document the actual costs and operational characteristics of commercial SCR systems on small prime movers.
- Provide the gas industry with the necessary database, analyses, and technology transfer with which to evaluate SCR systems under anticipated operating conditions.
- Develop a frame of reference for SCR NO_x controls to evaluate potential impacts of future regulations on the gas industry, and to better plan for permitting requirements and future procurement and installation.
- In the advent of wider SCR application, develop performance, efficiency, and cost reduction strategies for the gas industry to minimize state-of-the-art NO_x control and life cycle costs.

The specific objective of the Phase I effort was to document and develop a preliminary data base on all small, natural gas-fired prime mover SCR sites (reciprocating engines and turbines) in the U.S. The documentation focused on prime mover characterization (type, size, manufacturer, operating mode, NO_x permit conditions), SCR system performance (SCR system design and operating variables, operating history), and SCR system costs (capital and operating). Major sources of information included telephone contacts with SCR sites, SCR system suppliers, and engine/turbine manufacturers as well as Radian in-house projects and the GRI co-sponsored EPRI project (Environmental and Economic Evaluation of Gas Turbine SCR NO_x Control). In-depth analysis of the performance/cost data was not conducted in this phase as it is within the scope of Phase II activities.

This report summarizes the activities conducted in Phase I of the study. Section 1 of the report contains this introduction. Section 2 presents detailed documentation of the prime mover SCR sites. Characterization of the SCR systems is included in Section 3. SCR system operating experience and cost information are summarized in Sections 4 and 5, respectively. A brief overview of current regulatory and SCR NO_x control is presented in Section 6. Finally, a listing of references used in the study including the phone contacts is presented in Section 7. Results of the activities to be conducted under Phase II will be reported in a separate document.

2.0 SMALL PRIME MOVER SCR SITE IDENTIFICATION

2.1 DATA GATHERING

One of the objectives of this study was to identify all SCR applications at small, natural gas-fired prime mover sites in the U.S. For the purposes of this study, data gathering efforts focused on gas turbines and internal combustion (IC) engines at compressor stations and cogeneration facilities that are less than about 15,000-20,000 hp in size.

SCR installations were identified through contacts with SCR system vendors and reciprocating engine and turbine manufacturers. The SCR system suppliers contacted include the following:

Hitachi America (Babcock & Wilcox)
Cormetech (Mitsubishi/Corning)
Camet/W.R. Grace
Engelhard
Hitachi Zosen
Ishikawajima-Harima (IHI)
Johnson Matthey
Joy/Kawasaki Heavy Industries (KHI)
Nitrogen Nergas
Norton
Nippon Shokubai (NSKK)
Steuler

Engine and turbine manufacturers contacted as part of this effort include General Electric and Solar for gas turbines, and Caterpillar, Cooper Ajax, Cooper Bessemer, and Waukesha for engines.

Gas transmission companies with compressor stations located in southern California were contacted to confirm the database. In addition, existing data from the GRI co-sponsored EPRI study on gas turbine SCR and information from other in-house industrial projects were reviewed to identify SCR applications at prime mover sites. Other information sources reviewed include the Best Available Control Technology/Lowest Achievable Emission Rate (BACT/LAER) Clearinghouse, data bases from the Kern County Air Pollution Control District, California Air Resources Board, and SCAQMD, the SCAQMD Cogeneration Report, and the SCAQMD Rule 1110 and 1134 Staff Reports.[1-9] The Bay Area Air Quality Management District, SCAQMD, Kern County Air Pollution Control District, and Ventura County Air Pollution Control District were also contacted to verify the installation lists.

Tables 2-1 and 2-2 present the small prime mover SCR sites identified for gas turbines and IC engines, respectively. The tables list all known sites, including those no longer in operation, those recently permitted, and those currently under construction.

2.1.1 Gas Turbines

As shown in Table 2-1, all of the SCR applications on gas turbines are at cogeneration facilities, are located in California, and fire natural gas exclusively. Of the 17 sites identified, a total of 11 SCR units at seven sites are currently operational. Table 2-3 presents a listing of only those sites that are currently operating. Eight of the operating SCR units are in the 4,000-6,000 hp range, with three units in the 11,000-12,000 hp range. Construction of three SCR units is scheduled for 1991 at one site, one site was recently permitted, and a permit to construct is pending at yet another site. The seven remaining SCR units are not operational due to project cancellations during the permitting process or due to bankruptcy.

2.1.2 IC Engines

In Table 2-2, 21 SCR applications on IC engines are identified. Of the 26 SCR units at 21 sites, only 13 units are identified as currently operational, with 11 of these units located in California. In Table 2-4, the operating SCR units are grouped by application type, size, and start-up date. In this table, there are three SCR units at two sites that involve cogeneration. Two of these SCR units are on engines firing sewage digester gas, with another SCR unit on a dual fuel diesel engine designed to fire natural gas and diesel as well as only diesel.

The remaining operational SCR units are in transmission/compression/distribution applications. Only one SCR unit is currently operating on a 4,000-hp engine used for gas transmission, with seven SCR units in gas compression (including propane and air) and two SCR units in gas distribution applications. Nine SCR units that were operational in the early 1980s are no longer in service. In six of these cases, the units have been replaced with clean burn engines or electric motors.

TABLE 2-1. SMALL PRIME MOVER SCR SITES - GAS TURBINES

Site	Manufacturer	Model	Turbine Size (hp)	No. of Turbines	Application	SCR Vendor	No. of SCR Units	Status
A	Kongsberg	KG-2-3R	1,700	5	Cogeneration	Johnson Matthey	5	Bankrupt
B	Kongsberg	KG-2-3R	1,700	3	Cogeneration	Johnson Matthey	3	Cancelled
C	Solar	Mars	12,000	1	Cogeneration	W. R. Grace	1	Operating (1989)
D	Dresser	990	6,000	1	Cogeneration	KHI	1	Operating (1989)
E	Allison	501-KB	4,700	5	Cogeneration	IHI	1	Operating (1988)*
F	Allison	501-KB	4,400	1	Cogeneration	Engelhard	1	Cancelled
G	Solar	Centaur T4500	4,200	2	Cogeneration	Steuler	2	Operating (1989)
H	Solar	Centaur T4500	4,300	3	Cogeneration	Steuler	3	Operating (1989)
I	Solar	Centaur T4500	4,300	3	Cogeneration	Steuler	3	Start construction (1991)
J	Solar	Mars	11,300	2	Cogeneration	Johnson Matthey	2	Operating (1987)
K	Solar	Mars	11,900	3	Cogeneration	Johnson Matthey	NA	Cancelled
L	Allison	501-KB5	5,000	1	Cogeneration	Norton	1	Operating (1988)
M	Kongsberg	KG-5	3,900	4	Cogeneration	Johnson Matthey	NA	Cancelled
N	Allison	501-KB5	4,700	1	Cogeneration	Hitachi Zosen	1	Cancelled
O	Allison	501-KB5	4,700	1	Cogeneration	NA	1	Pending permit to construct
P	Ingersoll-Rand	6T-61-16	16,600	3	Cogeneration	NA	NA	Cancelled
Q	Solar	Centaur	4,700	1	Cogeneration	Norton	1	Recently permitted to construct

*Only two turbines operating.

NA = Not available from phone contacts

NOTE: All units fire natural gas exclusively except American Cogen (crude oil) and Cal Tech (designed for diesel back-up).

TABLE 2-2. SMALL PRIME MOVER SCR SITES - IC ENGINES

Site	Manufacturer	Model	Engine Size (HP)	No. of Engines	Application	SCR Vendor	No. SCR Units	Status
a	Cooper	GMW-10	2,500	1	Gas Transmission	ECS*	1	No longer in service
b	Clark	HRA-8	880	1	Gas Compression	Engelhard	1	No longer in service
c	Clark	HRA-6	660	2	Gas Compression	Nitrogen Nergas	2	Operating (1987)
d	NA	NA	NA	2	Gas Transmission	Nitrogen Nergas	1	No longer in service
e	Cooper	GMVA-8	1,100	1	Gas Compression	Johnson Matthey	1	No longer in service
f	Clark	RA	800	2	Gas Compression	Nitrogen Nergas	2	To restart operation in March 1990
g	Cooper	LSVB-16	6,710	1	Cogeneration	Steuler	1	Operating (1988); dual fuel
h	Delaval	HVA-12G	1,905	2	Cogeneration	KNI	2	Operating (1984); digester gas
i	Waukesha	742	712	1	Cogeneration	Nitrogen Nergas	1	Start-up 1990; digester gas
j	Cooper/ Enterprise	HVA-16	4,000	1	Cogeneration	Engelhard	1	No longer in service; digester gas
k	Cooper	NA	NA	1	Gas Compression	Nitrogen Nergas	1	No longer in service
l	Clark	HRA-6	600	1	Gas Compression	Nitrogen Nergas	1	No longer in service
m	Ingersoll-Rand	412DT KVS	2,000	1	Gas Distribution	Engelhard	1	Operating (1981)
n	Ingersoll-Rand	412DT KVS	2,000	1	Gas Distribution	UOP	1	Operating (1985)
o	Cooper	CBGMVA10	1,350	1	Gas Distribution	Engelhard	1	No longer in service
p	Clark	HRA-6	600	1	Gas Compression	Nitrogen Nergas	1	SCR system currently used on diesel rental unit
q	Worthington	UTC-168	1,850	1	Gas Distribution	Nitrogen Nergas	1	No longer in service
r	Clark	HRA-32	350	1	Gas Compression	Engelhard	1	Operating (1985)
s	Cooper	GMV8	800	1	Propane Compression	Nitrogen Nergas	1	Operating (1986)
t	Delaval	HV-16	4,000	1	Gas Transmission	Nitrogen Nergas	1	Operating (1984)
u	Clark	2-HRA-6/2-RA-6	660/600	4	Air Compression	Nitrogen Nergas	3	Operating (1988)

*Emission Control Systems, Inc.

NA = Not available from phone contacts.

NOTE: All units fire natural gas except Pfizer Chemical (dual fuel) and Pt. Loma, Escondido, and San Jose/Santa Clara which fire digester gas.

TABLE 2-3. OPERATING SCR UNITS - GAS TURBINES

Site	No. of Turbines	Turbine Size (hp)	Application	No. of SCR Units	Start-up Date
E[a]	5	4,700	Cogeneration	1	1988
L	1	5,000	Cogeneration	1	1988
G	2	4,200	Cogeneration	2	1989
H	3	4,300	Cogeneration	3	1989
D	1	6,000	Cogeneration	1	1989
J	2	11,300	Cogeneration	2	1987
C	1	12,000	Cogeneration	1	1989

[a]Only two turbines operating.

TABLE 2-4. OPERATING SCR UNITS - IC ENGINES

Site	No. of Engines	Engine Size (hp)	Application	No. of SCR Units	Start-up Date
r	1	350	Gas Compression	1	1985
c	2	660	Gas Compression	2	1987
u	4	660/600	Air Compression	3	1988
s	1	800	Propane Compression	1	1986
m	1	2000	Gas Distribution	1	1981
n	1	2000	Gas Distribution	1	1985
t	1	4000	Gas Transmission	1	1984
h	2	1905	Cogeneration	2	1984
g	1	6710	Cogeneration	1	1988

3.0 SMALL PRIME MOVER SCR SYSTEM CHARACTERIZATION

This section presents a brief description of the SCR technology and summarizes the system design and operating characteristics for the SCR units identified in this study. Tables 3-1 and 3-2 present the small prime mover SCR system characteristics for gas turbines and IC engines, respectively. All sites identified are characterized by NO_x permit limit, exhaust temperature, load pattern, catalyst type/material, SCR operating temperature, space velocity, pressure drop (actual), NO_x levels (in/out), percent NO_x reduction (design/actual), NH_3 slip, and NH_3/NO_x molar feed ratio.

Of the sixteen sites for which SCR design and/or operating information was obtained, seven are gas turbines and nine are IC engines. All of the SCR units at these sites are currently in operation.

3.1 SCR TECHNOLOGY DESCRIPTION

SCR is a post-combustion NO_x control technology (i.e., it treats the flue gas downstream of a combustion source) that is applied to combustion turbines and IC engines. Figure 3-1 shows a typical arrangement for an SCR system. Its major components include a catalytic converter (catalyst, reactor housing/supports), ammonia feed system, continuous emission monitors (CEMs), and control system.

The major reactions that describe the SCR process are the following:

$$4\ NO + 4\ NH_3 + O_2 \rightarrow 4\ N_2 + 6\ H_2O \quad (1)$$

$$6\ NO + 4\ NH_3 \rightarrow 5\ N_2 + 6\ H_2O \quad (2)$$

$$8\ NO + 2\ NH_3 \rightarrow 5\ N_2O + 3\ H_2O \quad (3)$$

$$4\ NO + 4\ NH_3 + 3O_2 \rightarrow 4\ N_2O + 6\ H_2O \quad (4)$$

$$6\ NO_2 + 8\ NH_3 \rightarrow 7\ N_2 + 12\ H_2O \quad (5)$$

Reaction (1) is the most important and desirable. NO_2 accounts for about 5 percent of the NO_x in flue gases, and reactions such as (5) are not significant. In addition to the NO/NH_3 reduction reactions, a number of undesirable reactions may also take place in the SCR system:

TABLE 3-1. SMALL PRIME MOVER SCR SYSTEM CHARACTERISTICS - GAS TURBINES

Site	NO_x Permit (ppm)	Exhaust Temperature (°F)	Load	Catalyst Type/Material	SCR Operating Temperature[a] (°F)	Space Velocity[b] (1/hr)	Pressure Drop[a] (in H_2O)	NO_x in/out[c] (ppm)	NO_x Reduction Design/ Actual (%)	NH_3 Slip[e] (ppm)	NH_3/NO_x
C	8	825	Base load	Honeycomb/ Platinum	470	49,000	1.5	NA/2-6	80/85	Neg.	1.0-1.2
D	9	850-925	Base load	Honeycomb/ Vanadium-Titanium	690	7,750	1.5	24-50/ 6.5-9	79-84/ 67-82	Neg.	NA
E[d]	14	NA	Base load	Honeycomb/NA	650	12,000	1.3	17/1.3[a]	NA/92	>10[f]	1.1[b]
G	15	750-820	Base load	Honeycomb/ Zeolite	650	NA	3	32/13	65/59	10	NA
H	14	850-800	One Base One Variable	Honeycomb/ Zeolite	650	NA	4	40/10	75/80	10	0.95
J	22	700-900	Base/Variable	Honeycomb/ Vanadium	650-720	10,200	3	130/18	85/86	32	NA
L	9	1039	Base load	Honeycomb/ Zeolite-Base Metal	760-850	6,500	3.5	NA/9	80/NA	20[b]	.9-1.0

NA: Not available from phone contacts.
[a]Actual.
[b]Design/estimated.
[c]At 15% O_2.
[d]Only two turbines operating; design values based on five turbines.
[e]Dilution air added.
[f]At NH_3/NO_x less than 1.1.

TABLE 3-2. SMALL PRIME MOVER SCR SYSTEM CHARACTERISTICS - IC ENGINES

Site	NO_x Permit	Exhaust Temperature (°F)	Load	Catalyst Type/Material	SCR Operating Temperature[a] (°F)	Space Velocity[b] (1/hr)	Pressure Drop[a] (in H_2O)	NO_x in/out[c] (ppm)	NO_x Reduction Design/ Actual (%)	NH_3 Slip[a] (ppm)	NH_3/NO_x[a]
c	80% Red.	850	Variable	Pellet/NA	790-850	4,500	Neg.	619/72	80/80	1400-2900	NA
g[d]	40 tons/yr	900-950	Base load	Honeycomb/ Zeolite	900	2000	2.4-2.6	392/20	95/96	NA	NA
h[e]	150 ppm[c]	950-1000	Base load	Honeycomb/ Vanadium Titanium	650-750	NA	3	700-800/ 100-150[f]	85/85-94	14-24	1.0
m	70% Red.	NA	Variable	Honeycomb/ Vanadium	800 (Max)	10,000	3.5	NA	90/80	10-15	0.9
n	70% Red.	NA	Variable	Honeycomb/NA	800 (Max)	10,000	4	NA	NA/80	10	0.85-0.9
r	80%/125 ppm[c] 2.42 g/Bhp-hr	550-650	Variable (20-30%)	Plate/Platinum	750	NA	Neg.	NA/25	80/>80	NA	NA
s	80%/125 ppm[c] 2.42 g/Bhp-hr	700	Variable	Pellet/Vanadium	550-650	7,500	5-6	900-1000/ 125-150	80/80	NA	NA
t	5 g/Bhp-hr	900-1100	Base load	Pellet/NA	850-900	NA	NA	NA	NA/20-80	NA	NA
u	70% Red.	NA	Standby	Pellet/NA	550-600	NA	2	200/20	80/80	20-100	0.59

NA: Not availabe from phone contacts.
[a]Actual.
[b]Design/estimated.
[c]At 15% O_2.
[d]Dual fuel.
[e]Digester gas fuel.
[f]Initial values.

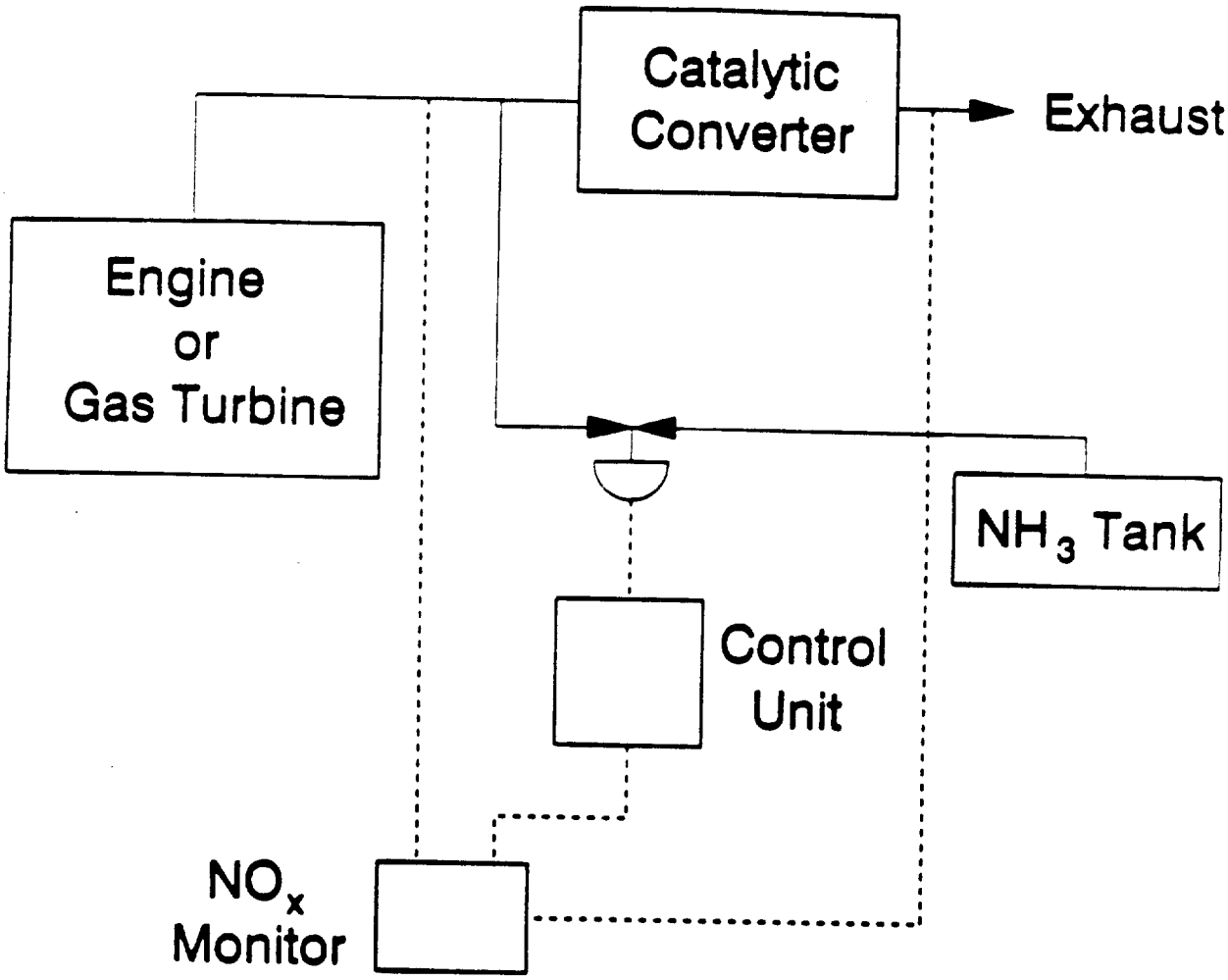

Figure 3-1. SCR System Block Diagram

$$4\ NH_3 + 5\ O_2 \rightarrow 4\ NO + 6\ H_2O \quad (6)$$

$$4\ NH_3 + 3\ O_2 \rightarrow 2\ N_2 + 6\ H_2O \quad (7)$$

$$2\ NH_3 + 2\ O_2 \rightarrow N_2O + 3\ H_2O \quad (8)$$

$$2\ SO_2 + O_2 \rightarrow 2\ SO_3 \quad (9)$$

In the SCR process, ammonia is injected into the flue gas upstream of the catalyst bed. On the catalyst surface, the ammonia reacts with NO_x from the combustion turbine/engine exhaust to form molecular nitrogen and water vapor.

NH_3 injection flow rate is generally varied to maintain the outlet NO_x below the required permit limit, and minimize NH_3 slip (unreacted NH_3). Typically, NO_x and O_2 are monitored continuously at the stack. Changes in operating conditions that affect the NO_x concentration require corresponding changes in NH_3 injection rate to maintain the desired NH_3/NO_x ratio. NH_3/NO_x injection ratio can be set manually and NH_3 flow adjusted automatically based on system performance.

Catalyst space velocity is a major parameter in determining NO_x reduction efficiency. Space velocity is defined as the exhaust gas volumetric flow rate (cubic ft/hr) divided by the catalyst volume (cubic ft). A higher space velocity for a given flow rate (smaller catalyst volume) results in a lower NO_x conversion.

There are a number of catalytic materials that are used, including noble metals (e.g., platinum), zeolites, and oxides of base metals (e.g., vanadium, titanium), either alone or in combination. For base metal oxides, optimum NO_x reduction occurs at catalyst bed temperatures between 500 and 750°F depending on the catalyst type. Platinum catalysts typically operate at temperatures lower than this range. A recently developed zeolite catalyst operates over the range 600 to 900°F.

A given catalyst exhibits optimum performance within a temperature range of $\pm$ 50°F. Below this range, the catalyst activity is greatly reduced, allowing unreacted ammonia to slip through. Above 750 to 950°F, ammonia is oxidized to form NO_x. Typical exhaust temperatures from IC engines and combustion turbines range from 900 to 1000°F. To maintain catalyst performance, temperature controls need to be established for the SCR system.

3.2 GAS TURBINES

The gas turbines in Table 3-1 are mostly base loaded cogeneration units. Turbine exhaust temperatures range from 700 to over 1000°F. With one exception, all SCR systems operate in the conventional 650-850°F range. One SCR unit uses a low temperature SCR catalyst and operates at approximately 470°F. Catalyst materials (platinum, vanadium, titanium, zeolite) vary with SCR vendor although the catalyst construction is typically honeycomb.

Space velocities for the non-precious metal catalyst systems range from 6,500 to 12,000 ft^3/hr of gas per ft^3 of catalyst. The space velocity for the low temperature platinum catalyst was reported at 49,000 ft^3/hr of gas per ft^3 of catalyst. The pressure drop range across the catalyst bed is 1.3 - 4 in. H_2O, averaging 2.5 in. H_2O. SCR design NO_x reductions range from 65 to 85 percent while the actual percent NO_x removals are in the 59 to 92 percent range. Three sites reported SCR outlet NO_x levels less than 10 ppm.

NO_x permit limits range from 8 - 22 ppm at 15 percent O_2. The 22 ppm limit is based on SCR only with no wet injection. Wet injection involves the injection of water or steam into the gas turbine combustor. The water/steam acts as a heat sink by reducing peak flame temperature, and therefore the formation of thermal NO_x. Projects with SCR and wet injection are characterized by a permit limit range of 8 - 15 ppm. Actual NO_x levels upstream of the SCR catalyst with wet injection range from 17 to 50 ppm.

Ammonia slip is limited to 20 ppm on two SCR units only. Both units are reporting negligible slip. The other units have no permit restrictions and are reporting ammonia slips in the range 10 to 32 ppm. Reported NH_3/NO_x ratios range from 0.9 to 1.2.

3.3 IC ENGINES

The IC engines in Table 3-2 represent two cogeneration and seven gas transmission/compression/distribution facilities (including two air and propane compression facilities). The two cogeneration units are base load applications. With the exception of the one main line station's base load application, the gas compression/distribution applications are variable load. Engine exhaust temperatures range from 550 to 1,100°F. The only engine operating in the 550-650°F range requires an electrical heater upstream of the SCR system to maintain 750°F at the catalyst.

Catalyst construction is honeycomb, pellet, or plate type. Catalyst materials used in the applications in Table 3-2 vary with SCR vendor and

include zeolite, vanadium, titanium, and platinum. Except for the Site g unit which uses a zeolite catalyst and operates at 900°F, the SCR units use vanadium/titanium/platinum catalysts and operate between 550-900°F. Reported space velocities are in the 2,000-10,000 ft^3/hr of exhaust gas per ft^3 of catalyst range. Pressure drop across the catalyst bed ranges from negligible to 6 in H_2O. Design NO_x reductions range from 80 to 95 percent while the actual NO_x removal levels show a wide variation, from 20 to 96 percent. Actual NO_x levels upstream and downstream of the SCR catalyst range from 200 to 1,000 and 20 to 150 ppm at 15 percent O_2, respectively.

NO_x permit limits for the IC engines in Table 3-2 are based either on percent reduction across catalyst, tons/year, ppm, or g/Bhp-hr. Installations at site m and site n originally had no permit requirement because they were part of the SCAQMD early 1980s test program.

There are no ammonia slip permit restrictions on IC engine SCR applications. Ammonia slips reported in Table 3-2 generally range from 10 to 100 ppm, but with one unit reporting over 2,900 ppm. Reported NH_3/NO_x ratios range from 0.6 to 1.0.

4.0 SMALL PRIME MOVER SCR SYSTEM OPERATING EXPERIENCE

This section summarizes the small prime mover SCR system operating experience for gas turbines and IC engines based on phone contacts with the SCR sites. Tables 4-1 and 4-2 present an overview of the SCR operating history for gas turbines and IC engines, respectively. The tables include all sites for which information was available.

As shown in Table 4-1, SCR units on gas turbines have been operational only since 1986, with the longest operating unit having logged about 30,000 hours. Typical start-up problems have included flow stratification and control system performance. The main operational problem area has been the CEMs. One unit has had the entire catalyst replaced and an additional layer of catalyst has been required in another. Except in one case, the operators are generally pleased with the operation of the SCR units.

The IC engine SCR experience is more substantial than the gas turbine SCR experience in this size range since a number of units were installed in the early 1980s. As Table 4-2 indicates, some SCR units have logged 30,000-40,000 operating hours. Start-up problems with these units have included control system, analyzer, and catalyst support failures. In some cases, the automatic controls were converted to manual control. Other problems with the operation of the SCR unit include overloading the engine and catalyst sintering. Catalysts have been replaced at three units and catalyst layers have been added at units with pellet catalyst due to sintering.

A number of IC engine SCR units are no longer in operation. Some of these units were part of the SCR test programs conducted in the early 1980s and are no longer in service. Most engine/SCR systems have been replaced with clean burn engines, electric motors, or rich-burn engine with non-SCR. Currently, three operators have plans to replace their SCR units in the near future, with one of the plans directly related to dissatisfaction with the SCR unit performance reliability.

The site-specific SCR operating experience is described below for individual gas turbine and IC engine sites.

TABLE 4-1. SMALL PRIME MOVER SCR OPERATING EXPERIENCE - GAS TURBINES

Site	SCR Start Up Date	SCR Operating Hours	Catalyst Replacement Date	Operational Problems[a]			Comments
				Catalyst Support	Control System	CEM	
C	June 1989	NA	None			X	Start-up problems. Operator pleased w/unit.
D	Oct 1989	NA	None				Initial flow stratification problems. Operator pleased w/unit.
E	Early 1988	8500 (Sept 89)	None			X	Operating-2 turbines only. CEM high maintenance.
G	June 1989	NA	None				Start-up problems. Operator pleased w/unit.
H	Dec 1989	NA	None				Start-up problems. Operator pleased w/unit.
J	Dec 1986	30000 (June 90)	Sept 1989[b]			X	Initial control and stratification problems. CEM problems.
L	Nov 1987	NA	Dec 1988			X	CEM problems. Operator unhappy w/unit. Catalyst replacement caused by boiler failure.

NA: Not available from phone contacts.
[a]Not including start-up problems.
[b]Additional layer of catalyst.

NOTE: All units have automatic controls.

TABLE 4-2. SMALL PRIME MOVER SCR OPERATING EXPERIENCE - IC ENGINES

	SCR Start-up Date	SCR Operating Hours	Catalyst Replacement Date	Operational Problems[a]					Comments
				Engine	Catalyst	Catalyst Support	NH_3 Feed System	CEM	
c	1987	17,000	Numerous	X	X			None	Overload engine for SCR temperature. Marginal performance. Manual control.
g	1988	3,500[b] (dual fuel) 2,700[b] (diesel)	None				X	X	Start-up problems. Switched to manual control.
h	1984	30,000	None					X	Control system oversized.
j	1985	NA	1986	X	X				High engine temperatures w/SCR. Replaced w/clean burn system.
m	1981	2-3,000 hrs/yr.	Routinely Washed						Initial analyzer problem. Operator satisfied w/SCR.
n	1985	2-3,000 hrs/yr.	None						Controls converted from manual to automatic feedback.
r	1985	40,000	Washed 1988					X	Analyzer failed. Manual control. Plan to remove by 6/91 to comply with hydrocarbon emission limits.
s	1986	18,000	Numerous			X	X	None	Continually replacing sintered catalyst. Manual control. Not satisfied w/SCR performance. Plan to remove by 6/91 and replace engine to meet hydrocarbon emission limits.
t	1984	30,000	Additions		X	X		None	SCR not reliable. Manual control. Plan to replace with clean burn system.
u	1988	1,500	None					None	Conversion adequate. Manual control. NH_3 slip concern. Piping too small.

NA: Not available from phone contacts.
[a]Not including start-up problems.
[b]October 1989.

4.1 SCR OPERATING EXPERIENCE - GAS TURBINES

Site C

The SCR system is meeting the site's expectations. The operator rated the SCR at 99 percent availability and the turbine at 97 percent. Start-up problems have included ammonia flowmeter malfunction, evaporator piping leaks, ammonia injection system problems, and analyzer problems. These problems have resulted in fluctuating conversion levels (76-85 percent). Since start-up, the CEM has been responsible for all 73 SCR shutdowns (February 1990).

Site D

The SCR system is performing to expectations. The system was sized to meet permit requirements on diesel fuel at the end of the two year guarantee; therefore, the SCR unit is oversized. Problems have resulted from the logistics of incorporating system design and catalyst, since the catalyst blocks are manufactured in Japan and the catalyst chamber was designed and built in the United States. Inadequate sealing of exhaust around the catalyst in the chamber has resulted in NO_x leakage in the stack. The unit had to be shutdown to better seal the chamber and also adjust the ammonia distribution grid to normalize NO_x concentrations in the stack. The emissions monitoring is the most labor intensive component of the system.

Site E

The CEM system is the component that fails the most often and requires intensive maintenance.

Site G

The two SCR units have been operating with the original catalyst since June 1989. Aside from initial start-up debugging, there have been no continual problems. Initial difficulties have resulted from working with unfamiliar German fittings and equipment.

Site H

The three SCR units have been operating since December 1989, with experiences similar to Site G.

Site J

Majority of the problems encountered with the SCR unit center around the control system. Start-up problems with the control system have included the unit shutting off ammonia flow and the turbine without giving a warning alarm. Flow stratification problems were also experienced initially. In addition, the CEM has experienced routine mechanical failures including source light power failures in the analyzers, filter plugging, and ammonium nitrate caking on flow transmitters and pressure regulators. Since start-up, the cabinet where the CEM is kept has been insulated and a larger air conditioner installed.

Since start-up in December 1986, a catalyst replacement was required after 3000 operating hours. In September 1989, a new catalyst layer (50 percent of total volume) was added. The catalyst box will be opened in April 1990 for inspection. The operator estimates that the first catalyst layer has lost all activity while the second layer is probably at 70-75 percent activity.

Site L

Apart from the CEM, the operator is pleased with the SCR system performance. The CEM system is "a very big headache" with frequent system failures. In July 1988, the boiler blew up and destroyed the SCR catalyst. The catalyst was replaced in December 1988 but the turbine did not start up until October 1989.

4.2 SCR OPERATING EXPERIENCE - IC ENGINES

Site c

The operators report that the two SCR systems currently achieve an 80 percent NO_x reduction but that it requires constant effort. On cool days when inlet NO_x levels are lower, the unit can not achieve the 80 percent reduction required by the permit. Therefore, the operator is forced to operate the engine at higher NO_x emission levels in order to get 80 percent reduction across the catalyst.

To achieve a 700°F minimum catalyst temperature, the engines must typically be overloaded, resulting in increased engine wear and maintenance. Also, the SCR systems have required use of synthetic lube oil for the compressors to prevent catalyst poisoning. On initial start-up, one of the two SCR units was damaged by an explosion that was unrelated to the SCR

system. To avoid catalyst disruptions during start-up and shutdown a bypass has been installed.

Since start-up in 1987, there have been numerous (over 16) catalyst replacements. Fifteen of the replacements occurred in the first three years of operation. One of the units replaced catalyst in January 1990 after approximately two years of service. The other unit currently has catalyst that is over two years old.

Site g

Operation of the SCR system on the dual fuel fired engine has been smooth with minor exceptions. According to the plant maintenance engineer, there was only one 24-hour period during which the cogeneration system had to be shutdown because of a problem with the automatic NH_3 feed controller. Currently, the system is operated on manual control. Other problems have included NH_3 recirculation pump failure, NH_3 tank level probe failure, and sample gas pump failure. Due to the conservative design and redundancy built into the system, these failures have not caused the plant to shut down. Recent problems have included NH_3 injection tubing corrosion, failure of relief values on pumps, and miscellaneous electronic failures.

Site h

The SCR control system (NH_3 feed controller/monitors) is reported to be a problem. It is located on the seawall and does not respond well to the windy conditions. The Thermoelectron analyzers have been reliable, but the ratio controllers have never operated properly. No engine operating problems attributable to the SCR system have been noted.

The site is currently being required to install an additional NO_x analyzer so that each of the two engines has dedicated monitoring.

Site j

At this site, the catalyst was removed after the SCR system was unable to meet the NO_x emission limit 1.8 g/Bhp-hr after 10,000 hours of operation. During the SCR operation, engine operating problems directly attributable to the SCR system were experienced. High cylinder temperatures at 1050-1150°F had resulted in valve problems and the engine manifold had to be replaced.

Site m

Aside from initial NO_x analyzer problems, no operating problems are reported. The original catalyst is still in operation and reporting 80 percent NO_x reduction. The permit limit requires 70 percent NO_x reduction across the SCR catalyst. The presence of SCR requires use of a low phosphorous oil in the engine to prevent catalyst poisoning. The SCR controlled engine is one of the six engines at the site. The other five are controlled with "clean burn" combustion modifications and have no exhaust gas control. No operating differences are reported between the SCR controlled and the uncontrolled engines.

Site n

The original catalyst is still in service. No SCR or engine operating problems are reported. Like Site m, permit limits require a 70 percent NO_x reduction across the SCR catalyst.

Site r

The SCR unit was originally equipped with automatic controls. It has been operated on manual bypass for the last two years after the NO_x analyzer failed. Since start-up in 1985, the catalyst was washed in late 1987/early 1988 to restore activity.

The operator plans to remove the engine and SCR unit by June 1991 and replace the seven small engines with one large "clean burn" unit.

Site s

The operator reported dissatisfaction with the SCR unit's marginal performance. The catalyst is very fragile and requires continual supplementation. Since start-up in December 1986, there have been several catalyst replacements. The catalyst was completely replaced in April 1988 and April 1989. In November 1989, two thirds of the catalyst was replaced. In addition, catalyst is continually added at a rate of one 55-gallon drum every three to four weeks to replace the disintegrated catalyst.

The engine was out of service for eight weeks when an engine backfire damaged the catalyst screens in September 1989. The engine experienced a similar backfire in January 1990.

The operator plans to replace the compressor by September 1991 as the engine will not meet the hydrocarbon limit for Rule 74.9.

Site t

The operator is not pleased with the SCR system performance. The NO_x conversion is erratic and the equipment is not reliable. There have been several mechanical failures with the structure that holds the catalyst in place. Since start-up in 1984, there have been no complete catalyst replacements. Due to the pellet catalyst disintegrating into fines, however, an unspecified number of catalyst additions have been required.

The site plans to replace the SCR system and add pre-combustion chambers to achieve the NO_x emission limit of 5 g/Bhp-hr. The chambers are currently installed and will be put into operation once turbocharger modifications to supply more air are complete.

Site u

The SCR system is performing to expectations and achieving adequate conversion. One problem encountered is with the valving and metering of the ammonia system. The piping is undersized and tends to freeze up with ammonia vaporization. In addition, the 1/4 in. differential pressure taps need to be modified to 3/8 in. to reduce plugging. The operator's major concern with the SCR system is the ammonia slip levels associated with the manual control operation.

5.0 SMALL PRIME MOVER SCR COST DATA

One of the objectives of this study was to gather capital and operating cost data from the prime mover SCR sites. Phone contacts with the sites identified in Tables 2-1 and 2-2 and review of the cost information collected as part of the EPRI/GRI SCR program form the basis of the information presented in this section. No effort was made to solicit quotes from SCR equipment vendors. Although the focus of the current study was SCR applications on units less than about 15,000-20,000 hp in size, capital cost data for gas turbines for larger units are also included for comparison purposes.

5.1 CAPITAL COSTS

5.1.1 Gas Turbines

As shown in Table 5-1, total installed capital cost data specific to the SCR unit were available in most cases. The total installed capital costs were less than $900,000 (1989 dollars) for gas turbines 12,000 hp or less in size. Actual costs reported by the SCR operating sites were normalized and converted to 1989 dollars using the Chemical Engineering plant cost indices to allow comparison of facility-specific costs on the same base year. For the SCR unit at the Site L facility, the total installed capital costs were estimated from the equipment purchase price by applying a factor of 1.6.

Except for catalyst costs, data on breakdown of capital costs into specific costs for the automatic control system, monitors, and installation were limited. Catalyst costs were about 30 to 40 percent of the total installed costs. All of the SCR units were identified as having automatic control systems and CEM monitors.

Figure 5-1 shows the distribution of total installed cost data by gas turbine size. The figure includes cost data for two larger units as well. Excluding the Site C cost data, which is indicated to be a low estimate by the site contact, a relatively smooth increase in costs is observed with increasing turbine size. In Figure 5-2, total installed costs per unit output are plotted against gas turbine size. As in Figure 5-1, a smooth decrease in costs per hp is exhibited with an increase in unit size, if Site C data are excluded.

TABLE 5-1. SCR SYSTEM CAPITAL COST DATA - GAS TURBINES

Site	Turbine Size (hp)	No. of SCR Units	NO_x Removal[a] (%)	Capital Cost per SCR Unit ($)						Total Installed Capital Cost ($)	Total Installed Capital Cost (1989 $)	Total Installed Capital Cost per hp (1989 $/hp)
				Cost Base Year	Catalyst	Control System	Monitors	Other/ Unspecified	Installation			
C	12,000	1	80	1988	NA	NA	60,000	NA	40,000	480,000	496,000	40
D	6,000	1	79-84	1988	300,000	<--- 125,000 --->		NA	NA	750,000	775,000	130
H	4,300	3	75	1989	200,000	NA	NA	NA	NA	600,000	600,000	140
J	11,300	2	85	1986	200,000	NA	NA	NA	NA	800,000	889,000	80
L	5,000	1	80	1988	100,000	<---------- 250,000 ---------->			NA	360,000[b]	579,000[b]	120[b]
E[c]	4,700	1	80	1986	NA	NA	NA	NA	NA	10,000,000[d]		
R[c]	29,500	1	60-65	1987	400,000	<--- 260,000 ---> (boiler modifications)		200,000	NA	1,000,000	1,093,000	35
S[c]	49,600	1	80-85	1986	NA	NA	NA	NA	NA	2,000,000	2,250,000	45

NA: Not available from phone contacts
[a]Design.
[b]Estimated from equipment purchase price.
[c]Obtained from the EPRI/GRI project files.
[d]Including extensive ductwork, duct burners, waste heat boiler, and stack.

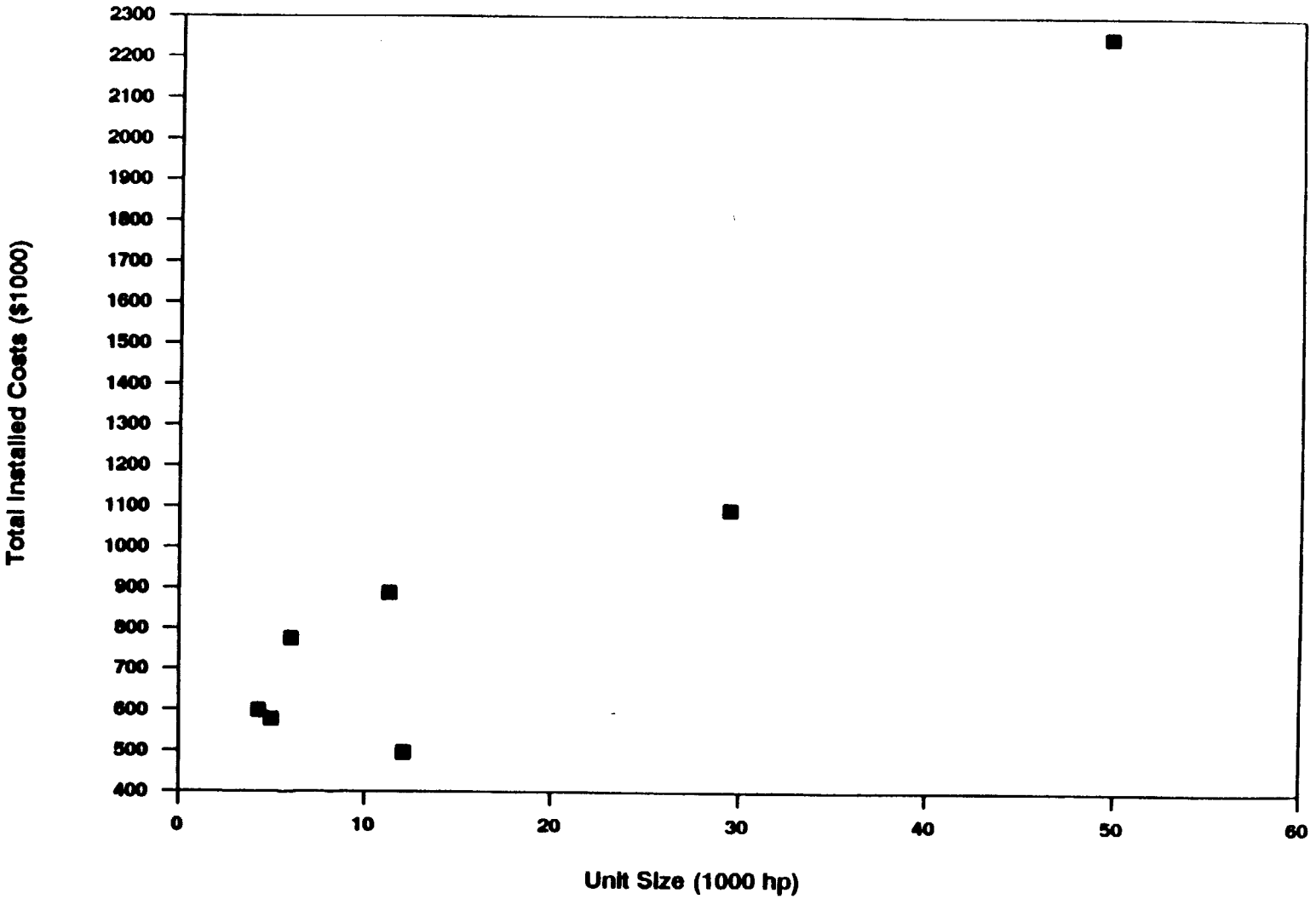

Figure 5-1. SCR Capital Costs for Gas Turbines

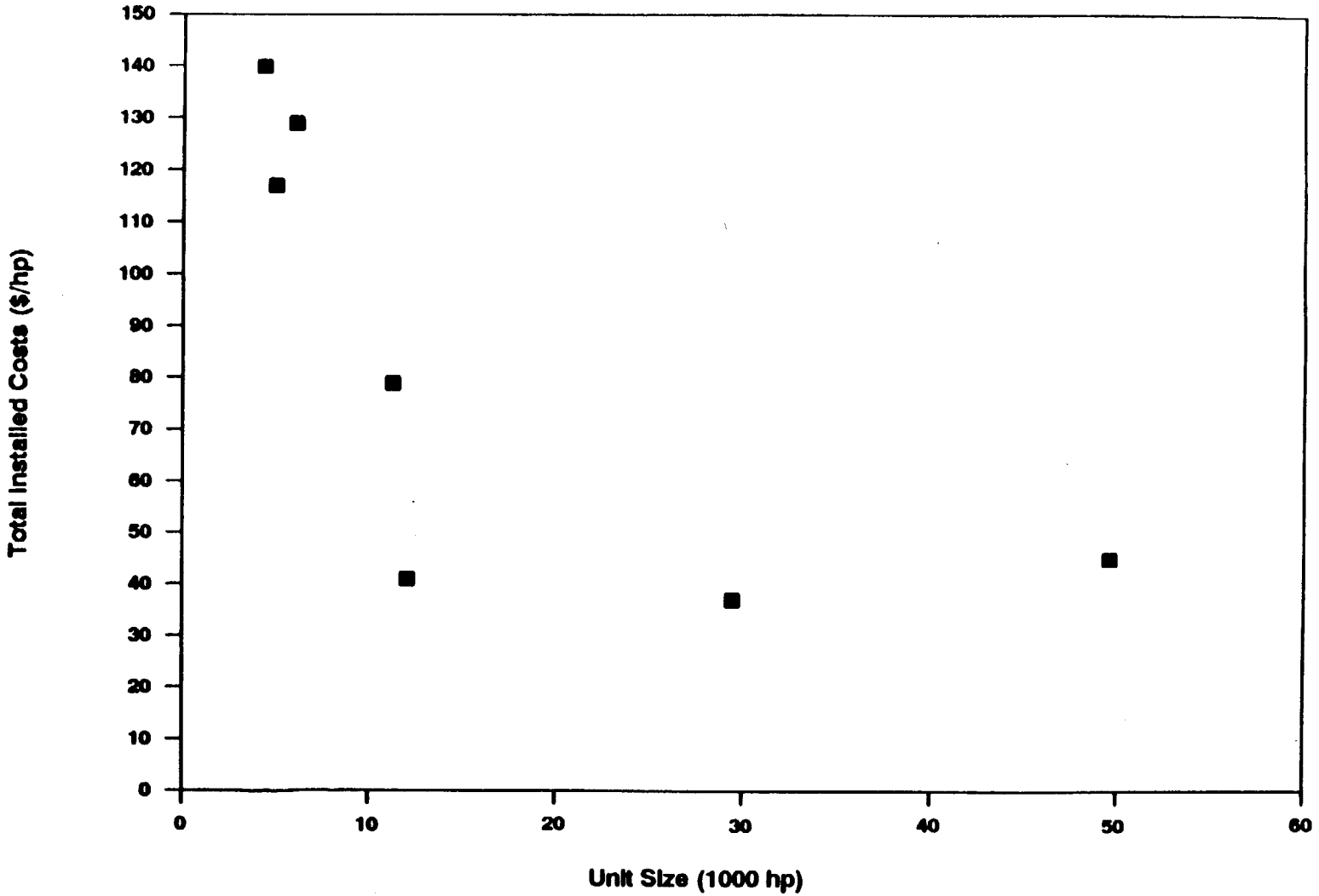

Figure 5-2. SCR Capital Costs Per Unit Output for Gas Turbines

5.1.2 IC Engines

Table 5-2 presents the capital cost data identified for SCR units on IC engines. In contrast to the gas turbine SCR applications, some of the IC engine applications date back to early 1980s. Hence, cost data for three of the operating units reflect prices before 1985, when catalyst prices were about 30 percent higher than current prices. In converting total capital costs to the 1989 base year, an allowance was made for this price change.

The data reported in Table 5-2 reflect costs for natural gas-fired engines less than 4,000 hp, a dual fuel fired engine (6,710 hp), and a digester gas-fired engine (1,905 hp). Except for the latter two engines, all of the engines are employed in gas transmission/compression/distribution service.

As with the gas turbine SCR data, data on the breakdown of capital costs into costs for specific system components such as control system, monitors, and installation are limited. Catalyst costs make up about 10-20 percent of the total installed capital costs. This is low compared to combustion turbine installations, but IC engine systems have required more catalyst additions/ replacements.

Figure 5-3 shows the total installed capital costs as a function of unit size. There is a significant amount of scatter in the data presented in Figure 5-3. Contributing to the scatter, as shown in the table, is the inconsistency in the scope of the SCR system supply. For example, there are three applications with automatic controls and monitors and four without any controls or monitors. However, since data are limited, it is difficult to correlate the costs with presence/absence of controls/monitors.

As indicated by the Site h contact, the current cost of a similar system for an identical application would be much lower than the cost back in 1984 because of changing market forces and maturing of the SCR technology. Excluding the Site h data point, the cost plot in Figure 5-3 shows an increase with engine size, with the exception of Site t data. Figure 5-4 presents the costs per unit output as a function of engine size. As in Figure 5-3, there is considerable scatter in the data.

5.1.3 Costs for Turbines and Engines

Figures 5-5 and 5-6 present the entire set of installed capital costs for turbines and engines as a function of unit size. In Figure 5-6, the costs

TABLE 5-2. SCR SYSTEM CAPITAL COST DATA - IC ENGINES

Site	Engine Size (hp)	No. of SCR Units	NO_x Removal[a] (%)	Capital Cost per SCR Unit ($)						Total Installed Capital Cost ($)	Total Installed Capital Cost (1989 $)	Total Installed Capital Costs per Hp (1989 $/Hp)
				Cost Base Year	Catalyst	Control System	Monitors	Support Structures	Installation			
c	660	2	80	1987	30,000	None	None	NA	NA	140,000	153,000	230
i	712	1	85-90	1989	NA	NA	None	NA	NA	120,000[b]	120,000	170
g[c]	6710	1	95	1988	NA	NA	NA	NA	NA	850,000 (650,000)[c]	878,000 (670,000)[c]	130 (100)[c]
h	1905	2	85	1984	160,000	NA	NA	NA	NA	1,300,000	1,358,000	710
m	2000	1	90	1981	75,000	65,000	NA	12,000	150,000	450,000	497,000	250
s	800	1	80	1986	30,000	None	None	NA	NA	140,000	156,000	195
t	4000	1	NA	1984	NA	None	None	NA	25,000	125,000	126,000	30
u	660/600	3	80	1987	NA	None	None	NA	10,000	65,000	71,000	110

NA: Not available from phone contacts.
[a]Design.
[b]Estimated from purchase price.
[c]Values for typical system excluding system upgrade/additional guarantees (90 percent removal).

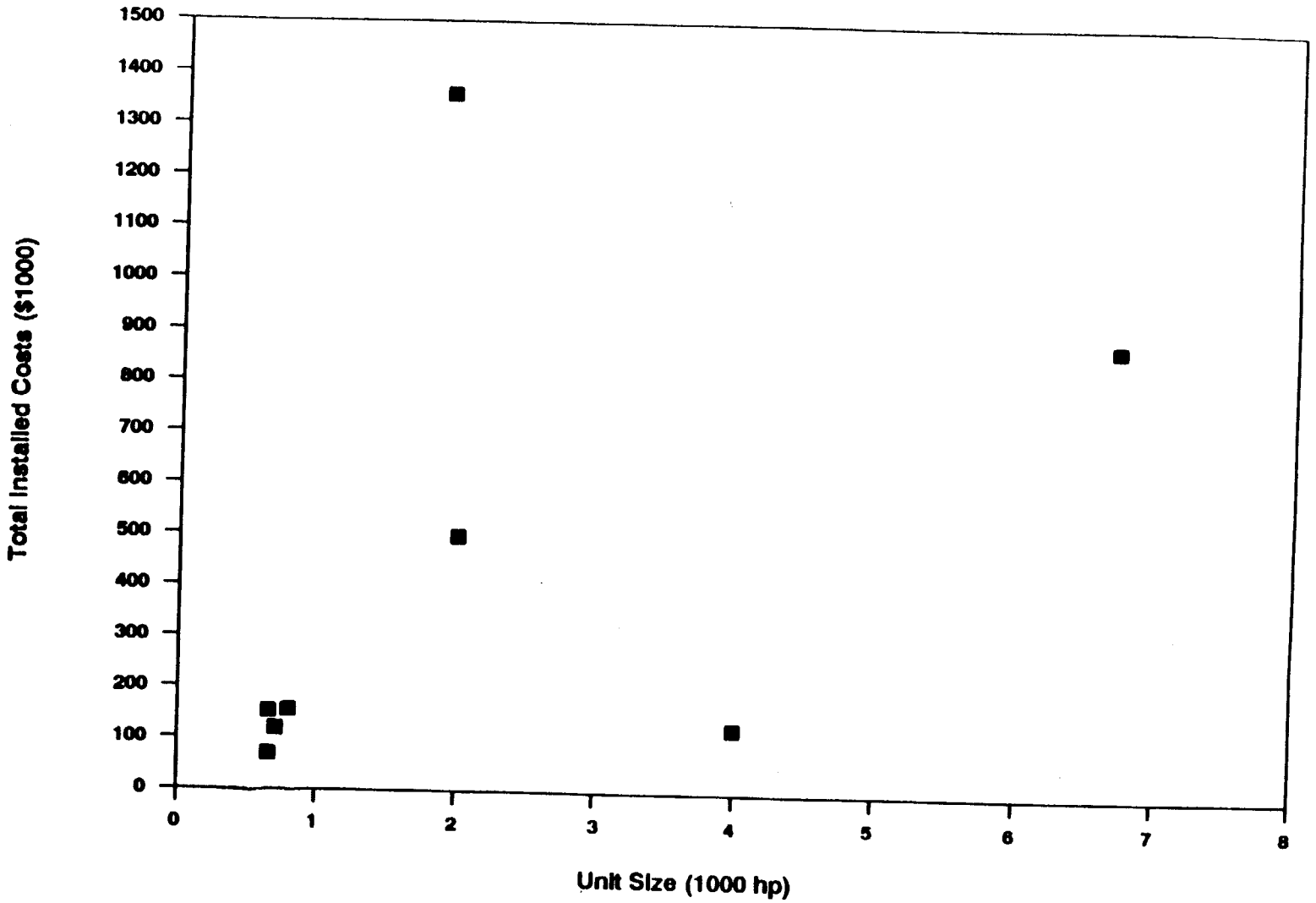

Figure 5-3. SCR Capital Costs for IC Engines

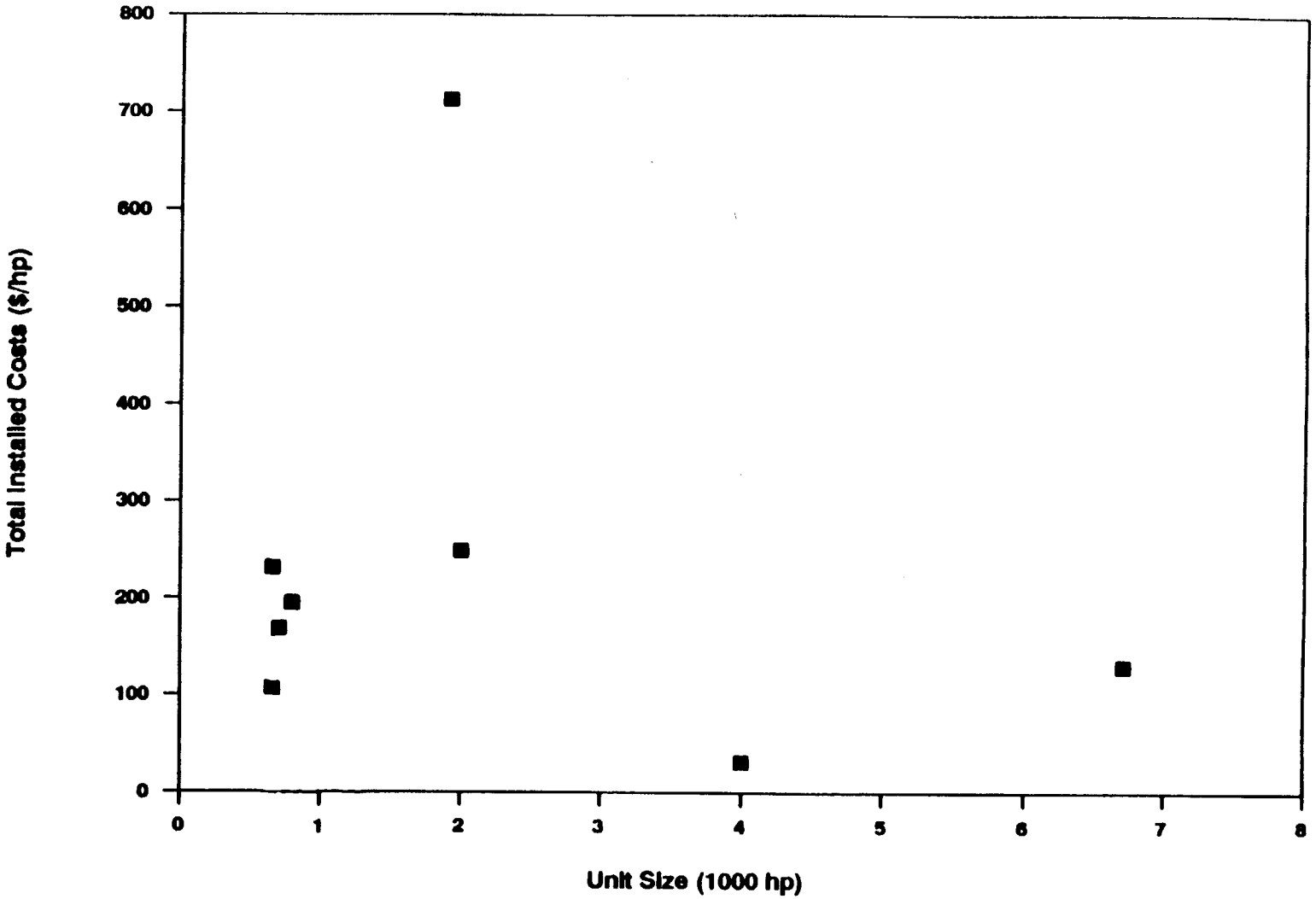

Figure 5-4. SCR Capital Costs Per Unit Output for IC Engines

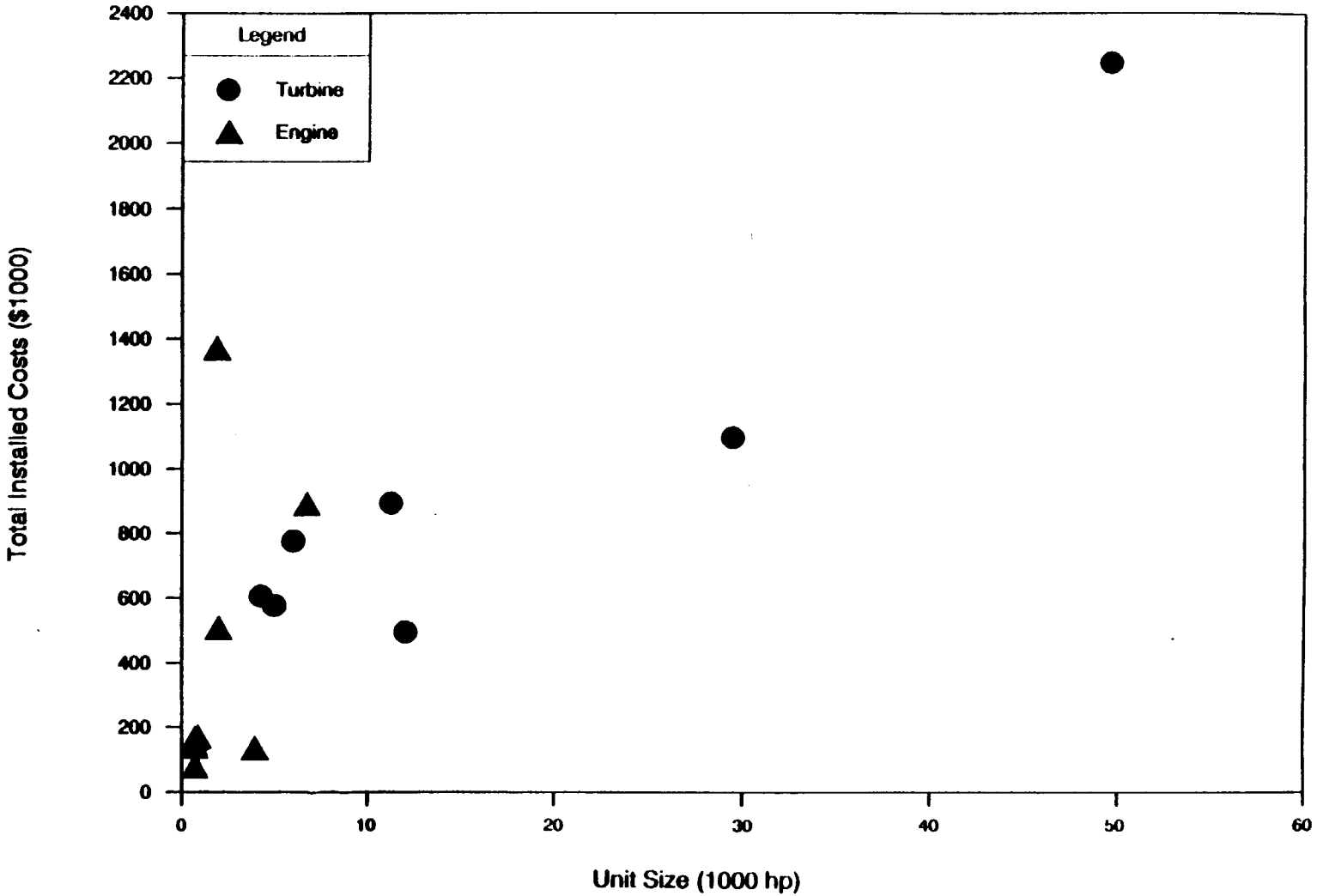

Figure 5-5. SCR Capital Costs for Gas Turbines and IC Engines

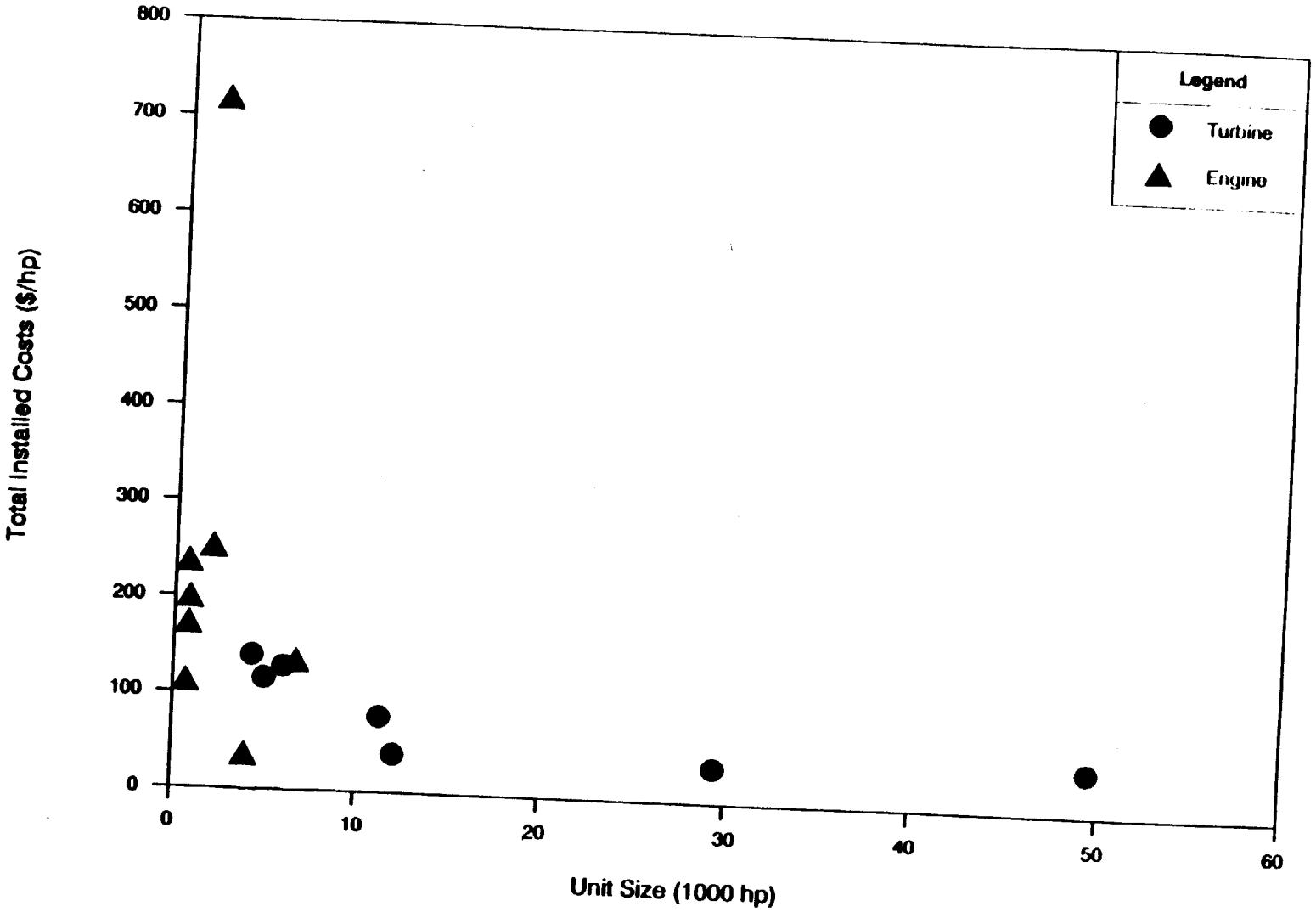

Figure 5-6. SCR Capital Costs Per Unit Output for Gas Turbines and IC Engines

are expressed on a per unit output (hp) basis. In both figures, there is scatter in the data, especially in the 0 to 12,000 hp range. From the figure, for a unit less than 2,000 hp in size, the costs range from 100 to 250 $/hp, excluding Site h data. For a 10,000 hp unit, the costs are less than 100 $/hp.

A preliminary comparison can be made between the costs in Figure 5-6 and the cost estimates from SCR cost algorithms developed by Southwest Research Institute.[57,58] The algorithms predict total installed costs of 125 $/hp and 110 $/hp (in 1989 dollars) for a 2,000-hp gas turbine and IC engine, respectively. These estimates agree with the low end of the range exhibited in Figure 5-6. For a 10,000 hp gas turbine and IC engine, the algorithms predict 65 $/hp and 55 $/hp (in 1989 dollars), respectively. The data in Figure 5-6 also appear to indicate values less than 100 $/hp.

Preliminary evaluation of the cost algorithms for specific gas turbine and IC engine SCR units in Tables 5-1 and 5-2 indicates wide discrepancy between the actual costs and the predicted values. No further analysis was conducted to resolve this discrepancy as it was outside the scope of Phase I activities.

5.2 OPERATING COST DATA

Tables 5-3 and 5-4 present the operating cost information obtained from the SCR site contacts. As shown in the tables, limited operating and maintenance cost data were available from the SCR sites. In some cases, costs were estimated from consumption and/or labor hour requirements specified by the site contact. In other cases, cost estimates were directly provided by the site contact. A large proportion of the operating/maintenance expenses at the turbine SCR sites is due to problems with CEMs. Figure 5-7 shows a plot of SCR operating costs versus engine size.

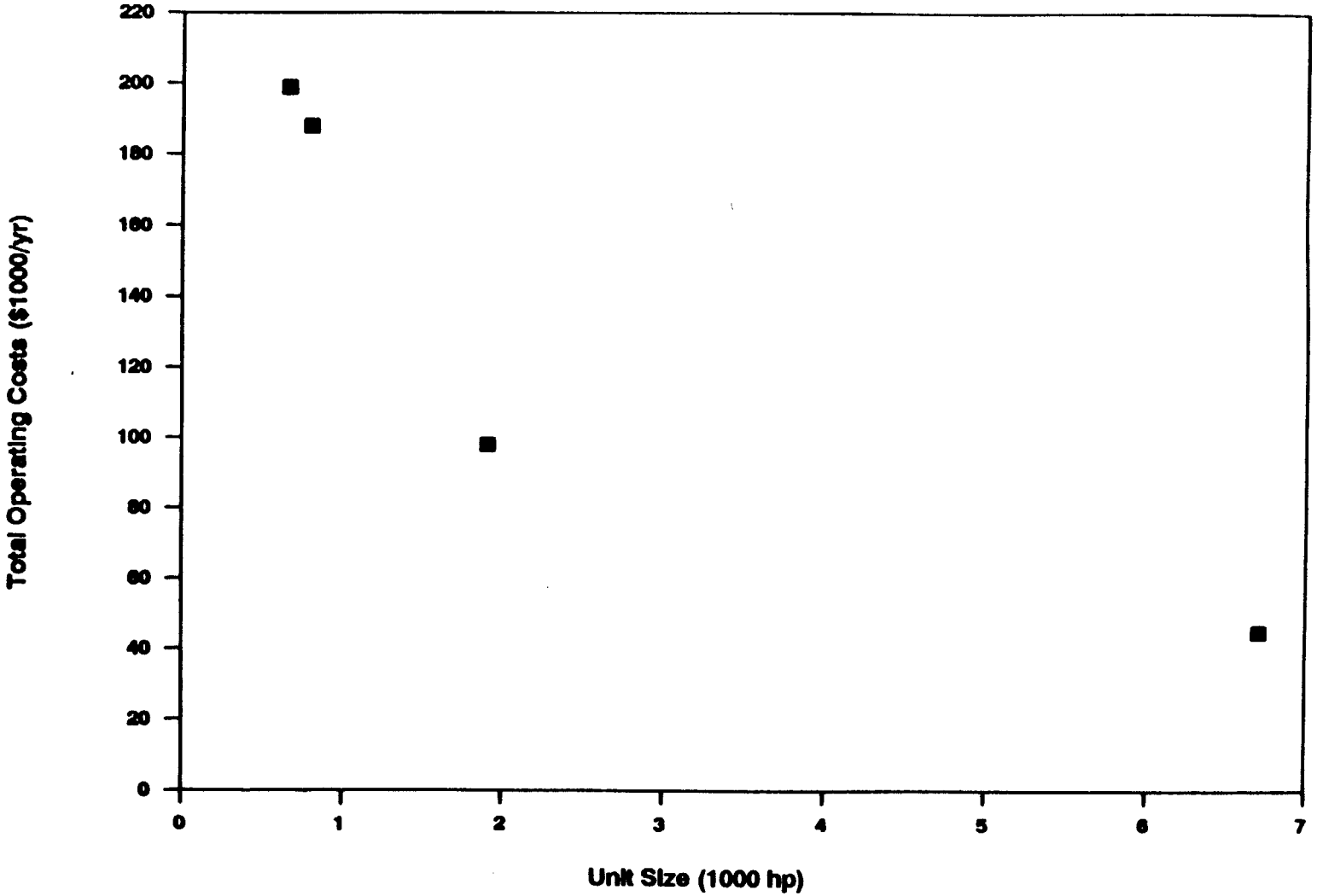

Figure 5-7. SCR Operating Costs for IC Engines

TABLE 5-3. SCR SYSTEM OPERATING COST DATA - GAS TURBINES

Site	Size (hp)	Estimated Operating Costs ($/yr)			Total Operating Costs ($/yr)
		Catalyst Replacement	NH_3	Operating/Maintenance Labor and Materials	
C	12,000	None	56,000	18,000	74,000
D	6,000	None	13,000	NA	NA
H	4,300	None	NA	50,000	NA
J	11,300	NA	17,000	22,000	NA
L	5,000	NA	NA	43,000	NA

NA: Not available from phone contacts.

TABLE 5-4. SCR SYSTEM OPERATING COST DATA - IC ENGINES

Site	Size (hp)	Current Operating Costs ($/yr)			Total Operating Costs ($/yr)
		Catalyst Replacement	NH_3	Operating/Maintenance Labor and Materials	
c	660	15,000	31,000	153,000	199,000
g	6710	None	35,000	10,000	45,000
h	1905	None	11,000	87,000	98,000
r	350	None	8,000	NA	NA
s	800	43,000	60,000	85,000	188,000
u	660	None	NA	insignificant	NA

NA: Not available from phone contacts.

6.0 OVERVIEW OF CURRENT REGULATORY AND SCR NO_x CONTROL APPLICATIONS

This section presents a brief overview of current regulatory information available from Radian in-house data bases, with emphasis on SCR NO_x controls applied to small prime movers. The in-house data base was complied from a phone survey of Federal and State regulatory authorities.

6.1 GAS TURBINES

Three regulatory bodies, SCAQMD, New Jersey Department of Environmental Protection (NJDEP), and NESCAUM have proposed or adopted NO_x emission limits for gas-fired turbines.

During the summer of 1989, SCAQMD proposed the following Rule 1134 for gas-fired turbines:

Turbine Size (MW)	Emission Limits (ppm NO_x @ 15% O_2)
0.3 to less than 2.9	25
2.9 to less than 60.0	9 (SCR emission limit) 12 (Non SCR emission limit)
60.0 and higher	9 (SCR emission limit) 15 (Non SCR emission limit)

In addition, continuous emission monitoring and annual source testing would be required, with a final compliance date of December 31, 1995. [Note: 1,000 kw = 1,340 hp]

On April 21, 1987, the NJDEP adopted the following control strategy for gas-fired turbines in cogeneration and electric generation:

Turbine Size (MM Btu/hr)	Emission Limits (lb/MM Btu)
1 - 100	0.2
100 - 250	0.2 until 5/1/92 0.1 after 5/1/92
> 250	0.1 for demonstrated NO_x control 0.2 until 5/1/92 for technology transfer of NO_x control 0.1 after 5/1/92 for technology transfer of NO_x control

[Note: At a nominal turbine heat rate of 10,000 Btu/kWh, a turbine size of 100 MM Btu/hr is approximately equivalent to 10 MW. An emission limit of 0.1 lb/MM Btu is approximately 25 ppm NO_x @ 15% O_2.]

In October 1988, the Stationary Source Committee of NESCAUM provided the following guidelines to member states (Connecticut, Maine, Rhode Island, Vermont, Massachusetts, New Jersey, and New York) for emission limits for gas-fired turbines:

Turbine Size (MM Btu/hr)	Emission Limits (ppm NO_x @ 15% O_2)
1 - 100	42
100 - 250	9 (If SCR or other "advanced" technology is shown to be inappropriate, then 25 ppm is the limit.)

In addition, NESCAUM recommended that the ammonia emissions or "slip" from an SCR system must be below 10 ppm. In the NJDEP and NESCAUM NO_x emission limits, application of wet injection has been adopted as the regulatory basis.

California has established BACT for NO_x at 9 ppm (at 15 percent O_2). Other areas of the country have adopted this NO_x level as BACT as well. In a recent BACT analysis involving an 11,100 hp turbine proposed for gas transmission, the EPA has considered $3,000 to $6,500 per ton of NO_x reduced as a reasonable range of costs for NO_x control.

6.2 IC ENGINES

The SCAQMD is currently proposing Rule 1110.2. Emissions from Gaseous and Liquid Fueled Internal Combustion Engines. This rule would require stationary engines over 50 Bhp or portable engines over 100 Bhp to be replaced with electric motors or to achieve proposed engine NO_x emission limits. The rule would permit engines to remain in service if they can meet 0.25 lb of NO_x per MW-hr (equivalent to 5 ppm of NO_x at 15 percent O_2 and 25 percent efficiency) or an alternative compliance limit based on NO_x and reactive organic gases by December 31, 2004. The compliance date for engine removal or electrification is December 31, 1999.

Most regulators in the early to mid-1980's permitted IC engines using the proposed New Source Performance Standards for stationary IC engines as a basis. As engine manufacturers have continued to develop NO_x combustion control technology, the distinction between control technology and basic engine design has blurred (e.g., precombustion chamber design). Regulators have begun to require selection of the lowest emitting engine that is suitable for the application as BACT.

Other recent BACT determinations have taken the next logical step and considered alternative power sources as engine BACT. The most common position

of regulators is to encourage combustion turbine installation instead of engines. So far, this alternative has been avoided with efficiency, load-following, and cost-effectiveness arguments. Many "clean burn" engines have been installed where natural gas interruption is not likely.

7.0 REFERENCES

1. Best Available Control Technology/Lowest Achievable Emission Rate (BACT/LAER) Clearinghouse Data Base.

2. Kern County Cogeneration/Resource Recovery Projects Database.

3. California Air Resources Board (CARB) CAPCOA BACT Clearinghouse.

4. South Coast Air Quality Management District (SCAQMD) Cogeneration Report. January 29, 1988.

5. SCAQMD Construction Permit Database. October 20, 1989.

6. SCAQMD Source Test Reports.

7. SCAQMD Third Staff Report - State of Technology related to Rule 1110 - Emissions from Stationary IC Engines. November 22, 1983.

8. SCAQMD Staff Report Proposed Rule 1110.2 - Electrification of Stationary IC Engines. December 11, 1989.

9. SCAQMD Summary - Hearing Panel Amended Rule 1134 #2. July 19, 1989.

10. Telecon, Site L representative, with Sheryl Watkins, Radian Corporation, February 20, 1990.

11. Telecon, Site E representative, with Sheryl Watkins, Radian Corporation, February 6, 1990.

12. Telecon, Site C representative, with Diana Stone, Radian Corporation, February 15, 1990.

13. Telecon, Site D representative, with Diana Stone, Radian Corporation, February 9, 1990.

14. Telecon, Site F representative, with Diana Stone, Radian Corporation, February 6, 1990.

15. Telecon, Site c representatives, with Diana Stone, Radian Corporation, February 6, 1990.

16. Telecon, Site i representative, with Diana Stone, Radian Corporation, February 9, 1990.

17. Telecon, Sites G, H, and I representatives, with Diana Stone, Radian Corporation, February, 1990.

18. Telecon, Site J representative, with Diana Stone, Radian Corporation, February, 1990.

19. Telecon, Site f representative, with Diana Stone, Radian Corporation, February 12, 1990.

20. Telecon, Site h representative, with Diana Stone, Radian Corporation, February 9, 1990.

21. Telecon, Site j representative, with Diana Stone, Radian Corporation. February 9, 1990.

22. Telecon, Sites k and l representative, with Diana Stone, Radian Corporation, February, 1990.

23. Telecon, Sites m, n, and o representative, with Diana Stone, Radian Corporation, February 7, 1990.

24. Telecon, Sites r and s representative, with Diana Stone, Radian Corporation, February, 1990.

25. Telecon, Site t representative, with Diana Stone, Radian Corporation, February 12, 1990.

26. Telecon, Site u representative, with Diana Stone, Radian Corporation, February, 1990.

27. Telecon, John Kamerosky, Johnson Matthey, with Diana Stone, Radian Corporation, January 25, 1990.

28. Telecon, Mohn Nazene, SCAQMD, with Diana Stone, Radian Corporation, February 1, 1990.

29. Telecon, Rod Milliken, SCAQMD, with Diana Stone, Radian Corporation, February 1, 1990.

30. Telecon, Rod Milliken, SCAQMD, with Diana Stone, Radian Corporation, January 26, 1990.

31. Telecon, Seone Min, L. A. Sanitation Department, with Diana Stone, Radian Corporation, February 1, 1990.

32. Telecon, Rod Milliken, SCAQMD, with Diana Stone, Radian Corporation, February 9, 1990.

33. Telecon, Tom Paxson, Kern County, with Diana Stone, Radian Corporation, February 13, 1990.

34. Telecon, Steve Turner, Norton, with Diana Stone, Radian Corporation, January 16, 1990.

35. Telecon, Reine Corbeil, Nitrogen Nergas/Kleenco Leasing, with Diana Stone, Radian Corporation, January 25, 1990.

36. Telecon, Bill Flynn, Ventura APCD, with Diana Stone, Radian Corporation, January 25, 1990.

37. Telecon, Chris Campos, Englehard, with Diana Stone, Radian Corporation, January 16, 1990.

38. Telecon, Ed Campobenedetto, B&W, with Diana Stone, Radian Corporation, January 16, 1990.

39. Telecon, Mr. IBE, Hitachi Zosen, with Diana Stone, Radian Corporation, January 16, 1990.

40. Telecon, Norataka Kosaka, IHI, with Diana Stone, Radian Corporation, January 16, 1990.

41. Telecon, Bert Brown, Joy Technologies, with Diana Stone, Radian Corporation, January 16, 1990.

42. Telecon, Reda Iskander, Cormetech, with Diana Stone, Radian Corporation, January 16, 1990.

43. Telecon, Alan Thomas, WR Grace, with Diana Stone, Radian Corporation, January 11, 1990.

44. Telecon, Site d representative, with Diana Stone, Radian Corporation, February 9, 1990.

45. Telecon, Site F representative, with Diana Stone, Radian Corporation, February 8, 1990.

46. Telecon, Site q representative, with Diana Stone, Radian Corporation, February 12, 1990.

47. Telecon, Site b representative, with Diana Stone, Radian Corporation, January 24, 1990.

48. Telecon, Sites m, n, and o representative, with Diana Stone, Radian Corporation, June 6, 1990.

49. Telecon, Site c representative, with Diana Stone, Radian Corporation, June 6, 1990.

50. Telecon, Site g representative, with Gunseli Shareef, Radian Corporation, February 6, 1990.

51. Telecon, Site g representative, with Gunseli Shareef, Radian Corporation, February 5, 1990.

52. Telecon, Don Dowdal, Caterpillar, with Gunseli Shareef, Radian Corporation, February 6, 1990.

53. Telecon, Al Burdette, Cooper Bessemer, with Gunseli Shareef, Radian Corporation, February 6, 1990.

54. Telecon, Bruce Christman, Cooper/Ajax Superior, with Gunseli Shareef, Radian Corporation, February 6, 1990.

55. Telecon, Manfred Grove, Steuler, with Gunseli Shareef, Radian Corporation, February 15, 1990.

56. Telecon, Marvin Schorr, GE, with Gunseli Shareef, Radian Corporation, February 19, 1990.

57. Urban, C. M., et al, NO_x Control Technology Database for Gas-Fueled Prime Movers - Phase I, Report prepared for Gas Research Institute, GRI-87/0229, April 1988.

58. Urban, C. M., Evaluation of NO_x Reduction Technology for Natural Gas Industry Prime Movers, Report prepared for Gas Research Institute, GRI-87/02757, September 1987.