United States
Environmental Protection
Agency

Office of Air Quality
Planning and Standards
Research Triangle Park, NC 27711

EPA-453/R-94-068
Final Report
October 1994

Air

EPA

Nitrogen Oxide Emissions and Their Control From Uninstalled Aircraft Engines in Enclosed Test Cells

Joint Report to Congress on the Environmental Protection Agency - Department of Transportation Study

U.S. Environmental
Protection Agency

U.S. Department of
Transportation

JOINT REPORT TO CONGRESS

on the

EPA-DOT

STUDY OF NITROGEN OXIDE EMISSIONS AND THEIR CONTROL FROM UNINSTALLED AIRCRAFT ENGINES IN ENCLOSED TEST CELLS

by the

Administrator of the Environmental Protection Agency

and the

Secretary of Transportation

Washington, D.C. 20591

September 1994

Report to the United States Congress
Pursuant to Section 233 (a) of the
Clean Air Act Amendments of 1990,
P.L. 101-549

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EXECUTIVE SUMMARY

The Clean Air Act Amendments of 1990 (CAAA), Public Law 101-549, requires the Administrator of the Environmental Protection Agency and the Secretary of Transportation, in consultation with the Secretary of Defense, to conduct a study and investigate the testing of uninstalled aircraft engines in enclosed test cells. Section 233(a) of the Act specifies the issues the study should address, at a minimum. These issues are:

"(1) whether technologies exist to control some or all emissions of oxides of nitrogen from test cells;

(2) the effectiveness of such technologies;

(3) the cost of implementing such technologies;

(4) whether such technologies affect the safety, design, structure, operation, or performance of aircraft engines;

(5) whether such technologies impair the effectiveness and accuracy of aircraft engine safety design and performance tests conducted at test cells; and

(6) the impact of not controlling such oxides of nitrogen in the applicable non-attainment areas and on other sources, stationary and mobile, on oxides of nitrogen in such areas."

Following completion of the study and submission of the required Report to Congress, Section 233(b) of the Act authorizes States to adopt or enforce any standard for emissions of oxides of nitrogen from test cells, after issuing a public notice stating whether such standards are in accordance with the findings of the study.

Test cells are facilities designed to operate and measure the performance of uninstalled aircraft engines. Aircraft engine testing may be categorized as engine development testing, engine production testing, and testing following engine repair. Engine tests vary widely depending on the purpose of the test, the test cell, and the aircraft engine. Finally, the testing of aircraft engines in test cells results in emission of oxides of nitrogen (NO_x). NO_x contributes to the formation of ozone in the atmosphere.

The majority of the test cells in the United States are owned and operated by the Department of Defense and aircraft engine manufacturers, although airlines and contract repair stations also own and operate enclosed aircraft engine test cells. Based on the information provided by test cell owners and operators, 368 enclosed test cells for testing uninstalled aircraft engines were identified in the United States. These 368 enclosed test cells were located at 130 test facilities. Only one of these 130 test facilities is devoted to the testing of internal combustion type aircraft engines; the overwhelming majority of test cells are used to test gas turbine type aircraft engines. Accordingly, the scope of this report includes only test cells that are used to test gas turbine type aircraft engines.

Pursuant to §233(a) of the Act, this report focuses on the testing of uninstalled aircraft engines in enclosed test cells. However, aircraft engines are also tested in facilities other than enclosed test cells. Aircraft engines may be tested using test stands, which are not fully enclosed structures. Testing is also performed in facilities where the engine remains installed on the aircraft. These facilities are sometimes referred to as hush houses.

Based on information identified during the study of the issues addressed under Subparts 1 through 6 in §233(a) of the Act, the following presents a summary of our findings:

1) Although technologies exist for the control of NO_x, none have been applied (full scale) to aircraft engine test cells in the United States. The differences in engines, engine tests, and test cell sizes and types complicate the design of applying a NO_x control system to a test cell. Various NO_x control technologies that have been applied to sources other than test cells are examined in this report for their applicability to test cells.

2) The effectiveness of add-on NO_x control technologies applied to test cells and other stationary sources is outlined in this report. However, the effectiveness of these NO_x controls applied to test cells cannot be determined until after installation and testing on a full-scale test cell.

3) The costs of applying conventional NO_x control technologies to test cells will be high, ranging from an estimated $167,000 to over $2.5 million per ton NO_x reduced. Cost estimates are based on the projected application of NO_x controls demonstrated on other stationary sources to model test cells developed in the study.

4) The NO_x control technologies using water or steam injection and fuel/water emulsions would directly adversely affect the safety, design, structure, operation, or performance of aircraft engines. To apply these technologies, temporary modifications to the engine would be required. For this reason, as well as the effects these technologies would have on performance tests (see below), water or steam injection and fuel/water emulsions should not be considered technically feasible options for application to test cells.

5) The effects of NO_x controls on aircraft engine safety design and performance tests cannot be fully addressed until research and development and test and evaluation programs have been completed. All of the known potential effects NO_x controls may have on the safety design and performance tests of aircraft

engines are addressed in the report. Unwanted back pressure effects may result from add-on NO_x control technologies.

6) The impact of not controlling NO_x emissions from test cells in the applicable ozone non-attainment areas is addressed by comparing the NO_x emissions from test cells to the non-attainment area stationary and total NO_x emissions. The contribution of test cells to NO_x emissions in ozone non-attainment areas does not exceed 3 percent of the stationary NO_x and 0.7 percent of the combined stationary and mobile NO_x sources. The vast majority of test cells contribute less than 1 percent of the stationary source NO_x emissions and less than 0.07 percent of the combined stationary and mobile source NO_x emissions.

CHAPTER 1

INTRODUCTION AND SUMMARY OF FINDINGS

Section 233 of the Clean Air Act Amendments (CAAA) of 1990, Public Law 101-549, mandates that the Administrator of the Environmental Protection Agency (EPA) and the Secretary of Transportation, in consultation with the Secretary of Defense, conduct a study of uninstalled aircraft engines in enclosed test cells.

SEC. 233. STATES AUTHORITY TO REGULATE.

(a) Study -- The Administrator of the Environmental Protection Agency and the Secretary of Transportation, in consultation with the Secretary of Defense, shall commence a study and investigation of the testing of uninstalled aircraft engines in enclosed test cells that shall address at a minimum the following issues and such other issues as they shall deem appropriate:

(1) whether technologies exist to control some or all emissions of oxides of nitrogen from test cells;

(2) the effectiveness of such technologies;

(3) the cost of implementing such technologies;

(4) whether such technologies affect the safety, design, structure, operation, or performance of aircraft engines;

(5) whether such technologies impair the effectiveness and accuracy of aircraft engine safety design and performance tests conducted at test cells; and

(6) the impact of not controlling such oxides of nitrogen in the applicable non-attaintment areas and on other sources, stationary and mobile, on oxides of nitrogen in such areas.

(b) Report, Authority to Regulate.

Not later than 24 months after enactment of the Clean Air Act Amendments of 1990, the Administrator of the Environmental Protection Agency and the Secretary of Transportation shall submit to Congress a report of the study conducted under this section. Following the completion of such study, any of the States may adopt or enforce any standard for emissions of oxides of nitrogen from test cells only after issuing a public notice stating whether such standards are in accordance with the findings of the study.

1.1 SCOPE OF STUDY

This report examines the six areas of investigation identified in §233(a) of the CAAA of 1990 relating to oxides of nitrogen (NO_x) emissions and the potential control of these emissions from enclosed test cells capable of testing uninstalled aircraft engines. It does not address various other facilities employed to test aircraft engines other than the enclosed structures examined in this study. For example, test stands are facilities which are typically used in long-term durability testing of aircraft engines. These structures are not fully enclosed and generally do not treat incoming engine or exhaust gas for acoustic abatement. Aircraft engine testing is also performed in facilities where the engine remains installed on the aircraft. These facilities, commonly called "hush houses", are typically used for a brief engine run-up and final airworthiness evaluation at military bases.

Enclosed uninstalled aircraft engine test cells (referred to in this report as test cells) may also be used in the performance evaluation and development of aircraft auxiliary power units (APU's), as well as marine and industrial engines. Auxiliary power units are turbine type engines used in aircraft to provide electrical power. Neither APU's nor marine and industrial engines are aircraft engines and were not addressed in this study given §233(a)'s limitation to aircraft engine testing. Accordingly, the NO_x emissions from facilities devoted solely to the testing of these other engines, and the portion of the NO_x emissions from facilities covered in this study while testing this type of equipment, have not been included in the NO_x inventory estimates or the NO_x control feasibility assessment presented in this report.

Information provided by test cell owners and operators identified test cells which are used exclusively to test reciprocating aircraft engines, also known as internal combustion or IC engines, and test cells which are used to test both turbine-based and IC engines. Of the approximately 130 test facilities identified from this study, only one performs IC aircraft engine testing in test cells. For this site, operating eight test cells testing IC engines, it is estimated that total annual NO_x emissions are 250 lbs. This represents less than 0.01 percent of the annual NO_x emissions attributed to test cell operation in the United States. Given this low contribution to overall NO_x emission from test cells, this report focuses on those test cells testing turbine (jet) type aircraft engines which are used in both commercial and military aircraft.

As described in more detail in Chapter 2 of this report, test cells may be grouped into two categories: sea level ambient condition testing and altitude simulating. The sea level test cell is used to evaluate the engine at the ambient conditions experienced at the time of testing. Test cells capable of simulating altitude conditions are large, complex facilities used to test the engine at conditions found in flight by providing air at controlled temperatures and pressures. (Of the 368 test cells identified from this study, 35 are altitude test cells.) As a result of the complexity of altitude test cells, the costs of applying NO_x controls to these types of facilities would be more than the predicted costs for applying similar technologies to sea level test cells. Therefore, the focus of this report in assessing the feasibility and costs of applying NO_x controls to test cells is on sea level test cells.

Finally, it should be noted that the DoD was consulted extensively in this study. The DoD provided much information and data, and reviewed and provided comments on drafts of this report.

1.2 SUMMARY OF FINDINGS

1.2.1 Feasibility, Effectiveness, and Costs of NO_x Control Technologies Applied to Test Cells

Subparts 1-3 of §233(a) of the Act pertain to the technical feasibility, effectiveness, and costs of NO_x control technologies for application to test cells. These issues are addressed in Chapters 4 and 5 of this report and are summarized as follows.

There are currently no NO_x controls applied to test cells in the United States. Various NO_x control technologies that have been applied to other stationary combustion sources are examined in this report for their applicability to test cells. Potentially applicable control technologies can be categorized as follows: 1) exhaust gas treatment methods established on other fossil fuel-fired systems (selective catalytic reduction (SCR), selective non-catalytic reduction (SNCR) and reburn); 2) emerging technologies (vermiculite-magnesium oxide (MgO) sorbent bed, low NO_x combustors); 3) established NO_x control methods for stationary gas turbines which would reduce emissions from test cells by temporarily modifying the engine tested (water/steam injection and water-in-fuel emulsion).

Selective Catalytic Reduction

SCR is a post-combustion NO_x control technology whereby ammonia is injected into the exhaust gas and reacts with nitric oxide (NO) to produce nitrogen gas (N_2) and water in the presence of a catalyst. The reaction is strongly temperature dependent with a narrow temperature operating range. This report examined two catalysts with temperatures centered on 490 °F and 650 °F. SCR has been demonstrated with a NO_x removal efficiency of 80 percent when applied to stationary gas turbines.

It is conceptually possible to design an SCR system using conventional catalyst materials that could be applied to test cells. A research and development and evaluation program would be required before decisions could be made on design characteristics for test cells incorporating such a NO_x control system. This would result in test cells which would control NO_x and not affect safety or performance of the engines when tested or affect subsequent in-flight safety. Present-day test cells may require major structural modifications to meet these new design characteristics. Various considerations, such as site conditions, may limit the practicality of retrofit and necessitate test cell replacement.

Due to relatively low stack gas temperatures associated with the operation of test cells, the application of SCR in most cases would require reheating of the exhaust gas to maintain the stack gas temperature within the appropriate catalyst temperature range. Both the duct burner which could be used to reheat the exhaust gas and the ammonia injection system must be tightly controlled via the use of feedback control systems to follow the characteristically rapid variations in gas temperature, mass flow rate, and NO_x concentration of the test cell exhaust gas. Controllers must be designed to track the transient conditions, but it is uncertain how effective the required feedback systems would be at tracking such a highly transient emission source. Lag time in the response of the ammonia injection system to changes in exhaust gas conditions would result in increased unreacted ammonia emissions and a decrease in the NO_x removal efficiency of the system.

The cost-effectiveness estimates for SCR applied to test cells range from $167,000 to $972,000 per ton NO_x removed, assuming the lowest cost solution catalyst and depending on the test cell size. The primary cost components are the catalyst and the SCR reactor vessel. Cost elements which have not been included in the cost analysis are system design/development costs and the cost of recalibrating the engine/test cell combination following retrofit to account for the change in air flow characteristics through the cell. It is not anticipated that these components will significantly alter the cost effectiveness estimates. Using the cost analysis methodology outlined in Chapter 5, every $1 million of capital investment increases the cost effectiveness estimates $4,000 per ton NO_x removed (cost recovery factor of

0.094 and 24 tons NO_x per year). A cost sensitivity analysis indicated that an increase in catalyst life, an increase in test cell annual usage, an increase in NO_x removal efficiency, and a decrease in test cell dilution air (augmentation air) would all decrease the SCR system dollar per ton estimates.

Total capital installed retrofit costs for SCR range from $1 million to $43 million for the lowest cost solution catalyst, depending on test cell size and operating characteristics. Total capital costs for a recently designed test cell capable of evaluating large turbofan type engines range from $18 to $20 million. Total capital installed retrofit cost to incorporate SCR to this test cell is estimated at $14 million.

Selective Non-Catalytic Reduction

SNCR involves the injection of either ammonia or urea into the exhaust gas stream. The ammonia or urea reacts with NO to produce N_2 within a temperature range of approximately 1,800 to 2,000 °F. SNCR has been demonstrated on utility boilers, process heaters and other fossil fuel-fired systems to achieve up to 50 percent NO_x removal.

Due to the low stack gas temperatures associated with the test cells, application of SNCR will require substantial reheating with a natural gas duct burner to maintain the stack gas temperature within the appropriate temperature range. Similar to SCR, both the duct burner which is used to reheat the gas and the ammonia or urea injection system will require controls capable of tracking the characteristically rapid variations in gas temperature, mass flow rate, and NO_x concentration. Controllers must be designed to track the transient conditions, but it is uncertain how effective the required feedback systems would be at tracking such a highly transient emission source. Lag time in the response of the controllers to changes in exhaust gas conditions would result in increased unreacted ammonia or urea emissions and a decrease in the NO_x removal efficiency of the system. It is conceptually possible to design an SNCR system using conventional materials that could be applied to test cells. However, until the research and development and test and evaluation programs have been completed, the safety and performance issues cannot be fully addressed.

Due to SNCR's lower NO_x removal efficiency, and the NO_x emissions from the duct burner, SNCR may actually cause a net *increase* in NO_x emissions from the test cell under most operating conditions. At the few operating conditions where SNCR may cause a net decrease in NO_x emissions, the cost-effectiveness estimate for SNCR ranges from $350,000 to over $1 million per ton NO_x removed. Natural gas reheat fuel is the primary cost component. Design and development costs have not been included in the cost effectiveness estimates. It is not anticipated that these cost components will significantly alter the cost effectiveness of SNCR. Using the cost analysis methodology outlined in Chapter 5, every $1 million of capital investment increases the cost effectiveness estimates $4,000 per ton NO_x removed (cost recovery factor of 0.094 and 24 tons NO_x per year).

Reburn

Reburn is a NO_x control technology which removes NO_x by firing natural gas in a second combustion zone to produce slightly fuel-rich conditions. The reduction of NO_x to N_2 occurs by reactions with hydrocarbon fragments formed in the fuel-rich state. This relatively new technology has been demonstrated on utility boilers.

Reburning in an oxygen-rich gas such as that from a test cell exhaust (greater than 15 percent oxygen) is referred to as lean reburning, where local fuel-rich conditions occur in an overall fuel-lean exhaust gas. The feasibility of lean reburn was examined at bench-scale as part of a Small Business Innovation Research (SBIR) effort. The SBIR study showed that lean reburn can remove NO_x at up to 60 percent efficiency at a NO_x inlet concentration of 1000 ppm, and the study documented the significant decrease in NO_x removal efficiency as inlet NO_x concentration dropped from 1000 ppm to 500 ppm. At a NO_x inlet concentration of 500 ppm, the removal efficiency dropped to 30 percent. The SBIR study did not test for NO_x removal at NO_x concentrations more typical of test cell operation (100 ppm or less). It is conceptually possible to design a reburn system using conventional materials that could be applied to test cells. However, until the research and development and test and evaluation programs have been completed, the safety and performance issues cannot be fully addressed.

However, cost-effectiveness for reburn applied to test cells was estimated assuming a NO_x removal efficiency of 10 percent, based on a fuel equivalence of 0.8 and an inlet NO_x concentration of 100 ppm. The high fuel requirement is due to the high oxygen levels in the test cell exhaust gas. The cost-effectiveness ranged from $480,000 to $9.4 million per ton of NO_x removed for different sized test cells, assuming reburn fuel as the only cost element.

<u>Vermiculite - Magnesium Oxide Sorbent Bed</u>

The vermiculite-MgO sorbent bed is a post-combustion control technology which removes NO_x from the gas stream by adsorption onto the bed material. Unlike SCR, this technology does not require exhaust gas reheat or ammonia injection. Short-term testing on a test cell using a 10 percent slipstream indicated 50 to nearly 70 percent NO_x removal. Long-term pilot-scale testing has not been conducted on test cells (or other combustion sources), and the technology has not been demonstrated on a full-scale test cell. There is a proposal to further evaluate this approach on a test cell. It is conceptually possible to design a vermiculite sorbent bed that could be applied to test cells. However, until the research and development and test and evaluation programs have been completed, the safety and performance issues cannot be fully addressed. Cost-effectiveness estimates are unavailable due to limited information on this technology.

Water or Steam Injection

Water or steam injection or water-in-fuel emulsion are established NO_x control technologies for stationary gas turbines. Water reduces the flame temperature, thereby reducing thermal NO_x formation. The use of either water/steam injection or water-in-fuel emulsion to reduce NO_x from engines evaluated in test cells would require temporary engine modifications and would significantly alter the performance characteristics of the engine under test. See Section 1.2.2 for more details.

Low NO_x Combustors

Although not actually a NO_x control technology for test cells, aircraft engine combustors are being designed to produce less NO_x and thus may ultimately lead to lower test cell NO_x emissions. Low NO_x combustor technology has been developed for stationary gas turbine applications. However, the transfer of this technology to aircraft engines is not straightforward. Aircraft engines place demands on the combustor technology that are not required for stationary gas turbine applications, such as rapid transient operation with low risk of flameout. Currently, some jet engine manufacturers and NASA are developing low NO_x combustors for use on their engines.

1.2.2 Effects of Test Cell NO_x Control Technologies on Aircraft Engine Safety, Design, Structure, Operations and Performance Testing

Subparts 4 and 5 of §233(a) of the CAAA pertain to the effects that NO_x control technologies might have on the safety, design, structure, operations and performance of aircraft engines and the impact on the effectiveness and accuracy of aircraft engine safety design and performance tests conducted at test cells. All of the known potential effects that the various control technologies may have on the engine or the engine test are addressed in Chapter 4 of this report and are summarized as follows. However, until the research and development and test and evaluation programs have been completed, the safety and performance issues on testing cannot be fully addressed.

Effects of Water or Steam Injection

As discussed previously, water or steam injection and fuel/water emulsion would directly affect the engine and engine test by altering the performance characteristics during testing. These modifications would result in the evaluation of an engine within the test cell which would require further modification before being returned for in-flight service. Also, this type of NO_x control would result in engines tested with performance characteristics which are not representative of the engine when prepared for in-flight service. This alone defeats the purpose of certification and validation testing following engine repair. For engine development-related test cell operation, critical component testing and engine performance determination would be invalid or provide data for unrealistic or non-representative engines and operating conditions.

Effects of Back Pressure

The back pressure associated with the post-combustion NO_x control technology equipment, such as catalysts, sorbent beds and duct burners, would impede the air flow through the test cell. Using conventional technology, designs can limit back pressure to 0.1 inch water for a duct burner and 1 to 2 inches of water for a catalyst bed.

The aerodynamics of the test cell affect the performance of the engine being tested. An increase in back pressure, as would occur with an add-on NO_x control technology, would also affect the aerodynamics of the test cell. Air flow recirculation, causing temperature and pressure distortion of the engine inlet air, can lead to uncertainty about engine performance measurements. Engine performance may become unstable and unrepeatable, leading to test rejection and possibly unnecessary engine rebuild. Recirculation of air within the test cell will also affect engine thrust measurement. In extreme cases, engine inlet air flow distortion may result in compressor stall and cause severe engine damage.

An increase in back pressure downstream of the test engine may reduce the augmentation ratio (an indicator of the amount of test cell dilution air which bypasses the engine). This would make it necessary to recalibrate the test cell for each engine model tested in that test cell. In addition, the increase in back pressure may make it necessary to decrease the maximum thrust capability of a test cell to compensate for the decrease in augmentation air flow. This resultant decrease in thrust capability would effectively limit the size of engines that can be tested in the cell. Continued testing of these engines would require a major modification of the test cell or construction of a new test cell which would use

NO_x controls and not affect the safety or performance of the engine.

One modeling study indicates that vortices in the test chamber may be avoided if the augmentation ratio is kept above 0.8. New test cells are designed so that augmentation ratios are typically greater than 0.8, and in practice, augmentation ratios are normally between 1 and 10. Therefore, although the add-on NO_x control technology may lead to a reduced augmentation ratio, there is some indication that if the new augmentation ratio remains greater than 0.8, inlet air vortices may be avoided. However, for low bypass ratio engine testing and engine core testing, the minimum augmentation ratio is determined by the cooling requirement on the aft portion of the engine. For this reason, low bypass ratio engine testing and engine core testing augmentation ratios must be maintained much higher than 0.8 to provide sufficient cooling.

1.2.3 Impact of Not Controlling NO_x Emissions From Test Cells in the Applicable Ozone Non-Attainment Areas

Subpart 6 of §233(a) of the CAAA pertains to the impact of not controlling NO_x emissions from test cells in the applicable ozone non-attainment areas. (An area is classified as non-attainment if it does not meet the national ambient air quality standard (NAAQS) for the pollutant in question.) This issue is addressed in Chapter 6 of this report and is summarized below. An inventory of the test cells in the United States, along with their annual emission estimates, serves to address the question of impact.

Results from this study (see Chapter 6) indicate that the total annual NO_x emitted from the current population of 368 test cells in the United States is approximately 2,830 tons.

Approximately 74 percent (2,070 tons) is emitted into ozone non-attainment areas. The NO_x emissions distribution for test cells located in ozone non-attainment areas is presented in Figure 1-1. A significant variation exists in test cell annual NO_x emissions, which are determined in part by the size of the engines tested within the test cell, the annual hours of operation, and the test schedules. Figure 1-2 presents the distribution of average test cell annual NO_x emissions. Data were generated from the average annual facility NO_x emissions divided by the average number of test cells per facility.

The relative contribution of test cell NO_x emissions to total NO_x emissions within the ozone non-attainment areas was determined by comparison to non-attainment area stationary and total NO_x emissions. This analysis is summarized in Table 1-1. The data show that the contribution of test cells to NO_x emissions in ozone non-attainment areas does not exceed 3 percent of the stationary NO_x and 0.7 percent of the combined stationary and mobile NO_x sources. The data also show that the vast majority of test cells contribute less than 1 percent of the stationary source NO_x emissions and less than 0.07 percent of the combined stationary and mobile NO_x source NO_x emissions.

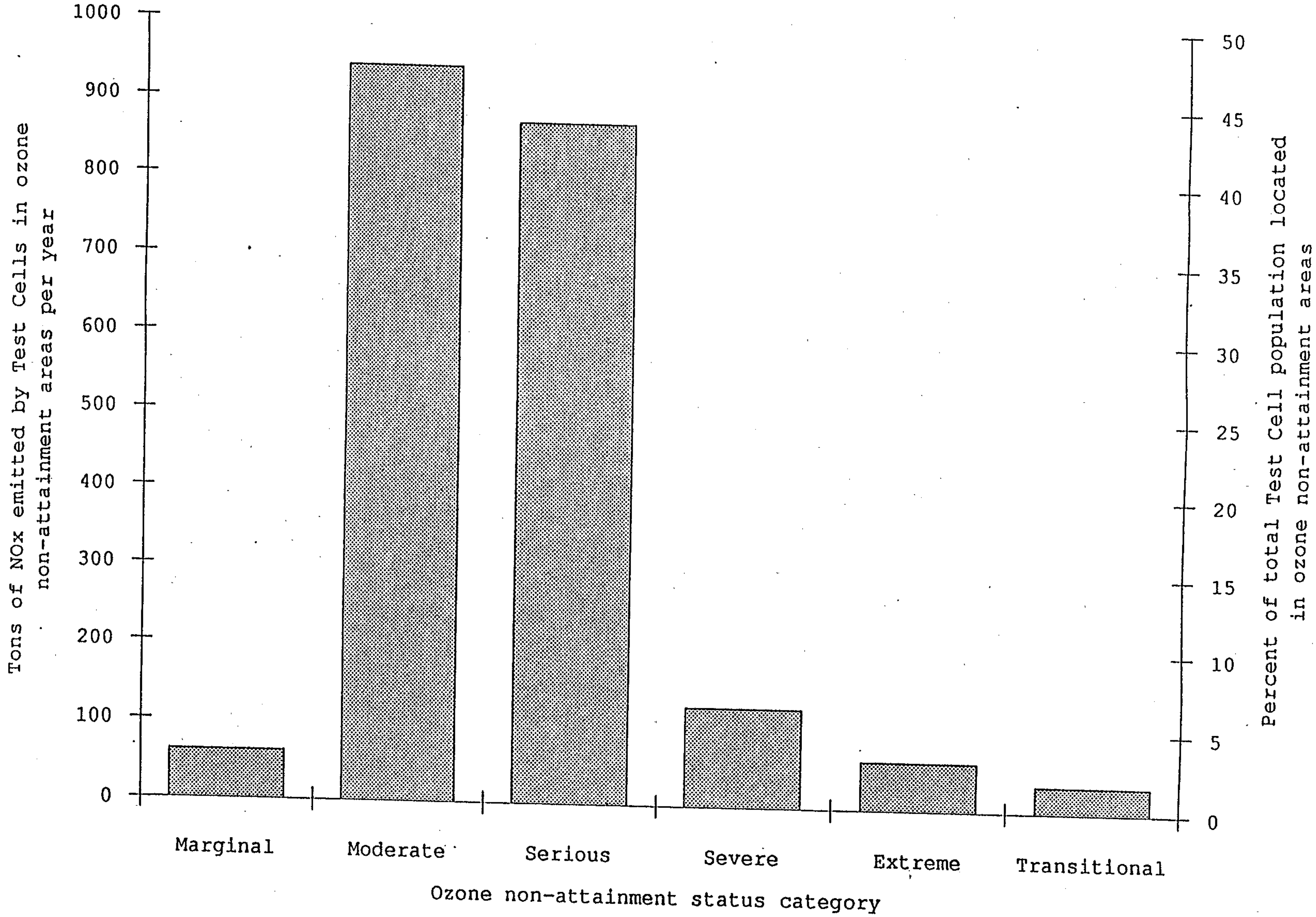

Figure 1-1. Annual test cell emissions by ozone non-attainment status category for test cells located in ozone non-attainment areas.

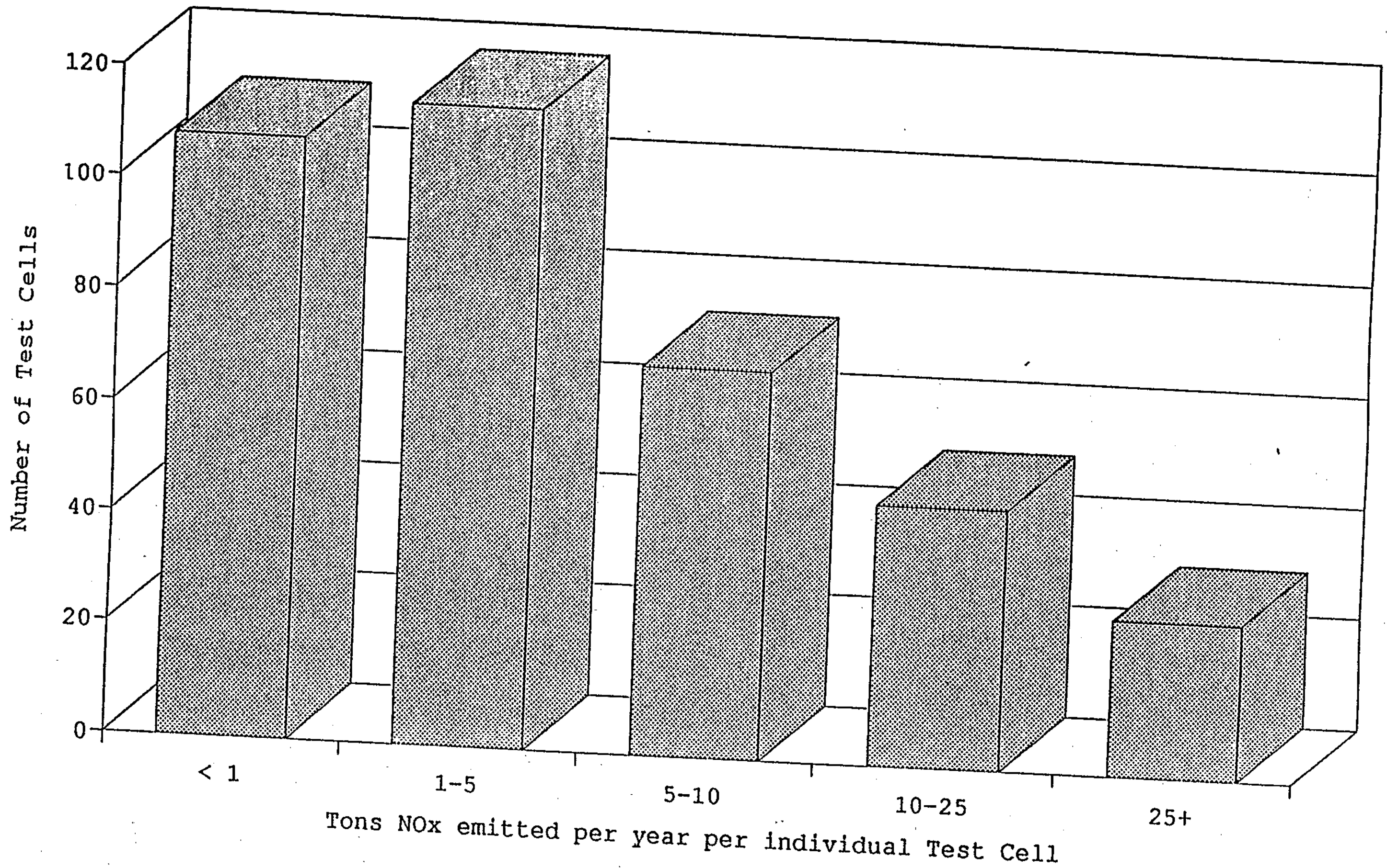

Figure 1-2. Average annual NO_x emission per test cell for all reported test cells.

TABLE 1-1. TEST CELL RELATIVE CONTRIBUTION TO OZONE NON-ATTAINMENT AREA STATIONARY SOURCE AND TOTAL ANNUAL NO_x EMISSIONS

Ozone non-attainment area (greater area)	Number of test cells	Test cell NOx (tons per year)	Total stationary source NOx (tons per year)	Total stationary source NOx (%) test cells	Total NOx, stationary & mobile sources (tons per year)	Total NOx, stationary & mobile sources (%) test cells
Phoenix, AZ	20	58.6	2,200	2.664	130,000	0.045
Greater Connecticut	49	672	27,000	2.489	101,000	0.665
Cincinnati, OH	13	716	77,000	0.930	155,000	0.462
Sacremento, CA	5	21.3	6,100	0.349	82,000	0.026
Norfolk, VA	6	52.5	18,000	0.292	77,000	0.068
Salt Lake City, UT	3	6.69	2,800	0.239	45,900	0.015
San Diego, CA	8	28.5	16,000	0.178	121,000	0.024
Boston, MA	24	178	100,000	0.178	263,000	0.068
Portland, OR	1	5.3	3,200	0.166	80,100	0.007
Brunswick, ME	1	0.22	147	0.150	3,600	0.006
San Francisco, CA	10	81.3	59,000	0.138	360,000	0.023
Indianapolis, IN	35	30.8	24,000	0.128	76,000	0.041
Dayton-Springfield, OH	1	5.97	6,500	0.092	46,300	0.013
Atlanta, GA	7	30.86	35,000	0.088	167,000	0.018
Atlantic City, NJ	1	8.63	11,600	0.074	25,300	0.034
Los Angeles, CA	9	62.22	123,000	0.051	552,000	0.011
San Joaquin Valley, CA	3	26.95	60,000	0.045	197,000	0.014
Phiadelphia, PA-Wilmington, DE	14	44.7	110,000	0.041	292,000	0.015
Ventura Co., CA	2	3	9,800	0.031	36,700	0.008
Seattle-Tacoma, WA	1	3.32	11,000	0.030	140,000	0.002
Dallas-Forth Worth, TX	5	8.74	48,000	0.018	377,000	0.002
Richmond, VA	1	3.35	24,700	0.014	59,500	0.006
Pittsburgh, PA	2	7.03	139,000	0.005	246,000	0.003
St. Louis, MO	1	5.08	147,000	0.003	260,000	0.002
Cleveland-Akron, OH	3	2.16	67,000	0.003	189,000	0.001
Washington, DC	5	2.44	76,000	0.003	205,000	0.001
Detroit. MI	9	3.2	237,000	0.001	441,000	0.001
Tampa-St. Petersburg, FL	3	0.78	95,000	0.001	157,000	0.000
Miami, FL	1	0.19	34,000	0.001	259,000	0.000
TOTAL	243	2069.83	1,570,047	0.132	5,144,400	0.040

NOTE: Test cell emissions represent composite values from a representative year.

CHAPTER 2
CHARACTERIZATION OF TEST CELLS

Test cells are facilities designed to operate and measure the performance of uninstalled aircraft engines. The Department of Defense (DoD), the commercial airline industry, aircraft engine manufacturers, and contract engine repair organizations operate test cells to achieve their specific goals, which include: engine development, maintenance and repair, and airworthiness evaluation.

Test cell designs vary widely to meet the owner/operator requirements, although as will be discussed in Section 2.1, these facilities can be broadly categorized by their ability to conduct either "altitude simulation" or "sea level" testing. As will also be discussed in Section 2.1, aircraft engine testing is performed using facilities other than test cells, including test stands and hush houses. These two types of facilities described briefly in Section 2.1 do not conform to the scope of work in this report and are not included in either the emission inventory presented in Chapter 6 or the NO_x control feasibility assessment presented in Chapter 4. The physical size and exhaust gas characteristics (temperature, flowrate and NO_x concentration) of test cells are determined to a large extent by the engines tested within the facility. A brief description of the types of engines typically tested within test cells and their impact on the test cell exhaust gas characteristics is presented in Section 2.2. The operation of an individual test cell is primarily determined by the test goals of the owner/operators and can vary widely, for example, between aircraft engine development and commercial airline airworthiness assessments. Section 2.3 presents a discussion of the types and objectives of tests performed in test cells. The distribution of test cells by owner/operator within the United States and the role of test cell operation within the various owner/operator groups is presented in Section 2.4.

2.1 TEST CELL DESCRIPTION [1, 2, 3, 4, 5]

Test cells are structures designed to hold and operate aircraft engines; use advanced test instrumentation to measure and document engine performance; and suppress noise to the surroundings during engine tests. Test cells may be found at Air Force, Navy and Army bases, at commercial airline facilities, NASA, aircraft engine manufacturers' facilities, and at contract engine repair facilities. Test cells exist in a large variety of configurations, and generally no two are exactly alike. However, three principal components found in all test cells are: (1) a building which encloses the engine and the instrumentation and provides fuel and structural support during testing; (2) an augmentation tube; (3) and a blast room and/or exhaust stack. A schematic of a generic test cell containing the above mentioned components is shown in Figure 2-1. Although there is great variety in design, test cells can be grouped into two categories: sea level ambient condition testing and altitude simulating. This section will discuss the physical properties of, and differences between, these types of test cells. Engine testing is also conducted in facilities other than test cells such as test stands and hush houses. Although these two types of facilities are not covered by this study, a brief

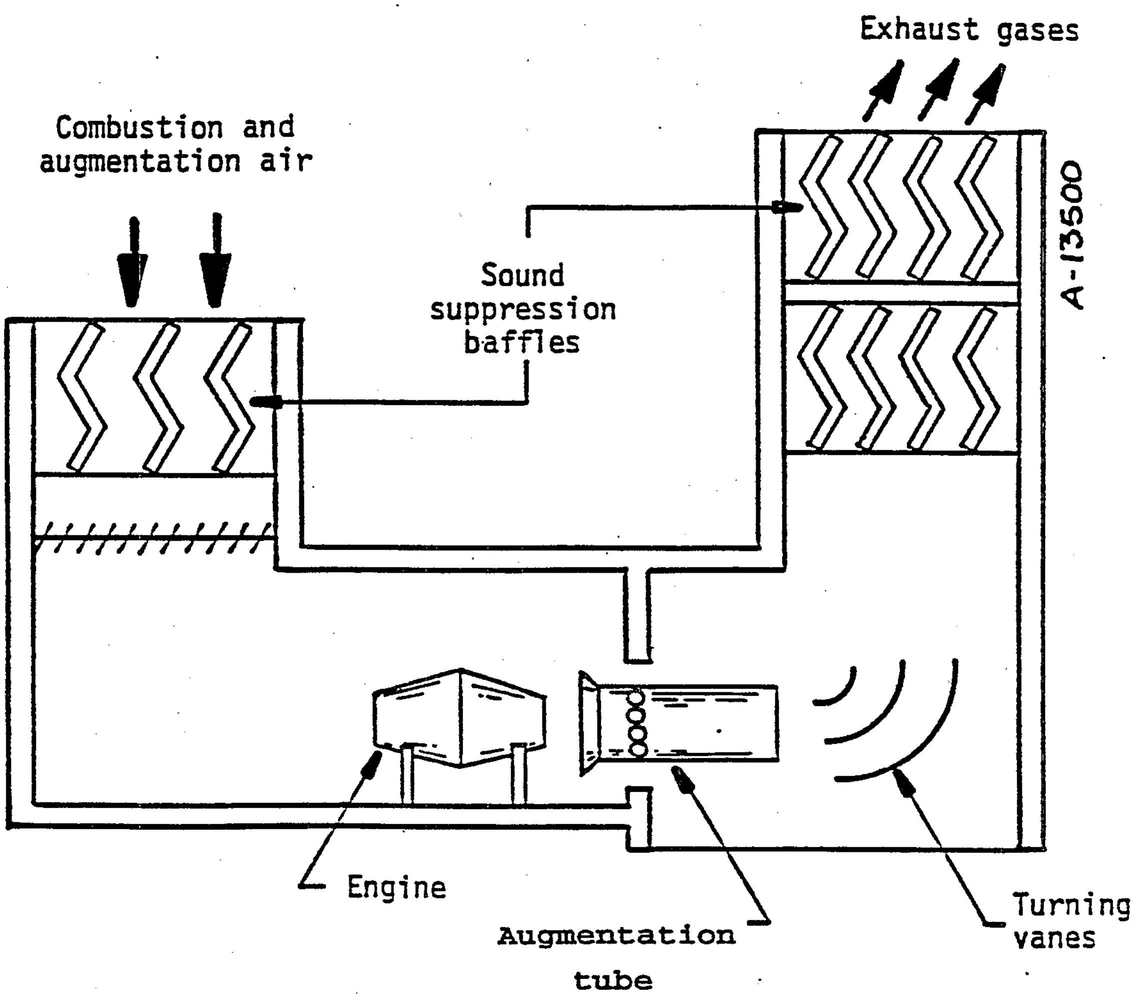

Figure 2-1. Schematic of a generic sea level test cell.

description of each is provided at the end of this section in order to distinguish them from test cells.

2.1.1 Sea Level Test Cell Description

The sea level test cell is used to evaluate the engine at the ambient conditions experienced at the time of testing. Figures 2-2, 2-3, and 2-4 are schematic diagrams of typical sea level test cells. While there are fundamental differences between the facilities shown, these test cell designs are capable of conducting similar engine tests. The primary air, which consists of the air that goes into the engine, and the secondary or augmentation air, which is the air that flows out the stack but does not flow through the engine, have different flow patterns through these facilities. In Figure 2-2, the air enters the facility through a single inlet. The air flow is divided into the primary air and the secondary/augmentation air. The augmentation air does not pass through the front of the engine but is used for the purpose of dilution, cooling, and to limit the negative pressure in the cell. Figure 2-3 depicts a test cell with a single air inlet without physical separation of the primary and secondary air. In this design of test cell, the secondary air is entrained around the engine by the lower pressures created from the high velocity exhaust gas (ejector effect). Figure 2-4 shows a test cell that has two air inlets, one for the primary air and a separate one for the augmentation air.

Test cells are usually massive reinforced concrete structures designed to withstand the intense vibrations, negative pressures generated within the facility, and the heat generated by the engine. Typically, air is drawn into the test cell by the engine through various kinds of acoustical

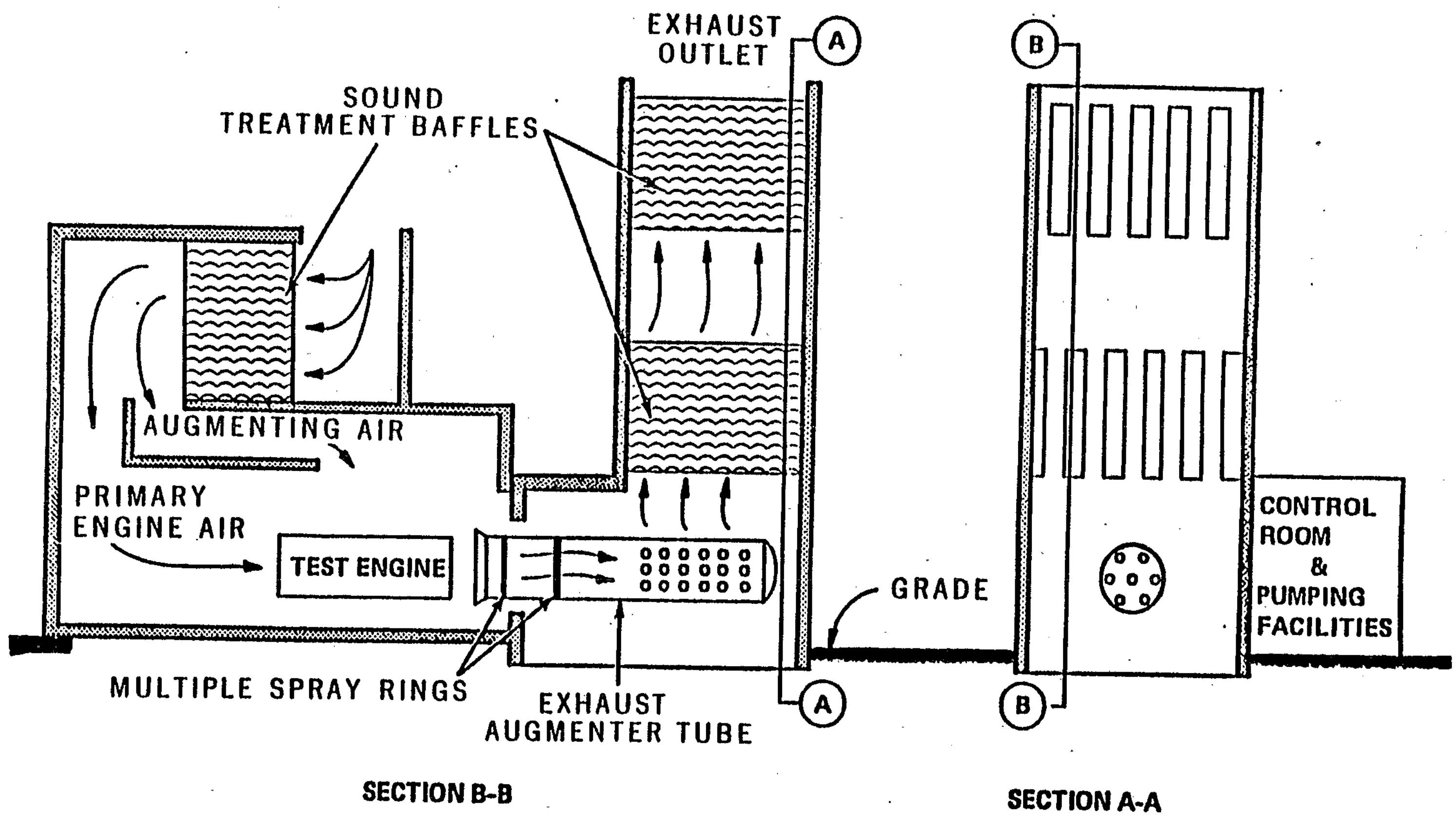

Figure 2-2. Typical sea level test cell (single air inlet with air flow division).

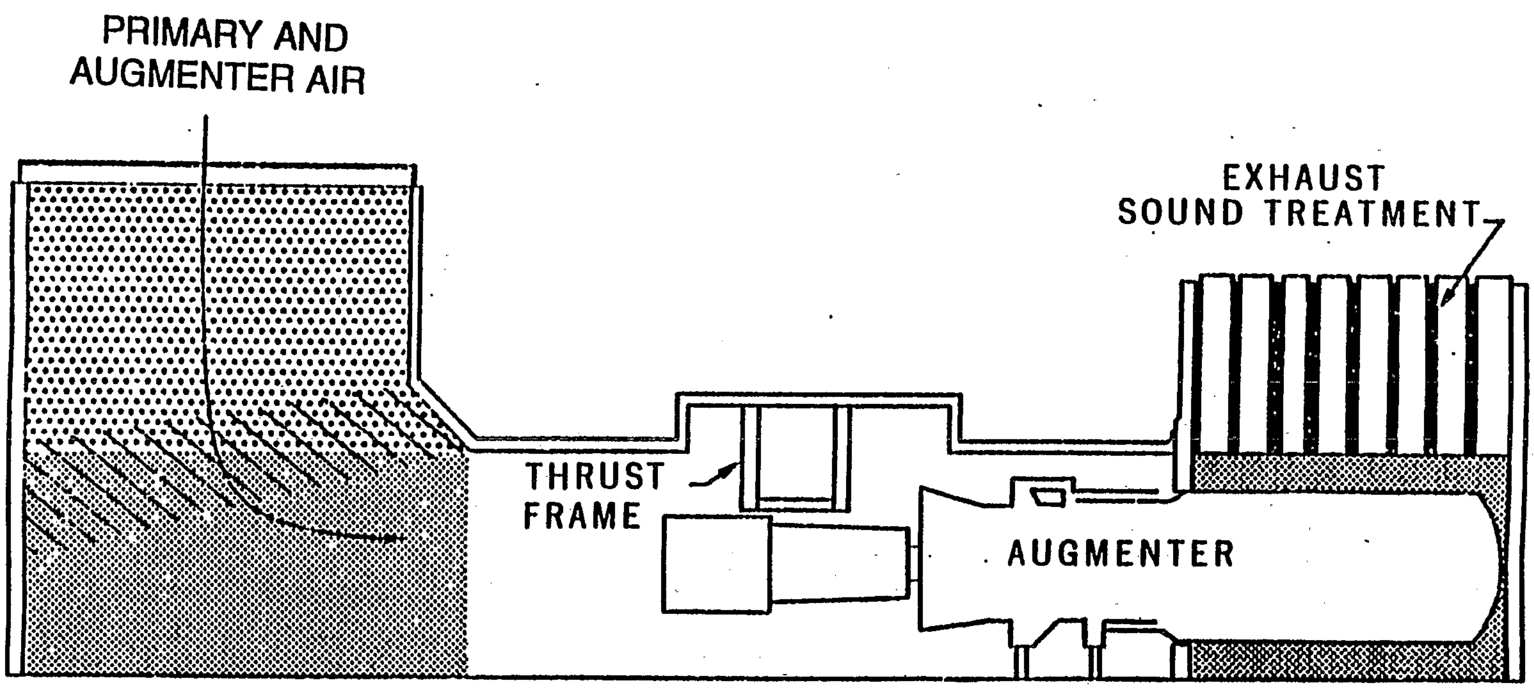

Figure 2-3. Typical sea level test cell (single air inlet).

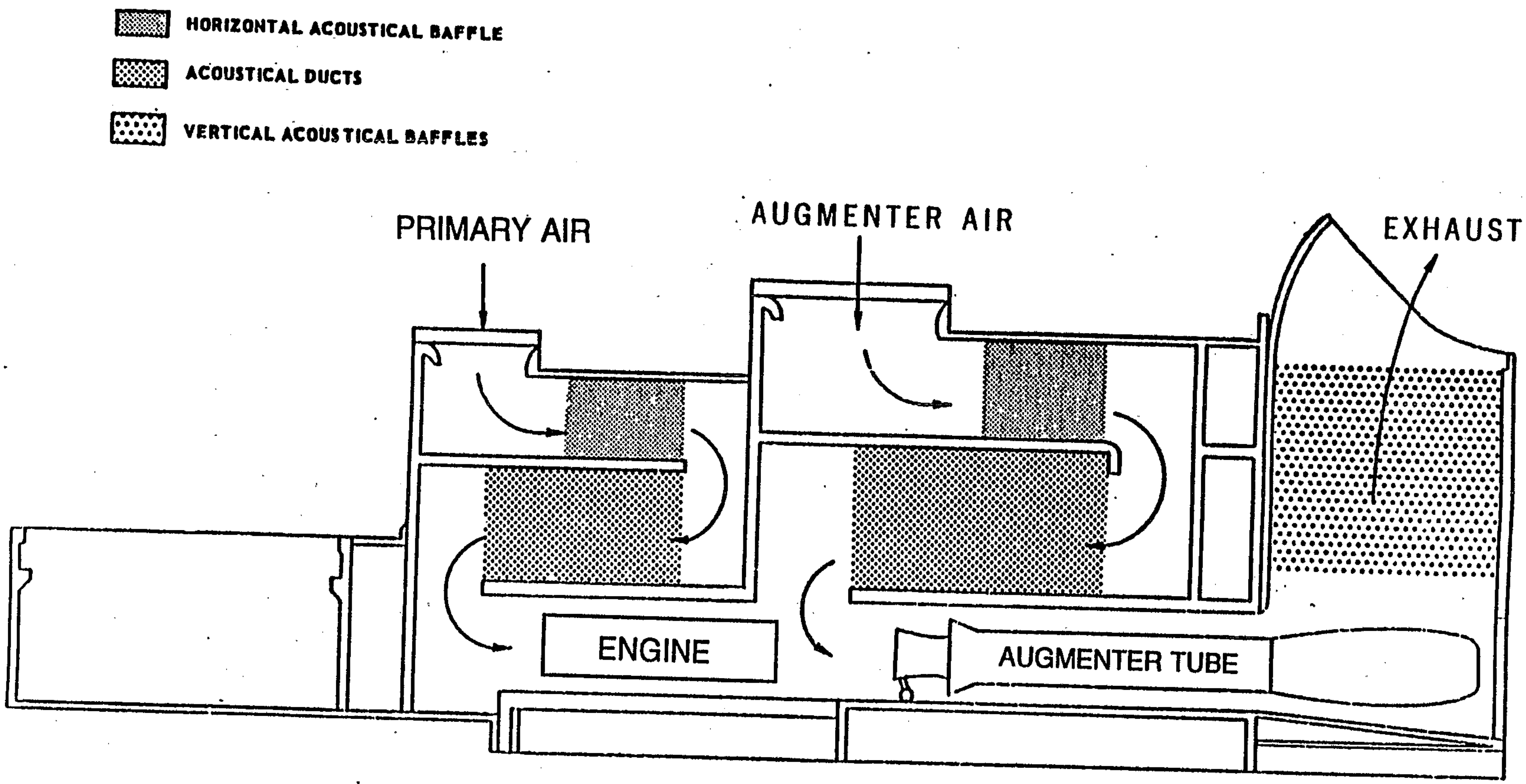

Figure 2-4. Typical sea level test cell (two air inlets).

baffling and/or turning vanes. The test engine is fastened to a thrust frame which is anchored to the test cell. The thrust frame incorporates load cells and other instrumentation to monitor and evaluate the engine during testing. The test cell also provides the fuel, necessary hardware and controls to simulate the aircraft for which the engine is used. The thrust frame and associated instrumentation are used to measure the observed engine thrust exerted on the frame.

The corrected (actual) thrust is determined using the observed thrust and the test cell/engine correction factor. The correction factor is determined for each specific model of engine for each test cell by placing a calibrated engine of the same model with known thrust characteristics in the test cell and monitoring such items as the observed thrust, fuel flow rate, and engine rpm. The correction factor relating observed thrust to actual thrust is required to account for dissimilar air flow around the engine as well as the effect of variations in ambient air conditions. Thrust measurement is a critical parameter in test cell operation; test cell operational goals include the desire to minimize the required thrust corrections, and to ensure for test repeatability. Minor changes to the test cell or mounting arrangement of the engine within the facility can significantly impact air flow around the engine. This change in air flow would necessitate recalibration and determination of a new thrust correction factor for each engine tested in the altered test cell.

In a test cell, the augmenter tube is located behind the engine. The augmenter tube has two primary purposes: (1) to reduce negative static pressures in the test cell during the test by enhancing augmentation air flow; (2) and to promote air flow around the engine, which cools the engine as if in flight. The air entrained by the engine exhaust which did not pass through the engine cools and dilutes the engine exhaust.

This dilution helps to protect the test cell from the heat of the engine exhaust by maintaining a temperature of typically less than 400°F in the test cell exit gas.

Augmenter tube design varies in shape and size. Most augmenter tubes have a bell mouth at the front to promote secondary air flow. The engine exhaust gas and secondary air are mixed and flow down the augmenter tube, usually made of steel, to a position under the stack. The augmenter tube is usually perforated at the end to distribute the exhaust gases in a uniform manner and to minimize the creation of localized hot spots which may damage the concrete. Some augmenter tubes do not have either the bell mouth or the perforated ending to the augmenter tube. Figure 2-5 shows a schematic diagram of the F402 test cell at the Naval Aviation Depot Cherry Point. In lieu of the perforations in the augmenter tube, this facility has permanently mounted angular slats at the bottom of the stack in order to direct the exhaust gases. This particular test cell design incorporates acoustic dampening along the augmenter tube region, eliminating the need for sound baffles in the stack.

In addition to air cooling, test cell designs can incorporate water sprays to cool the exhaust gases in the augmenter tube. Water is usually sprayed radially through spray rings, which are routinely used for test cells testing military engines that have an afterburning mode. Water cooling systems can be operated at all power settings above idle, or automatically triggered when a specific stack temperature is reached.

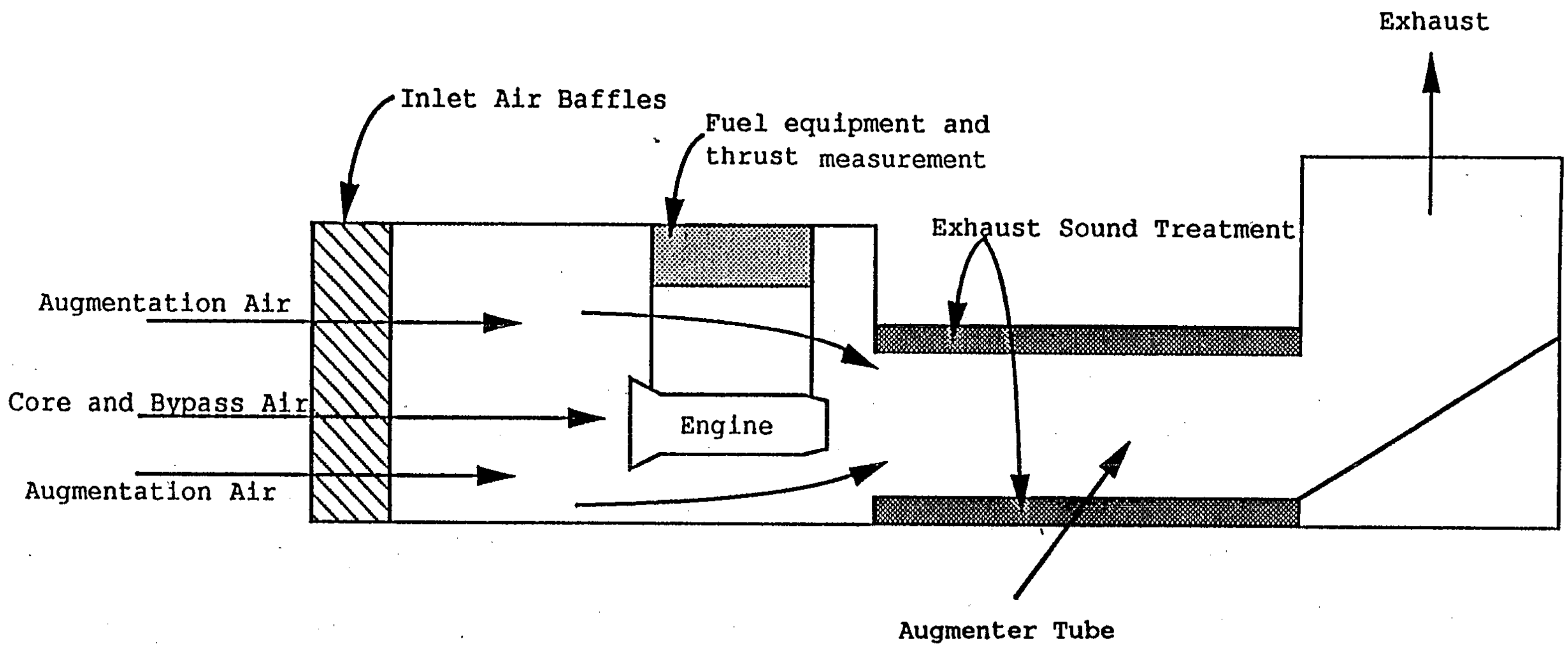

Figure 2-5. Schematic of F402 test cell at Cherry Point Naval Aviation Depot.

2.1.2 Altitude Simulating Test Cell Description

Test cells capable of simulating altitude conditions are large, complex facilities used to test aircraft engines at conditions found in flight. These facilities not only measure engine performance as in sea level test cells, but also provide air at controlled temperatures and pressures to simulate actual flight conditions. Although individual facility capabilities can vary, altitudes ranging from sea level to nearly 70,000 feet, air speeds up to Mach 3, and inlet air temperatures from below -20°F to nearly 500°F can be achieved in several of these type test cells. These facilities are generally owned and operated by the engine manufacturer, DoD, or NASA and are used for all types of testing including certification, fuel economy determination, and high altitude performance assessment.

When simulating altitude conditions, air flow through the engine is tightly controlled, with both the engine and additional exhaust pumps moving the air through the test cell. Figure 2-6 depicts a generic schematic of an altitude simulating test cell. In order to simulate flight conditions at altitude, air pressures must be independently controlled both upstream and downstream of the engine. This condition requires that a pressure seal arrangement be used, isolating these two sections of the test chamber. Typically, the engine is mounted through a bulkhead and closed off with a pressure seal. Test cell secondary air, primarily used for cooling, is introduced behind the bulkhead.

Although different altitude test facilities use different methods and equipment to evacuate the test chamber, the basic approach remains the same. One or more vacuum pumps driven by gas or steam drivers or by electric motors are used to pull air through the test chamber. The test engine exhaust gas

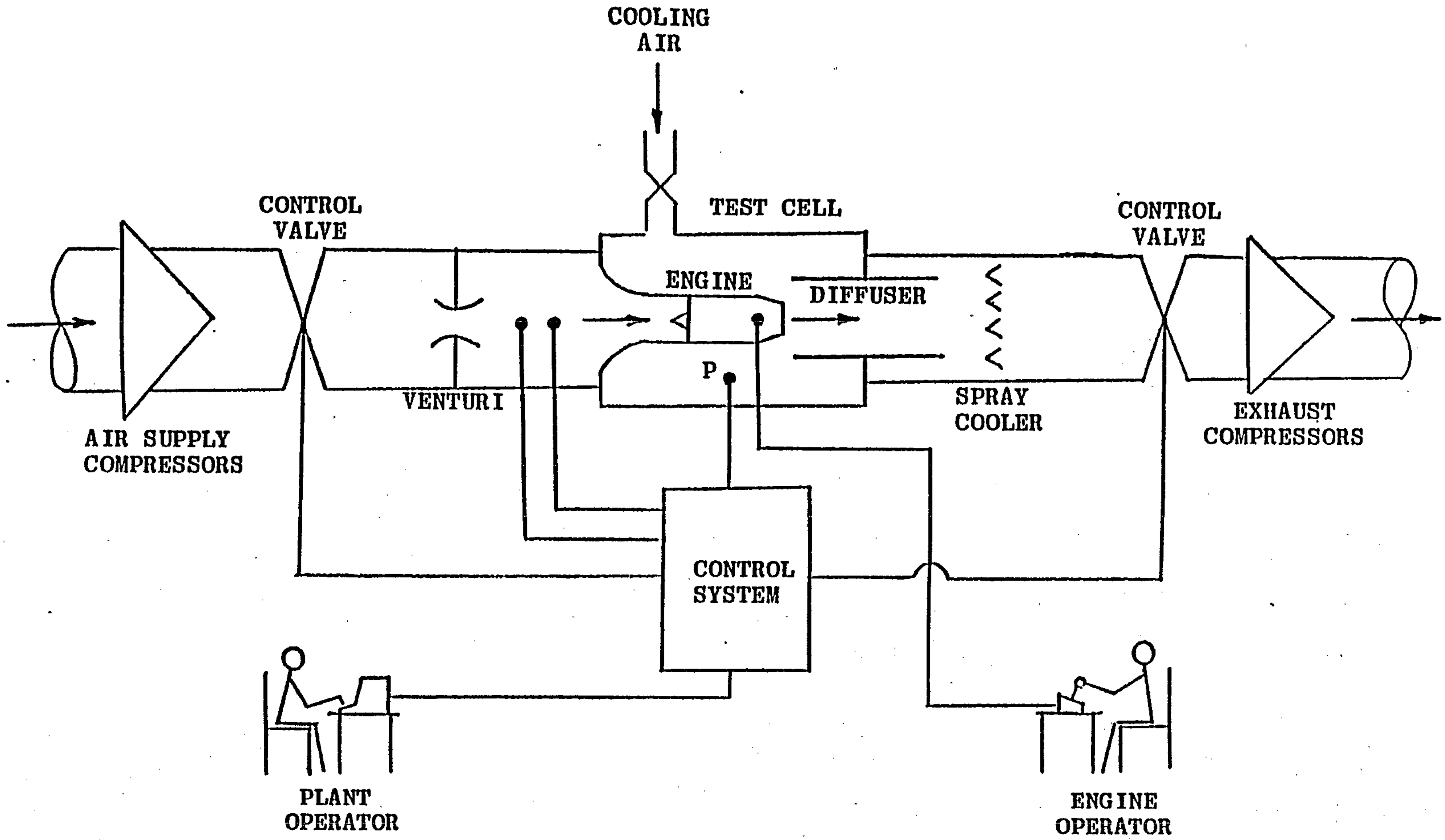

Figure 2-6. Generic schematic of an altitude simulating test cell.

stream typically passes through a temperature control device prior to entering the exhaust vacuum pumps. Modulating discharge valves are usually included in the ductwork between the test chamber and the vacuum pumping equipment and are used in conjunction with the vacuum pump(s) to set air flow rates and to control pressure. For example, the chamber is maintained at approximately 1/4 atmosphere pressure to simulate 35,000 feet altitude conditions. The simulated Mach number is determined by the ratio of inlet engine pressure to test chamber air pressure. This ratio is approximately 1.5 to simulate 0.8 Mach number, which is a typical commercial engine test condition to demonstrate cruise performance. Modulating valves upstream of the engine inlet are used to set the pressure level at the front face of the engine.

The Willgoos turbine laboratory, owned and operated by Pratt and Whitney, is an altitude simulating facility.[5] The facility provides air at controlled temperatures and pressures to simulate actual flight conditions at altitudes ranging from sea level to 65,000 feet and Mach number up to 3. The facility uses various combinations of 16 steam turbine driven compressors and 6 gas turbine driven compressors for several test cells. The steam turbines are powered by steam from six marine type boilers.

The auxiliary equipment (steam compressors, gas compressors, refrigeration system, process heaters, and conditioning chambers) operates in a transient nature and responds to sudden upsets in flow as a result of the engine test, such as simulated flame out testing at altitude which results in engine discharge temperatures swinging from 1000 °F to -20 °F.

Due to the overall design of the facility, which incorporates bypass flows to assist in controlling engine inlet and exhaust conditions, the swings in auxiliary equipment throughput are less severe than those experienced by the test engine during normal testing. However, during simulated or actual test engine flame out, transient conditions exist in all of the facility's auxiliary equipment. These transients place significant loads on the auxiliary equipment, causing rapid changes in the gas and emission characteristics of the exhaust stream of the equipment and the test engine.

Test cells capable of altitude simulating tests are used to fulfill several test requirements in the engine development cycle including: operability, cruise performance, endurance certification, and compliance to both commercial and military contracts and Federal Aviation Administration (FAA) guidelines. A description of these tests will be discussed in Section 2.3.

2.1.3 Test Stands

A test stand is a facility typically used for long-term durability testing of uninstalled aircraft engines. Test stands differ from test cells in that they are not completely enclosed and generally do not use the level of instrumentation found in test cells. Because test stands are not fully enclosed facilities, they do not experience the negative pressures found in test cells during engine operation. Test stands do not typically control the inlet flow or muffle the engine exhaust noise. Test stands do not conform to the scope of the work as defined in Chapter 1, and data were not obtained for these facilities in the NO_x inventory as described in Chapter 6.

2.1.4 Hush Houses

A hush house is a facility designed to test an engine while still installed on the aircraft. These facilities are often used in the final test of engine air worthiness.

The aircraft is moved into a facility and anchored to the floor during testing. Figure 2-7 shows a side view of an F-14A in a hush house located at the Naval Weapons Industrial Reserve Plant in Calverton, New York. Hush houses do not conform to the scope of work as described in Chapter 1, and data were not obtained on these facilities for the NO_x inventory as described in Chapter 6.

2.2 AIRCRAFT ENGINES EVALUATED IN TEST CELLS [6,7]

The majority of test cells operated in the United States are owned and operated by jet engine manufacturers and the DoD (see Section 2.4). As a result, the current population of test cells is used to evaluate a variety of turbine-based aircraft engines. Turbine-based or "jet" aircraft engines incorporate a variety of engine designs, including turbofan, turbojet, turboprop, and turboshaft configurations.

Typically, large commercial airlines use high bypass turbofan engines. Turbofan engines refer to a class of aircraft engines which derive a portion of engine thrust from the fan section of the engine, and not solely from the high velocity, high temperature exhaust exiting the turbine region of the engine. A high degree of bypass air flow is associated with an engine incorporating a large fan section, as shown in Figure 2-8. In this engine, the majority of air entering the front of the engine does not pass through the compressor blades, the combustor, or the turbine blades, but is compressed in the fan region and throttled out the back of the engine to create engine thrust. As mentioned above, the relative level of thrust obtained from the bypass air can vary. Figure 2-9 illustrates a turbofan engine with significantly less bypass air flow than the engine shown in Figure 2-8.

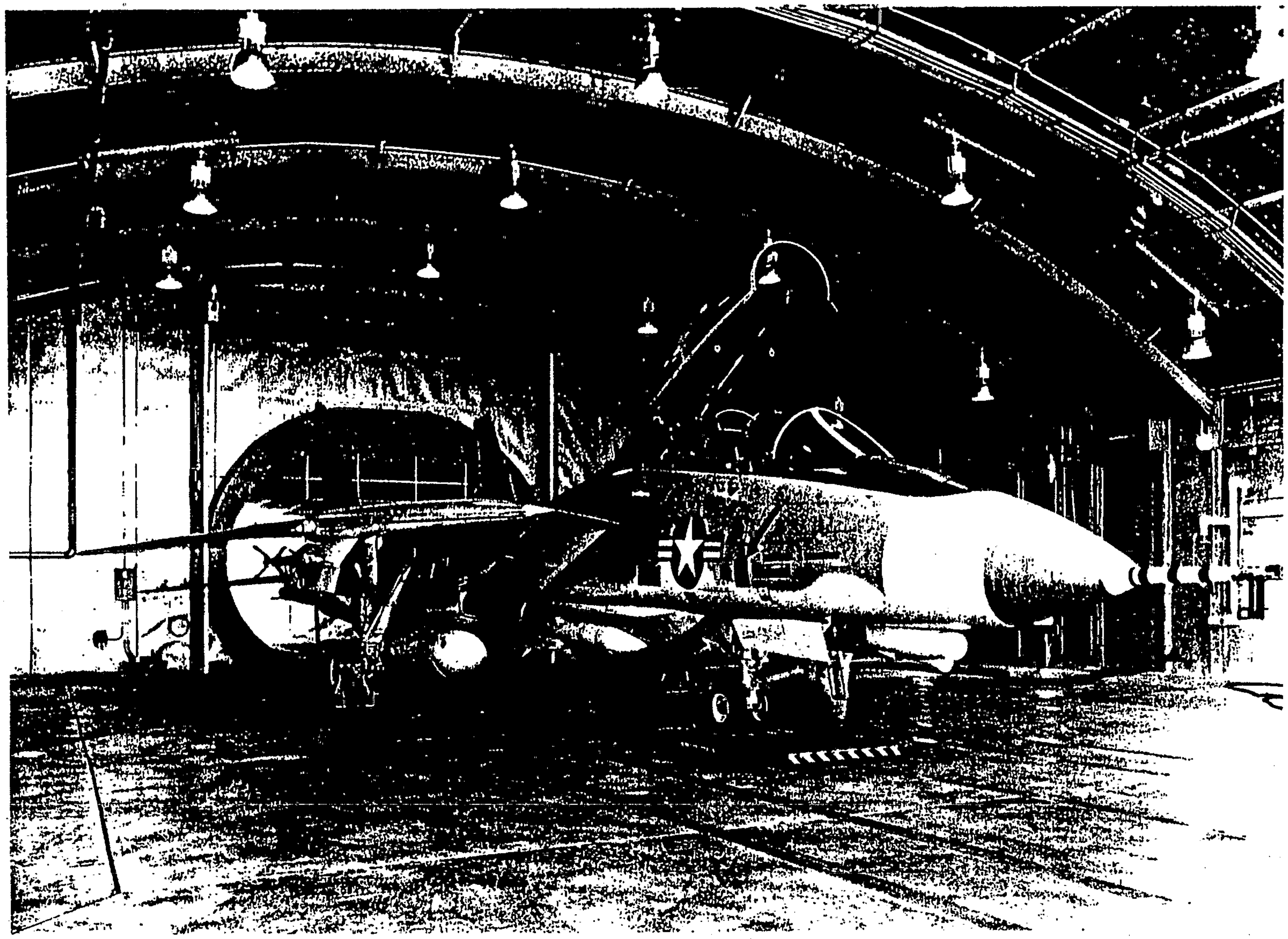

Figure 2-7. Side view of an F14A in a hush house.

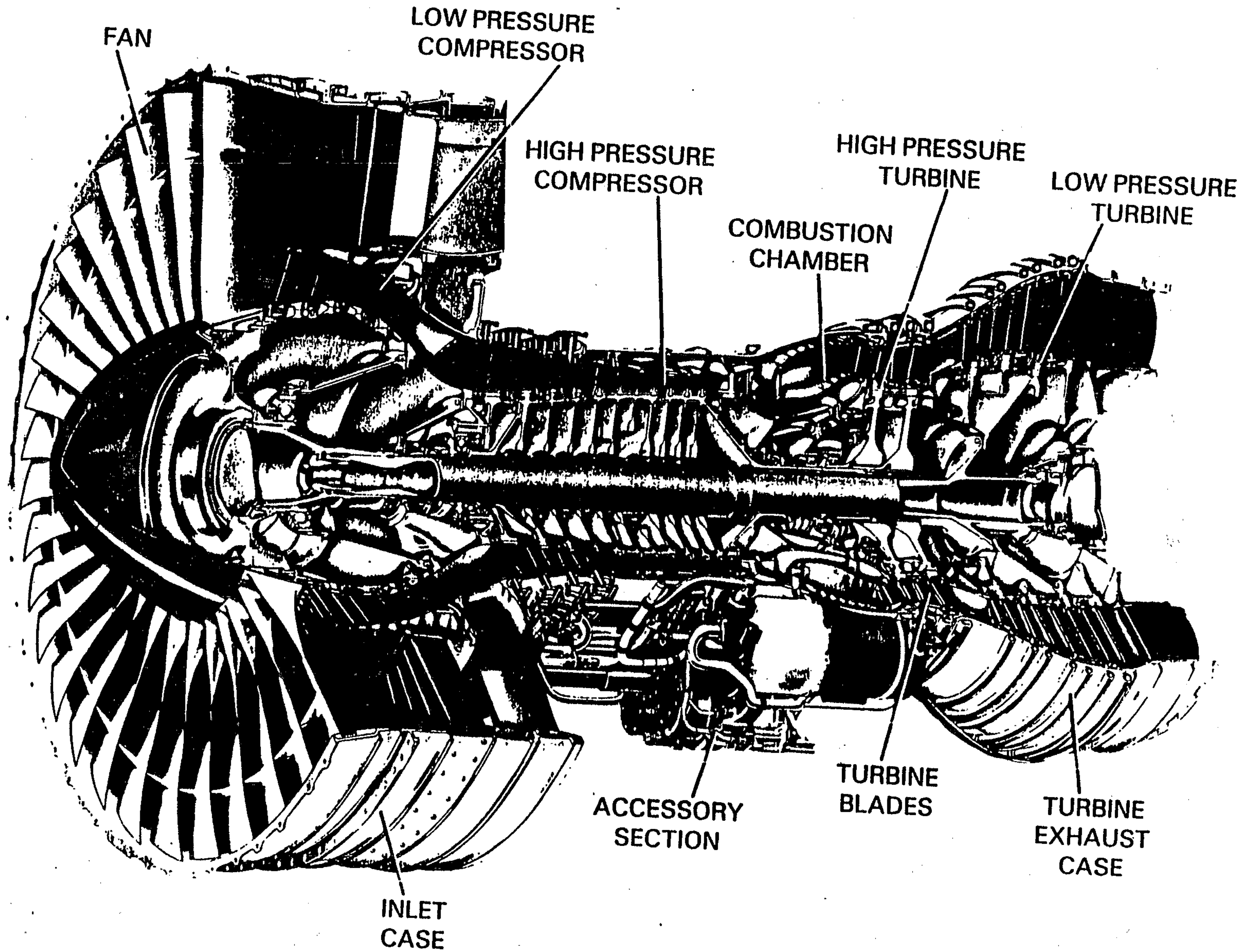

Figure 2-8. High bypass turbofan engine (PW4000 engine).

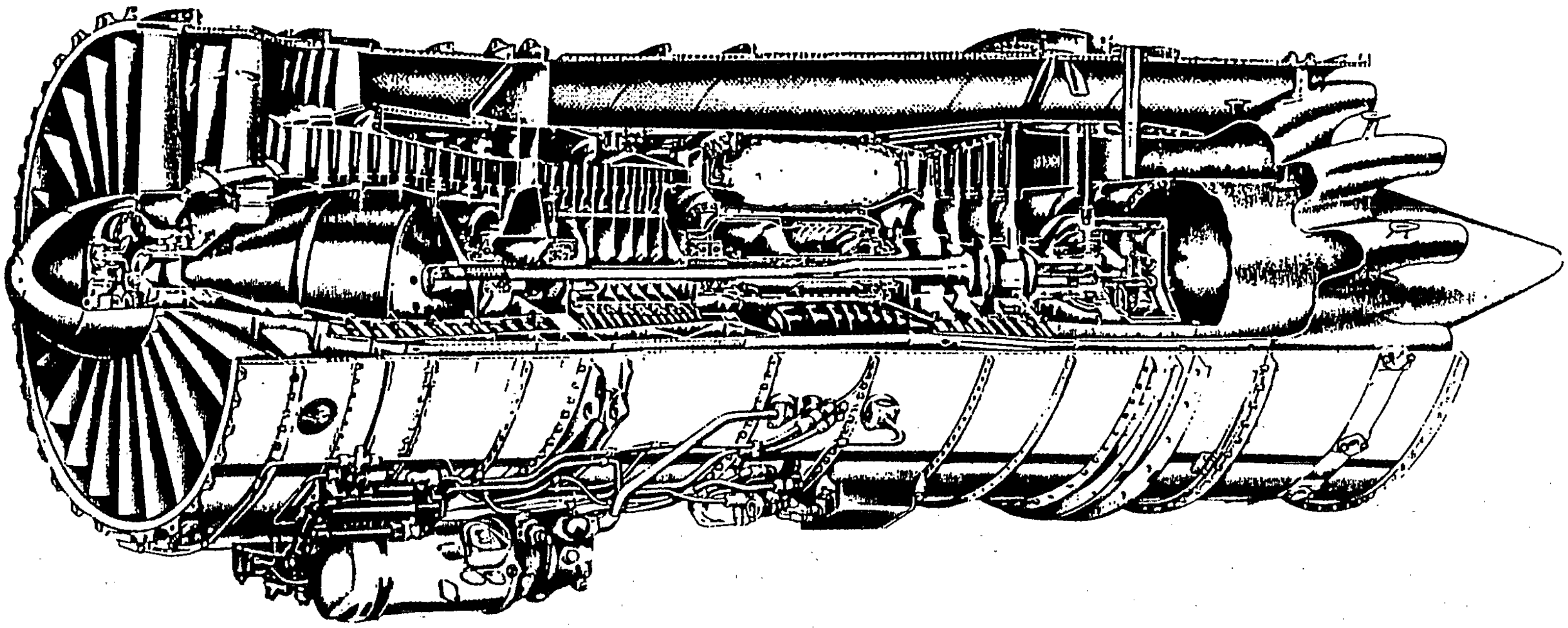

Figure 2-9. Low bypass turbofan engine (JT8D-200 turbofan engine).

A turbojet type engine is distinguished from the turbofan engine in that there is no fan region, and all of the engine thrust is derived from the high velocity, high temperature exhaust exiting the engine. However, the vast majority of "jet" engines currently in service incorporate some degree of bypass flow.

Figure 2-10 illustrates a turboprop/turboshaft type engine. The turboprop/turboshaft type aircraft engine differs fundamentally from the turbofan/turbojet style engine in that work is extracted from the exhaust by high and low pressure turbine blades to create shaft horse power. Typically, these engines are used on smaller commercial style propeller aircraft and helicopters. The primary difference between the turboshaft and turboprop engine is that the turboprop is used to power a propeller directly while the turboshaft is used to drive a gear box, which in turn powers a propeller/rotor blade.

The exhaust gas characteristics of turbofan, turbojet, turboprop/turboshaft type engines are different, and therefore the test cell exhaust gas characteristics testing these engines will be different. A high bypass, turbofan type engine significantly cools the hot turbine exhaust gas as it is mixed with the fan air. The exhaust of a turbojet type engine would not be subject to this mixing process. For turboshaft/turboprop type engines, every effort is made to extract the maximum shaft horsepower from the turbine exhaust. For test cell operation, turboshaft/turboprop engines are typically connected to a dynamometer to extract and measure the horsepower produced by the engine. Test cells testing a turboprop/turboshaft type engine would have a much lower stack gas volumetric flow rate, as well as a lower velocity, and do not typically require the augmenter associated with the turbofan/turbojet testing test cells.

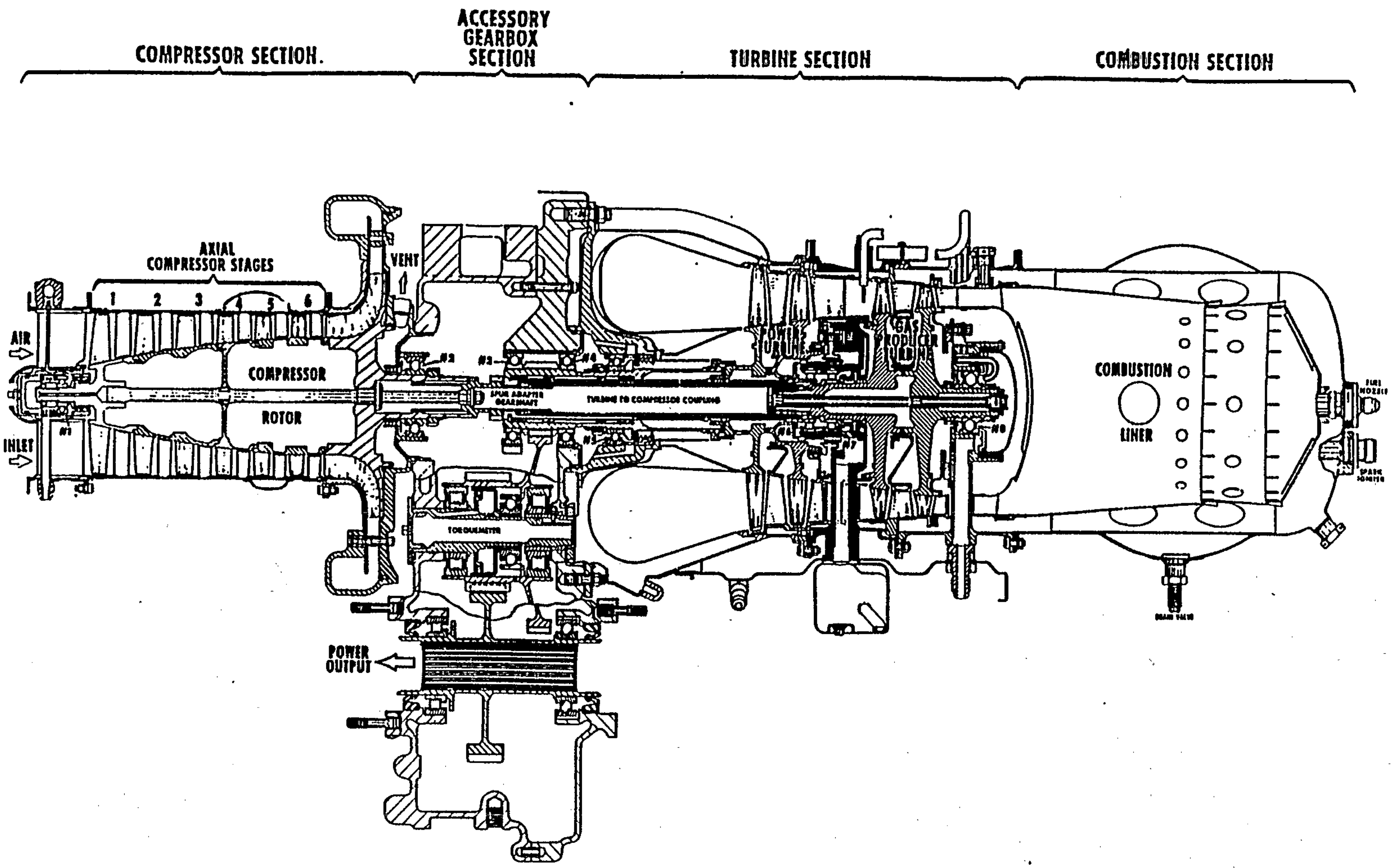

Figure 2-10. Turboprop/turboshaft type engine.

As previously described in Sections 2.1 and 2.1.1, the augmentation air cools the test cell exhaust, cools the engine, and affects test cell negative pressures. However, depending on the engine type, the minimum amount of augmentation air required for test cell operation varies significantly. Test cells testing high bypass turbofan engines can typically operate with minimum augmentation ratios around 1 (the augmentation ratio is defined as the ratio of air flowing into the test cell, but not through the engine, to the total engine inlet air flow). This is due in part to the large amount of fan air available to cool the engine. For test cells testing low bypass turbofans or turbojet engines, minimum augmentation ratios of 2 to 3 are required to provide sufficient cooling on the aft portion of the engine.[8]

2.3 TEST CELL TESTING AND TEST DESCRIPTION [9, 10, 11]

Figure 2-11 presents an engine test schedule illustrating the rapid transient nature of engine testing performed in test cells. Most owners and operators of test cells have developed their own test schedules, although engine manufacturers provide the engine owner with a suggested test program following repair. The variety of test schedules is diverse, although within many owner/operator groups the test purpose remains the same, that is, evaluation of engine performance by determining critical engine parameters. Parameters which are used to assess engine performance include but are not limited to the following: thrust, fuel flow, engine compressor and turbine rpm, and the engine pressure ratio (engine pressure ratio, epr, is the ratio of the inlet pressure and the exhaust pressure immediately behind the turbine blades). For engine manufacturers, testing involves engine development as well as basic performance evaluation.

The DoD, commercial airlines, engine manufacturers, the National Aeronautics and Space Administration (NASA), and

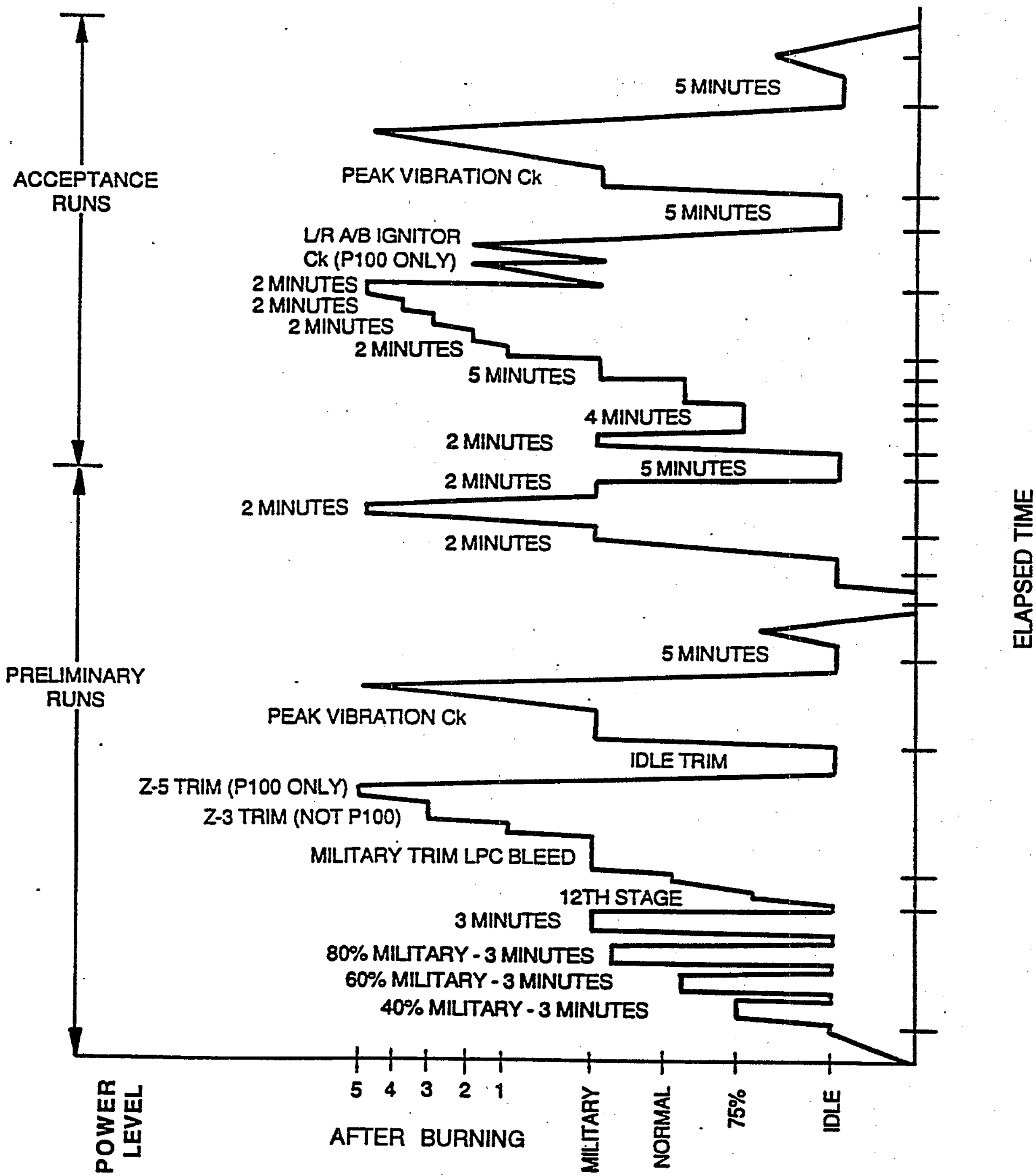

Figure 2-11. Engine test schedule illustrating how engine load varies with time during cycle.

contract repair facilities have developed test schedules to fit the purpose of the test. Although the test objective may be similar, the test schedule will be customized for the individual test cell and engine undergoing the test.

Aircraft engine testing may be categorized as development testing, production testing, and engine testing after an overhaul. Overhaul testing is performed at engine manufacturer sites, overhaul sites, government and airline owned test facilities. Production testing is done by manufacturers. Development testing is done by manufacturers and a few of the DOD facilities.

2.3.1 Development Testing

The two major types of development testing are full engine testing and component testing. Full engine development testing is performed in both altitude simulating test cells and sea level test cells. Verification of the altitude performance of the engine is critical to determine both operational safety and operating cost. Altitude simulation testing in test cells is a critical element in the engine development cycle, and testing is conducted to evaluate the following:

- Operability. These tests demonstrate the engine response to various throttle movements. Aircraft engine altitude performance and operability require design tradeoffs. These tradeoffs chosen during the engine design stage need to be verified to ensure the best possible fuel efficiency while achieving stall-free transient operation. Because this testing requires rapid transients to verify the engine's stall-free characteristics, this type of testing places the most demands on the altitude simulating test cell.

- Cruise performance. Engine manufacturers typically guarantee fuel efficiency to their customers, and therefore, they include a verification of that performance element as part of the altitude test process. This is not just a single demonstration test, but rather a series of back-to-back tests. These tests evaluate various design configurations throughout the multi-year engine development cycle to ultimately end up with the best engine configuration to provide to the customer at certification.

- Endurance certification. There are several altitude endurance tests required of engine manufacturers to verify engine operation at maximum continuous power for up to 45 hours. These tests are typically conducted once during the development of a new engine model.

- Compliance. This special altitude test is sometimes included in military and commercial contracts. It is a one-time test conducted on one production engine configuration. Test results can be used in negotiations for any subsequent engine warranty claims.

Sea level development testing is performed in both open and enclosed test cells. The following is a description of the tests performed in a sea level test cell for development testing:

- Operability. These tests are similar to the altitude operability test in that they are used to verify engine compression system stability during rapid throttle transient. On a particular engine model, this testing is usually conducted at sea level before altitude due to relatively lower costs. Once a particular configuration is chosen that is best at sea level, it is then verified at altitude.

- Performance. Some performance testing can also be accomplished at sea level, particularly during configuration optimization testing. Verification is then done at altitude.

- Endurance. Virtually all endurance testing is done at sea level. This testing is done for various purposes but, in general, it is done to accumulate operating time and heat cycles on the engine and all its components to assess durability. One particular version of endurance, called Initial Maintenance Interval (IMI), is conducted to determine appropriate engine operating intervals prior to maintenance for the production engines once they are out in the airline fleet.

- Certification. There are many tests conducted as part of the engine certification process, including determination of maximum rotor speeds, blade out, water ingestion, bird strikes, emissions and a 150-hour engine run. In order to obtain FAA or DoD certification, each of these tests must be successfully completed.

2.3.2 Production/Overhaul Testing

Production testing is almost always related to the verification that is done on each and every production engine built by the manufacturer. Each aircraft engine makes at least one production test run, typically 4 to 6 hours in length. Successful completion of these tests results in the engine's readiness for shipment to the customer. Engines manufactured early in the production run of a new engine model go through two engine tests, with substantial engine teardown between each. As engine maturity is demonstrated, audit levels are reduced so that only one test run is required if all other conditions are met.

Overhaul testing is virtually the same as production testing, except that it is conducted on an engine after it has been in service and has just completed a major overhaul or repair. These tests are conducted to determine if the engine performance is back to pre-overhaul limits so that it can be re-installed for fleet operation. This testing may be done at manufacturers' facilities or at overhaul shops owned by the airlines, the government, or private repair facilities. Figure 2-12 presents a typical production run engine test schedule.

Within the categories of production and overhaul engine testing, specific tests are completed in test cells to achieve the owner/operator goals. These engine test programs can be categorized as endurance, performance and special.

- Endurance. As mentioned previously, endurance tests are done to demonstrate engine reliability. Most endurance tests are done in sea level facilities and usually incorporate engine thermal cycling. Typically, cycles consist of allowing the engine to cool for several minutes at idle, making a rapid throttle change up to take-off power, and remaining there for several minutes before rapidly returning to idle power. Although there are many variations in cycle detail, all of the engine test cycles of this kind are designed to simulate some portion of

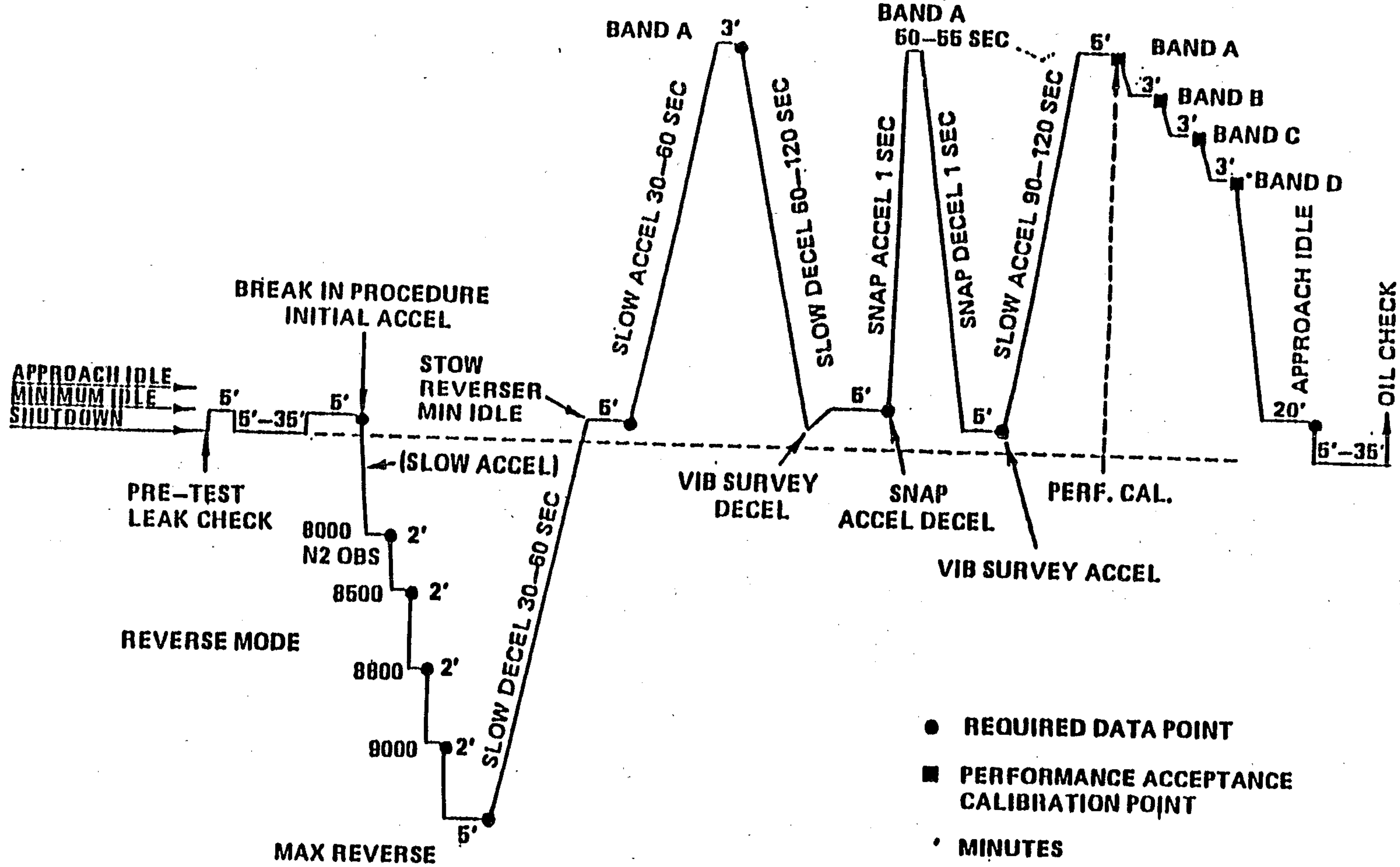

Figure 2-12. Typical production run engine test schedule (power level vs. time).

an engine's expected service life. Recent trends, aimed at providing a mature propulsion package at fleet introduction, include testing of the entire engine over the spectrum of expected operating conditions. This attention to detail during the development process can reduce the number of "nuisance" problems traditionally experienced when a new aircraft engine is introduced into the fleet.

Figure 2-13 presents an example of an endurance engine test cycle.

- Performance. Engine performance testing is conducted both at altitude and sea level facilities. Its purpose is to demonstrate the performance of the engine or its sub-components, or to demonstrate the relative performance of one engine configuration to another. This testing is done at sea level where possible and at altitude if necessary.

- Special. There are several types of special tests including ice ingestion, water ingestion, and bird ingestion where engine reliability is demonstrated during simulated events which may occur later during the engine's service. These tests are performed in sea level facilities. Other specialty tests include "blade out" (a fan blade failure during take-off mode to ensure airplane safety), hot fuel, cold fuel, hot oil, and altitude restarts.

2.4 OWNER/OPERATOR PROFILE

The DoD uses both altitude simulating test cells and sea level test cells to conduct a variety of tests. DoD facilities, primarily Navy and Air Force Bases, conduct some

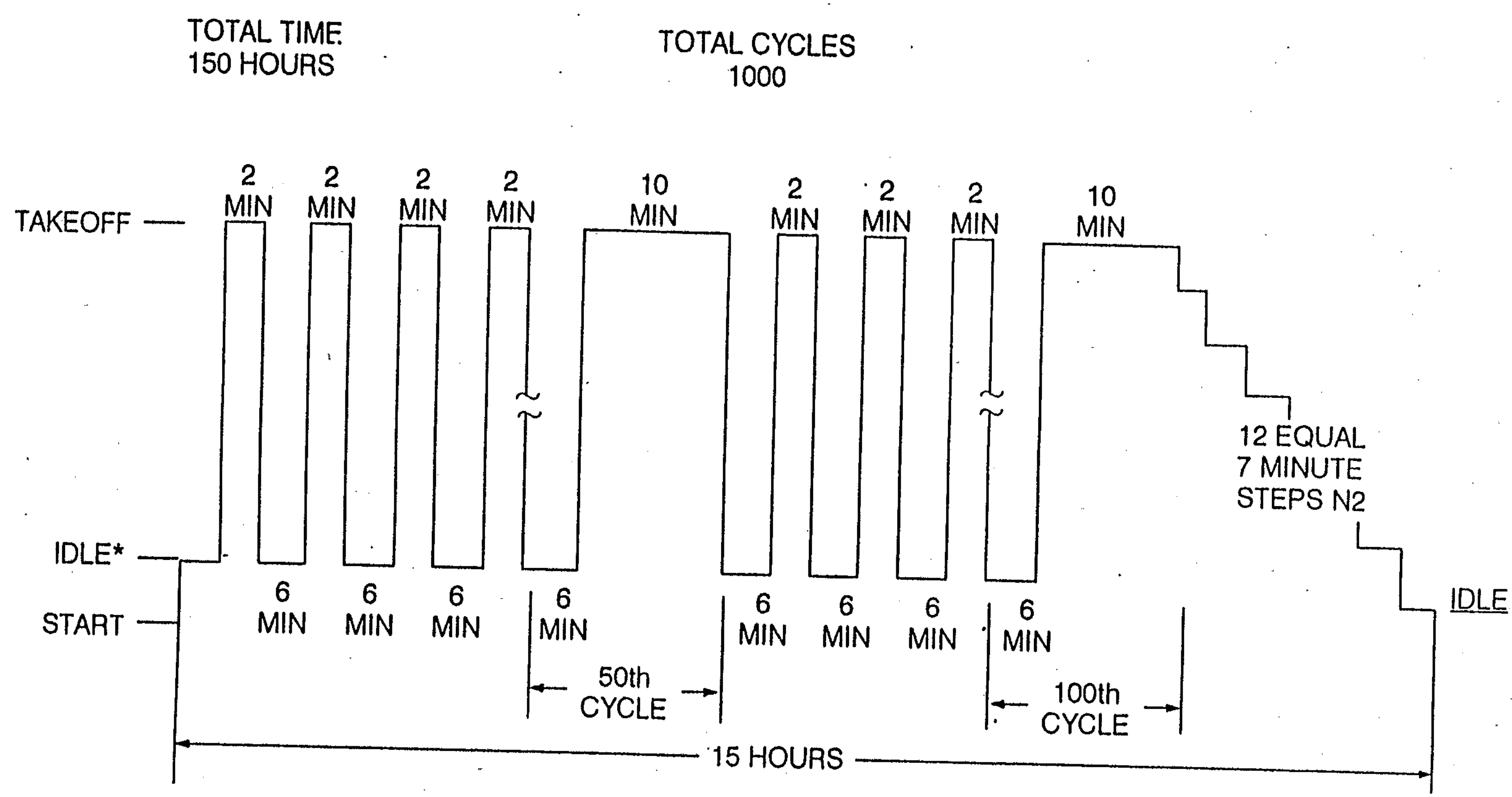

Figure 2-13. Endurance engine test cycle.

levels of development testing, including altitude simulating developmental testing. The DoD also performs overhaul testing at many facilities across the United States. The DoD conducts endurance tests and performance tests in both altitude simulating and sea level test cells. The DoD has established a hierarchial structure to conduct engine repair and testing to maintain fleet readiness. For example, the Navy has a repair and maintenance hierarchy to maintain fleet readiness consisting of three levels (operational, intermediate, and depot).

The operational ("O") level maintenance is performed by an operating unit (squadron) on a day-to-day basis. This maintenance is performed to keep assigned aircraft, engines, and systems in a fully mission ready status. The engine maintenance performed at the "O" level is limited to removal and installation of quick engine change gear (QEC). This type of maintenance does not require engine verification using a test cell, although it might require an engine run-up while installed on the aircraft.

Intermediate ("I") level maintenance is performed at designated locations to support a group of operational units. The "I" level mission is to enhance and sustain the combat readiness of the supported activities (squadrons). Maintenance at this level is performed to a greater depth than the "O" level, and is performed both on and off aircraft. Maintenance at the "I" level is most often limited to hot section repair (turbine and combustor(s)). At the "I" level, engine certification is most often conducted using a test cell, however, it may also be done using an open-air test stand.

Maintenance at the depot "D" level consists of all "O" and "I" level activities as well as cold section repair (compressor section). Although the work done at the "I" level is not of the same complexity as work done at the depot level, both require engine verification. Due to the depth of maintenance, all depot type repairs and overhauls require full engine performance verification using test cells. The operation and use of test cells are a major part of the depot level of effort. Thirty percent of the DoD test cells are on this tier of the organizational hierarchy. These test cells are used for both routine maintenance to major overhaul engine verifications and air worthiness determinations. The test cells are required at depots to run a thorough analysis of the engine before it is returned to fleet service.

Commercial airline use of test cells consists of the same level of maintenance and repair as the depot level of the Navy test cells. The commercial airlines' purpose for testing is primarily air worthiness determination, engine safety performance guarantees, and fuel efficiency. Airlines routinely disassemble an engine to its individual components for repair and maintenance. Test cells are then used to determine that the post-maintenance engine performance capabilities are similar to the pre-maintenance performance capabilities. Commercial airlines use only sea level test cells to test the engines and will contract any altitude simulating testing that may be necessary to a capable facility. Specifically, commercial airlines perform sea level testing and overhaul testing and use endurance and performance tests as described above.

The aircraft engine manufacturers use both sea level and altitude simulating test cells. The manufacturers are the only owner/operator group that performs all testing and conducts all tests mentioned above. Production testing is solely performed by engine manufacturers as are most specialized tests.

The National Aeronautics and Space Administration (NASA) provides the aeronautic community with testing and evaluation capability in support of their research and technology charter. The test cells operated by NASA are used for performance evaluation, component development/evaluation, qualification tests, endurance tests, and technology development.

Independent contract repair facilities use test cells in the same manner as the commercial airlines. These facilities perform sea level overhaul testing and conduct the endurance and performance tests for engine certification following major engine maintenance. These facilities do not have altitude simulating test cell capabilities.

2.4.1 Test Cell Population Distribution

Table 2-1 provides the distribution of sea level and altitude simulation capable test cells by owner/operator category. This information was compiled from test cell users to estimate the NO_x emissions from test cells. Based on the results, there is a total of 368 test cells operated in the United States. The DoD and the engine manufacturers operate the largest number of test cells at 50 percent and 40 percent of the current test cell population, respectively. The Air Force operates 62 percent of the DoD-owned test cells.

2.5 SUMMARY

There are 368 test cells operated in the United States. These facilities are owned and operated by the aircraft engine manufacturers, DoD, commercial airlines, contract repair organizations, and NASA. Test cells are used primarily for aircraft engine developmental testing and air worthiness assessment following engine repair. Test cell exhaust gas

TABLE 2-1. DISTRIBUTION OF SEA LEVEL AND ALTITUDE SIMULATING TEST CELLS BY OWNER/OPERATOR CATEGORY *

Owner/ Operator	Sea Level Test Cell	Altitude Simulating Test Cell	Totals
Commercial Airlines	13	0	13
DoD, Total	{169}	{14}	{183}
Navy	57	0	57
Army/Air Force	112	14	126
Aircraft Engine Manufacturers	129	19	148
NASA	1	2	3
Contract Repair Facilities	21	0	21
Total	**333**	**35**	**368**

* *This table represents a summary of information provided by test cell owners/operators, 1993.*

characteristics are controlled by test cell design and operation of the engine tested within the test cell, and the test schedule used in the engine test program. Engine test programs are typically transient in nature, with many rapid swings in engine throttle position. These engine transients are accompanied by rapid fluctuations in engine air flow rates, exhaust gas temperatures, and NO_x emissions.

Altitude simulating capable test cells are facilities which are capable of independently controlling the inlet air temperature and pressures both upstream and downstream of the test engine. These test cells are typically large complex facilities with many subsystems operating in concert with the engine test schedule. Altitude simulating capable test cells are primarily used by the DoD and engine manufacturers and represent approximately 10 percent of the total test cell population within the United States.

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6. Pratt & Whitney. Figures 2-8 and 2-9, cutaway views of Pratt & Whitney aircraft engines, provided to the EPA.

7. Letter from Spratt, J.J. Allison Gas Turbine Division of General Motors Corporation, to Donaldson, G.C., EER Corporation. June 4, 1993. In response to a request for a cross-sectional view of a turboprop/turboshaft engine.

8. Meeting minutes. Representatives from the Aerospace Industries Association, Department of Defense, Federal Aviation Administration, EPA, and EER. February 3, 1994. Discussion of technical aspects of and industry concerns with the Report to Congress.

9. Letter from Dimmock, R.L.,Pratt & Whitney, to Wood, J.P, EPA/ESD. October 19, 1992. Discussion of test cell operation descriptions.

10. Johnson, S.A., and C.B. Katz (PSI Technology Company). Feasibility of Reburning for Controlling NO_x Emissions from Air Force Jet Engine Test Cells. Prepared for Air Force Engineering & Services Center. Tyndall AFB, FL. ESL-TR-89-33. June 1989. p 8.

11. Letter from Rountree, G., Aerospace Industries Association, to Wood, J.P., EPA/ESD. March 13, 1993. Aerospace Industries. Association information on test cells used by member companies.

CHAPTER 3
MODEL TEST CELL DEVELOPMENT

3.1 OVERVIEW

Given that it is conceptually possible to apply NO_x control technologies examined in this study to aircraft engine test cells, the technical feasibility and cost of implementing the NO_x controls depend on the pollutant concentrations, gas mass flow rates, gas flow velocities, and gas temperatures downstream of the engine tested within the test cell. The NO_x mass emissions from a specific test cell for a particular test are determined solely by the aircraft engine under evaluation and the test cycle used to evaluate the engine. The test cell itself does not contribute to the NO_x mass emissions. The stack pollutant concentrations, gas flow rates, gas velocities, and gas temperatures downstream of the engine are determined by the specific engine and test program, as well as the volume of the air entrained though the test cell. As discussed in Chapter 2, the volume of air entrained through the test cell is governed in part by the engine and setup of the engine within the test cell, as well as the design and operation of the test cell itself. Adjusting the stack gas to a fixed percentage oxygen level (15 percent, for example) corrects for the dilution effect of the entrained air and allows for direct comparison of test cell exhaust characteristics; however, both total gas volume flow and stack gas exit temperatures are significantly affected by the entrained air.

The EPA has compiled the emission characteristics for a wide variety of stationary sources,[1] including boilers, heaters, and most other fossil fuel-fired combustion systems. This body of data is compiled from measured stack test data and can be readily categorized according to a variety of basic parameters, including the type of fuel burned and the basic operating characteristics of the source. For test cells, the wide range of current engines that can be tested in an individual cell, the ongoing development of new engines to be tested, and the variety of engine evaluations required to meet the test goals preclude this type of characterization. Additionally, stack emission measurements from test cells are not routinely made. Therefore, measured test cell stack data are not widely available to reliably characterize the NO_x emissions of a particular class of test cells.

This chapter describes the development of five model test cells which are used to estimate the stack exit temperatures, flow rates, and NO_x concentrations necessary to evaluate the feasibility and cost of implementing NO_x controls to a large portion of the current test cell population. The five model plants are divided into two main categories according to the type of engine tested: turbojet/turbofan test capable test cells and turboshaft/turboprop test capable test cells. As discussed in Chapter 2, these engines are primarily differentiated by the energy in the exhaust gas. Measured engine emission data are combined with models of the temperature rise across the engine and air flow through the test cell to predict the stack gas conditions. As will be discussed in Chapter 6, test cells testing these two classes of engines contribute the majority of NO_x emissions from the current population of test cells in the United States.

The stack gas conditions predicted using the model test cell analysis are supplemented with detailed velocity, temperature, and NO_x concentration data measured in the exhaust stream of a test cell testing a military engine. These measured data provide additional information regarding the characteristics of the exhaust gas stream that can impact the feasibility and cost of implementing NO_x controls. Additionally, these measured data are used to verify the temperature estimates obtained from the model test cell analysis.

3.2 AIRCRAFT ENGINE EMISSION FACTORS

Aircraft engine NO_x emission factors for a large portion of the existing engine population have been documented.[2] Typically, these emission factors are expressed in units of pounds of NO_x per 1,000 pounds fuel consumed and are determined at several thrust levels. Generally, the emission factors are determined by the engine manufacturers and the DOD using core flow measurements (with probes located immediately behind the engine exhaust), and detailed guidelines for their determination exist.[3] The body of emission factor data for military service engines is less well developed, although databases have been developed and many of the more common engines in service have been characterized.[4, 5]

Table 3-1 presents a typical emission factor summary. Several features of jet engine emissions (and therefore test cell emissions) are displayed in this sheet. NO_x emissions for this particular engine range from a low of 2.38 lbs/NO_x per 1,000 lbs fuel at idle to a high of 12.32 lbs/NO_x per 1,000 lbs fuel at full military power (maximum thrust). Over this same range, fuel consumption increases from 779 lbs/hour to 9,479 lbs/hour. These values can be combined to compute the mass emission rate of NO_x per hour of operation. At idle, this engine produces approximately 1.85 lbs NO_x per hour; at military power, NO_x is produced at a rate of approximately 116.8 lbs/hour. This significant range in emission output illustrates the impact that the test cycle used in the engine

TABLE 3-1. EXAMPLE OF GASEOUS EMISSIONS TABLE FROM AN AESO DOCUMENT FOR THE J52-P-408 ENGINE

Power setting	Carbon monoxide measured, ppm	Carbon dioxide measured, %	Oxides of nitrogen measured, ppm, NO_x	NO	Hydrocarbons measured, ppm	Oxygen % meas.	calc.
Idle	361.98	1.24	9.39	9.20	320.00	-	-
Intermediate 1	92.59	1.68	31.29	28.17	20.40	-	-
Intermediate 2	44.27	2.82	71.08	67.23	16.30	-	-
Normal	31.59	3.28	101.70	99.11	17.40	-	-
Military	26.88	3.70	137.18	137.18	18.20	-	-

Power setting	Fuel flow, lb/hr	Thrust, lb	Speed, rpm	Emission index, lb/1000 lb of fuel CO	CO_2	NO_x	Hydrocarbons
Idle	779	548	-	55.96	3018	2.38	28.33
Intermediate 1	2547	3420	-	11.12	3162	6.17	1.40
Intermediate 2	5752	7629	-	3.18	3177	8.38	0.67
Normal	8078	10142	-	1.95	3179	10.29	0.61
Military	9479	11349	-	1.47	3180	12.32	0.57

Power setting	Oxides of nitrogen, corrected to 3% oxygen, ppm, meas.	calc.	Emissions, pounds per hour CO	CO_2	NO_2	Hydrocarbons	Combustion efficiency, %	F/A
Idle	-	-	43.6	2351	1.86	22.07	-	0.006
Intermediate 1	-	-	28.3	8054	15.71	3.57	-	0.008
Intermediate 2	-	-	18.3	18272	48.21	3.85	-	0.014
Normal	-	-	15.7	25678	83.13	4.96	-	0.016
Military	-	-	13.9	30104	116.76	5.40	-	0.018

NOTE: values in this table are taken from Scott Env. Tech., Individual Engine Test & Model Summary Reports, Mod. 6, Alameda Testing, USAF Contract F29601-75-C-46, October 20, 1976.

evaluation can have on both the instantaneous and total stack emissions during the test.

Test cell stack NO_x concentrations when corrected to a fixed percentage oxygen level are determined solely by the engine under test. Engine NO_x emission rates (per pound of fuel consumed) combined with the fuel consumption rate determine these NO_x levels. Observed NO_x concentrations and test cell stack oxygen levels (in the absence of additional cooling air) are a function of the engine mass emission rate, as well as the air flow through the engine. As discussed in Chapter 2, two types of engine air exist: combustion air and bypass air. The combustion air flow through the engine can be determined from the fuel rate and the fuel-to-air ratio at the given thrust level. The bypass air passes through the front of the engine, is compressed, but is bypassed around the combustor. Depending on the specific engine design, these gas streams will begin mixing either downstream of the engine or just before exiting the engine. Most modern jet engines incorporate some degree of bypass air flow. For military turbofan engines, typical bypass ratios are between 1 and 2. For large civilian transport applications, high bypass ratio turbofan engines are used with up to 6 volumes of air entering the front of the engine for every 1 volume of air used in combustion of the fuel. The NO_x concentration exiting the combustor is diluted by the bypass air flow. In typical test cell operations, the gas is further diluted by the additional air entrained through the test cells by the high velocity engine exhaust. Although the dilution air will increase stack oxygen levels and reduce observed stack NO_x concentrations, the NO_x mass emission rate does not change.

3.3 TURBOFAN/TURBOJET MODEL TEST CELL DESCRIPTION

Four model test cells have been developed to assist in both the technical and cost assessment of implementing NO_x

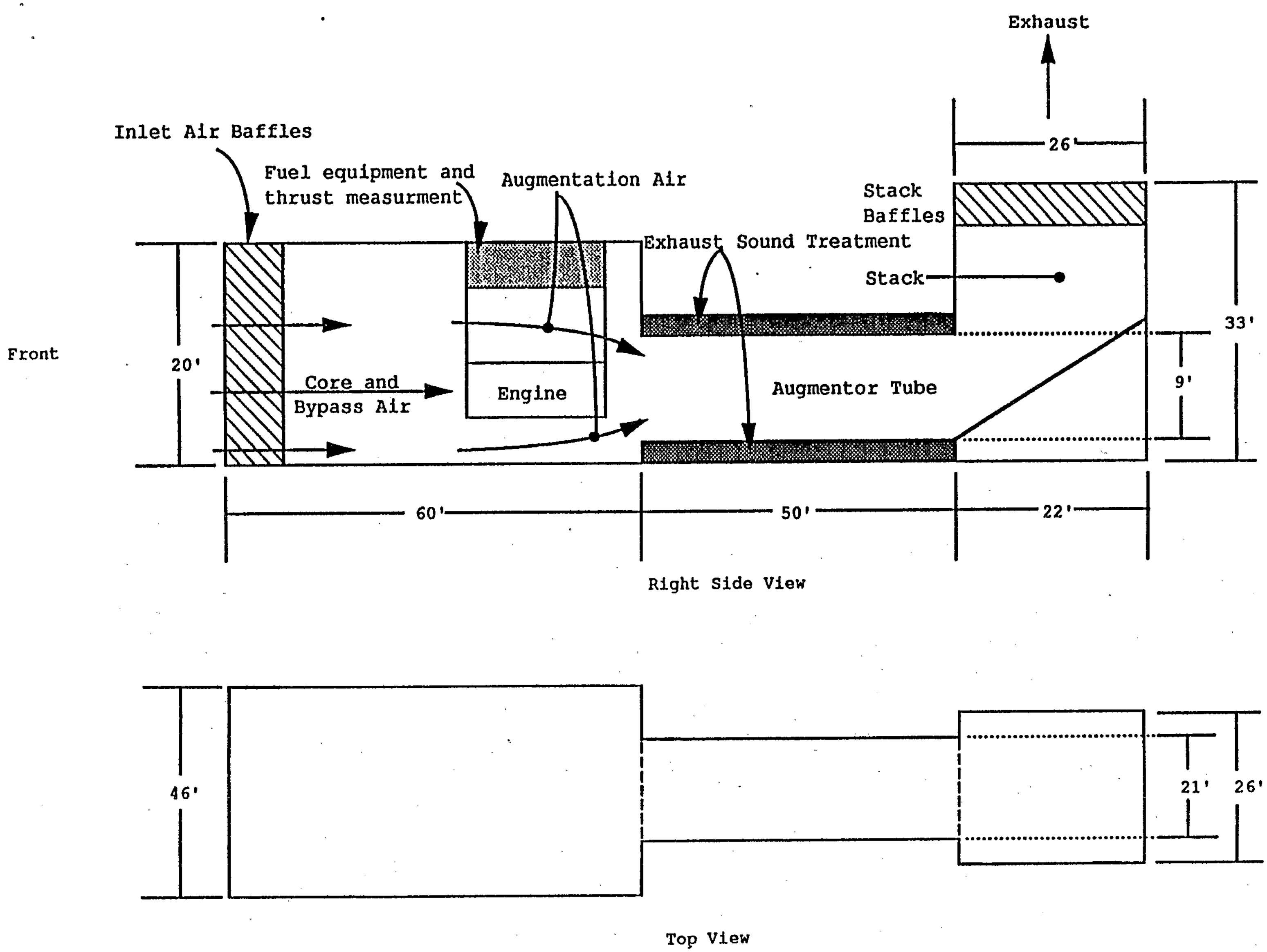

Figure 3-1. Schematic of turbofan/turbojet model test cell (relative dimensions for Model B Test Cell).

controls for test cells capable of testing turbofan and turbojet type engines. Figure 3-1 presents a schematic diagram of these model test cells. Although the specific dimensions will vary with design, the dimensions shown in Figure 3-1 are associated with a test cell which has a maximum thrust capacity of 20,000 lbs. For each model test cell, the independent parameter in the analysis is the augmentation air ratio associated with the operation of the test cell. As discussed in Chapter 2, the augmentation ratio is defined as the ratio of air flowing into the test cell but not through the engine to the total engine inlet air flow. In actual test cell operation, the augmentation ratio will vary with thrust setting and critically impacts the accuracy of the thrust measurements, as well as the negative pressures experienced in the test cell. In order to simplify the model test cell calculations, the augmentation ratio is held constant (independent of thrust). However, the sensitivity of the predicted test cell stack exit conditions to changes in augmentation ratio is determined by varying the augmentation ratio from 1 to 10.

The four individual air-cooled model test cells are distinguished primarily by the maximum thrust capacity of the test cell. In the model test cell development, the maximum thrust, fuel flow, pollutant emissions, engine air flow, and engine exit temperature are prescribed by the engine selected for each of the model plants. The aircraft engines selected for all of the model test cells are either turbofans or turbojets and span the thrust ranges and engine types of the current population of engines in service. The engines selected for each of the individual model test cells are as follows:

Model Test Cell (A): This model test cell uses the CF6-80A2 turbofan engine used in the Boeing B-767-200 with a maximum thrust level of approximately 48,000 lbs.

Model Test Cell (B): This model test cell uses the F101DFE used as the model for the present F-16 Falcon engine with a maximum thrust of approximately 15,000 lbs.

Model Test Cell (C): This model test cell uses the J79-GE-10B turbojet engine, an afterburning engine with a maximum thrust of 17,000 lbs used in the F4 Phantom. This test cell is distinguished by the significant increase in engine exhaust temperature associated with the injection of raw fuel (afterburning) into the exhaust of the engine. This has the effect of significantly increasing engine thrust, and is used solely on military aircraft engines.

Model Test Cell (D): This model test cell uses the J52-P-6B turbofan which is currently used in the A-4 Skyhawk with a maximum thrust of approximately 8,500 lbs.

Engine data, including emission factors, fuel flow, and air-to-fuel ratio, were obtained from an AESO document for the F101DFE, J79-GE-10B, and the J52-P-6B engines.[6] Engine data for the CF6-80A2 were obtained from the FAA/International Civil Aviation Organization (ICAO) database.[2]

Table 3-2 summarizes the power schedule used in the model test cells required to estimate the total NO_x emissions. Where engine emission data were not available at the exact intermediate settings, values at thrust settings closest to 30 percent and 80 percent of maximum power were selected. For Model Test Cell (C), the power schedule is slightly different. Five percent of the time the engine is operated in afterburner mode, and 20 percent of the time the engine is operated at the 80 percent thrust level while the other levels remain the same.

TABLE 3-2. MODEL TEST CELL POWER SCHEDULE

Percent Maximum Thrust (%)	Percent time at Thrust Setting (%)
100	25
80	25
30	20
idle (3-5%)	30

The engine core exit gas temperatures for each of the model test cells are estimated using Equation 3-1. The development of this equation is provided in Appendix A.

$$tc = ta + 1/Cp\ (LHV*FA - 1/2*(Tc/Mc)^2) \qquad \text{Eq. 3-1}$$

where:

tc: engine core exhaust temperature (°F)
ta: atmospheric temperature (°F)
Cp: heat capacity (BTU/lb °F)
FA: fuel-to-air ratio (lb fuel/lb air)
Mc: core air mass flow rate (lbs/sec)
Tc: core thrust (lb_F)
LHV: jet A lower heating value (18,500 BTU/lb)[7]

Figure 3-2 presents the computed engine core exhaust temperatures for the model test cells at the various thrust settings. During an observed test of a CF6-80-A2 at a thrust setting of 100 percent, a core exit temperature of 1,440°F was measured.[8] Using Equation 3-1 and the engine specific parameters, a core exhaust temperature of 1,423°F is predicted.

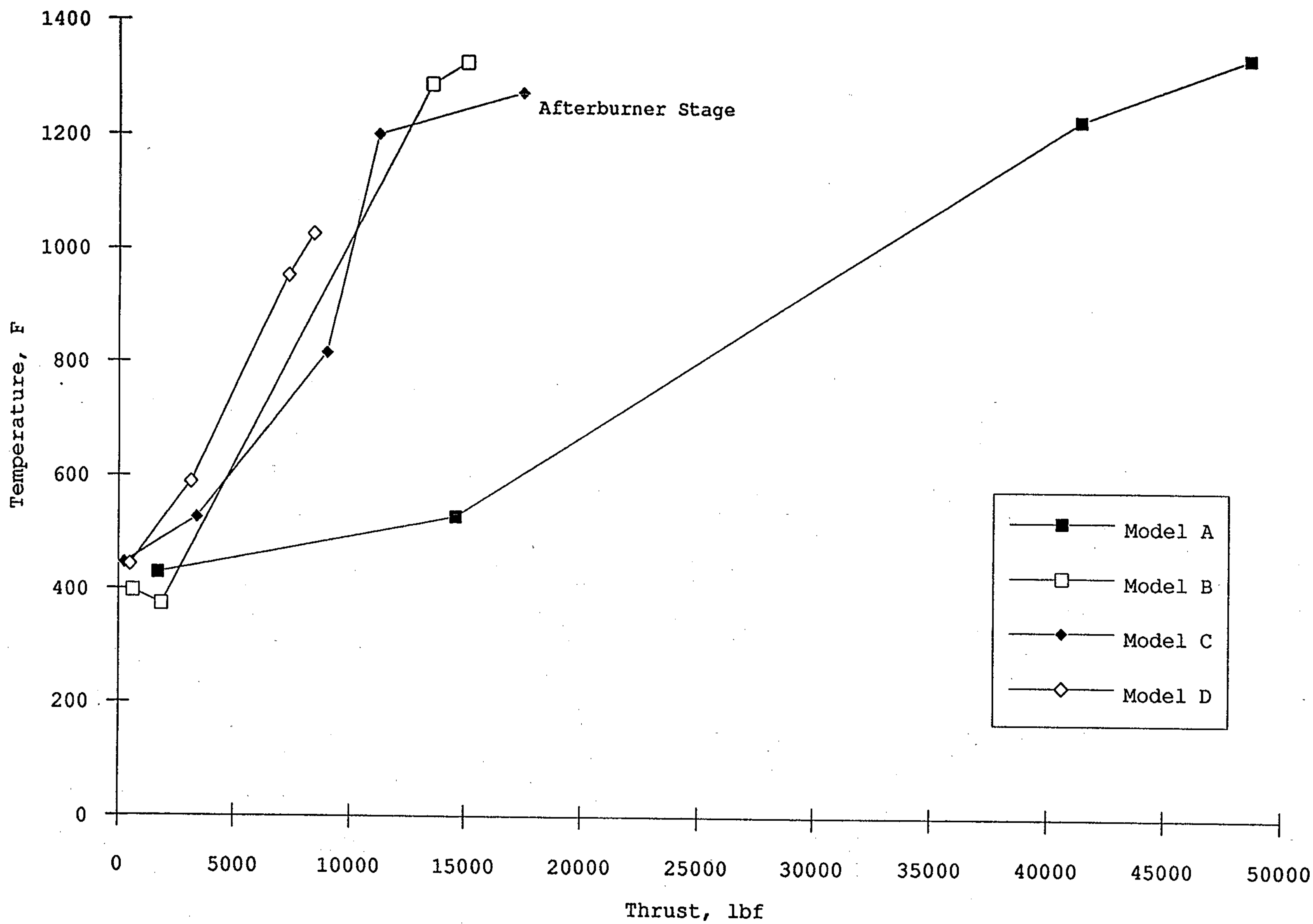

Figure 3-2. Predicted engine core exhaust temperature vs. core thrust by engine.

The engine core exhaust gas is cooled as it is mixed with both the bypass engine air stream and the entrained augmentation air stream. Equation 3-2 is used to predict the fully mixed stack gas temperature.

$$tstack = (tc + BR*tb + (1 + BR)*AR*ta)/(1 + BR+(1 + BR)*AR) \quad \text{Eq. 3-2}$$

where:

tstack: fully mixed stack gas temperature (°F)
tc: engine core exhaust temperature (°F)
BR: engine bypass ratio
tb: bypass flow gas temperature (°F)
ta: atmospheric temperature (°F)
AR: test cell augmentation ratio

Figure 3-3 presents the predicted stack gas temperatures for the model test cells operating the engines at the prescribed throttle settings at an augmentation ratio of 5. Using a complete set of data acquired for a J79-GE-10B,[9] the stack exit temperature using Equations 3-1 and 3-2 and an augmentation ratio of 2 is predicted to be 413°F at 100 percent thrust. Actual test data recorded a stack exit temperature for a J79-GE-10B engine of 413°F in an older model test cell that operates with an augmentation ratio of nearly 2. The current model neglects any heat transfer to the surroundings and assumes constant, temperature-independent heat capacity values. Despite these simplifications, the agreement between the measured and predicted temperatures is quite good and is considered sufficient for the technical and cost assessments to be presented in Chapters 4 and 5.

The effect of augmentation air (the independent model parameter) on stack gas temperatures is presented in Figure 3-4. A significant drop in the stack gas temperature occurs

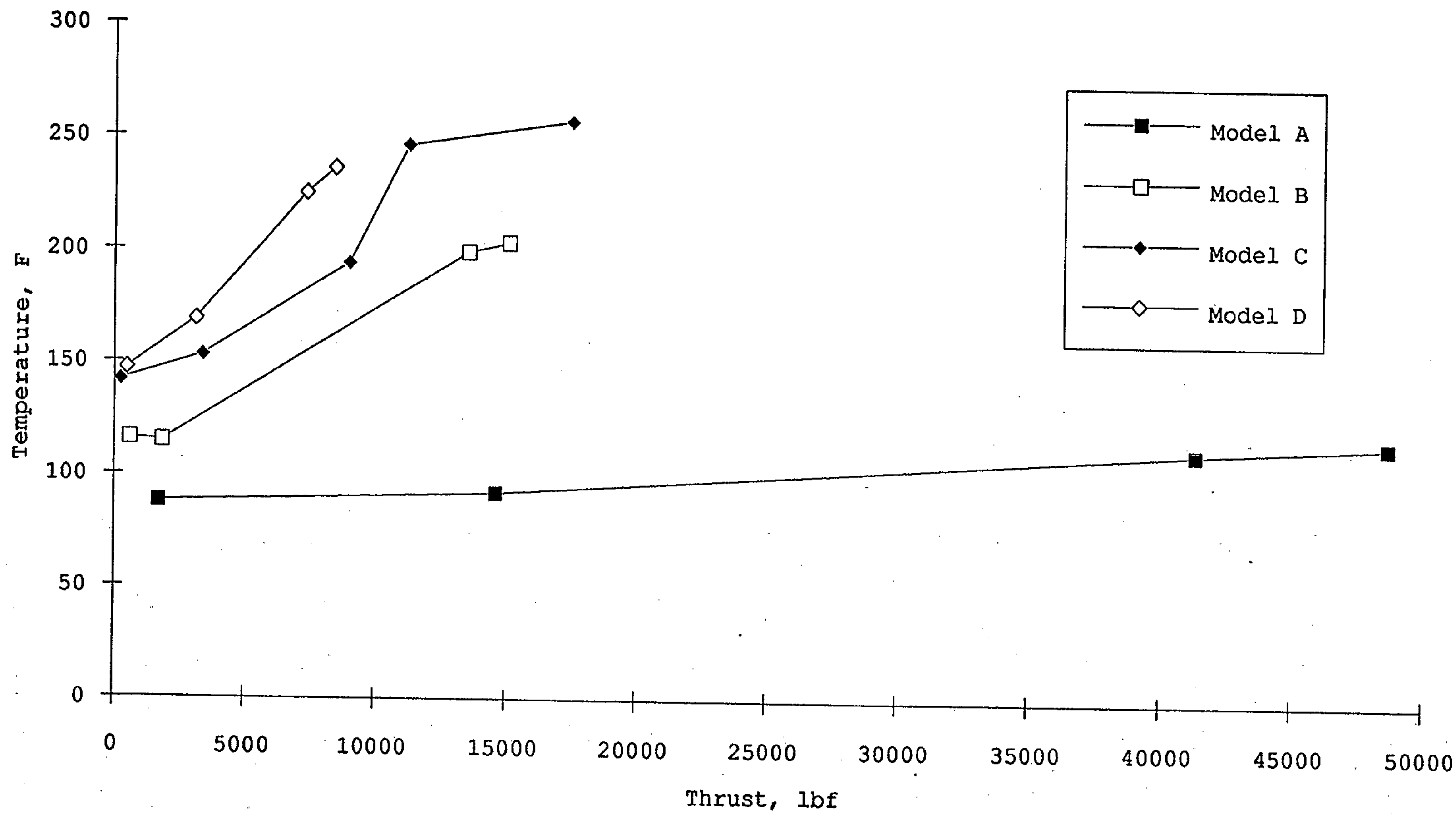

Figure 3-3. Predicted stack gas temperature vs. thrust (augmentation ratio = 5.0).

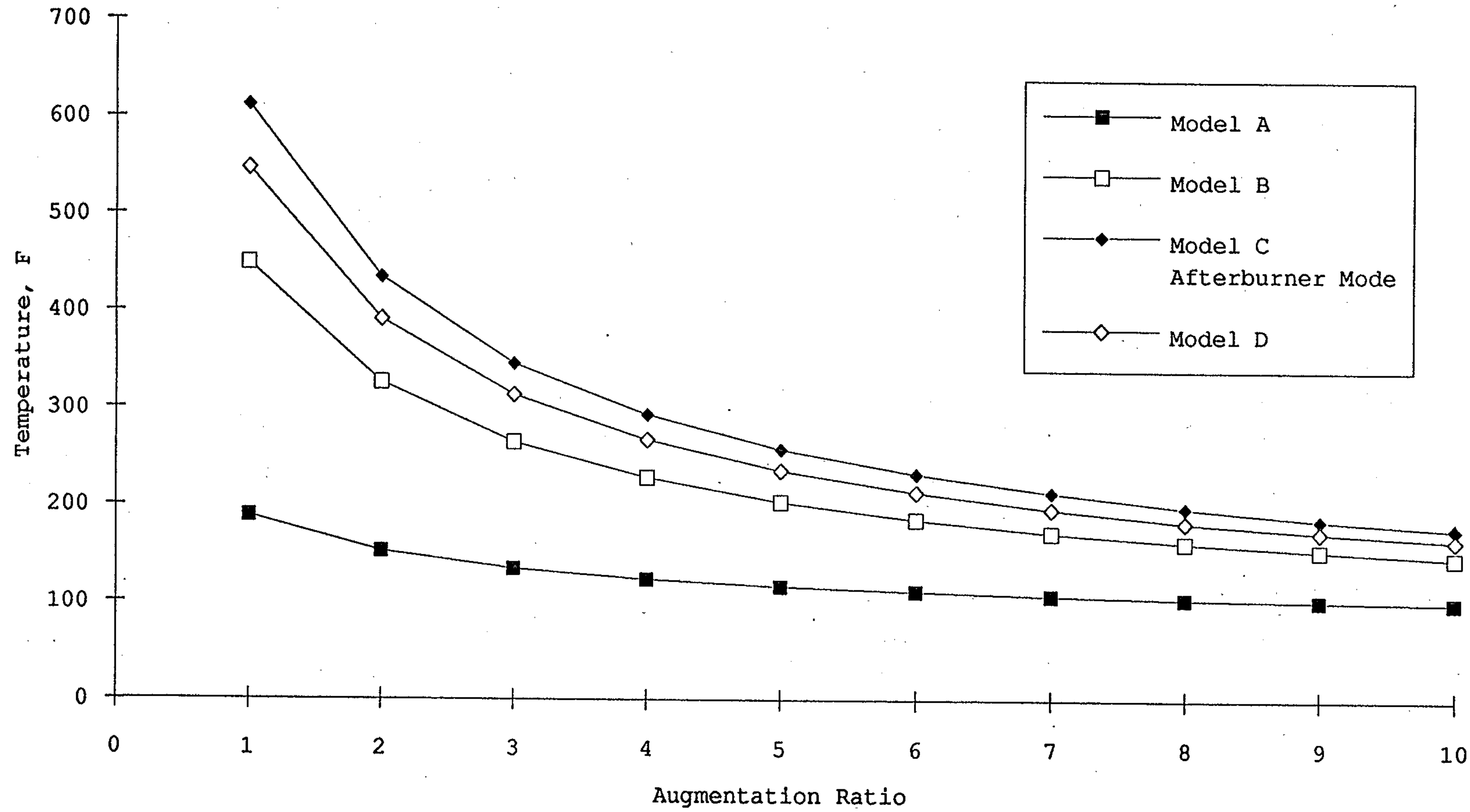

Figure 3-4. Predicted stack gas temperature at peak thrust as a function of augmentation ratio.

as the augmentation ratio is increased from 1 to 3. Beyond the augmentation ratio of 3, the rate of decrease in stack temperature is reduced. Figure 3-5 presents the stack gas mass flow rate as a function of the augmentation ratio for the model test cells. For Model Test Cell (A) which incorporates the high bypass engine (CF6-80A2), significant increases in mass flow occur as the augmentation air ratio is increased. This is associated with a decreasing effect on the stack gas temperature as shown in Figure 3-4.

Table 3-3 summarizes the NO_x emissions from the four model test cells calculated using an augmentation ratio of 5 with an annual usage of 200 hours (based on data summarized in Chapter 6). NO_x concentrations have been corrected to a uniform 15 percent O_2. The equations used to predict NO_x levels are summarized in Appendix B. Figure 3-6 presents the predicted stack NO_x concentrations. Stack NO_x levels are not significantly different at peak thrust levels despite the large variation in engine design used in the analysis. The exception to this are the NO_x emissions calculated for the Model Test Cell (C) when operating the engine in afterburning mode. During afterburning operation, large reductions in NO_x levels occur; however, these are generally associated with an increase in carbon monoxide (CO) production. Predicted annual total NO_x emissions for the model test cell testing the large civilian CF6 engine are 24.5 tons. Predicted annual NO_x emissions for the Model D testing the smallest turbofan/turbojet engine are less than 3 tons.

3.4 OBSERVED TEST CELL DATA

The model test cells described in Section 3.3 predict the resulting stack gas temperatures, NO_x emission concentrations, and total annual NO_x emissions. As will be discussed in Chapters 4 and 5, the technical feasibility and cost of implementing selective catalytic reduction (SCR), selective

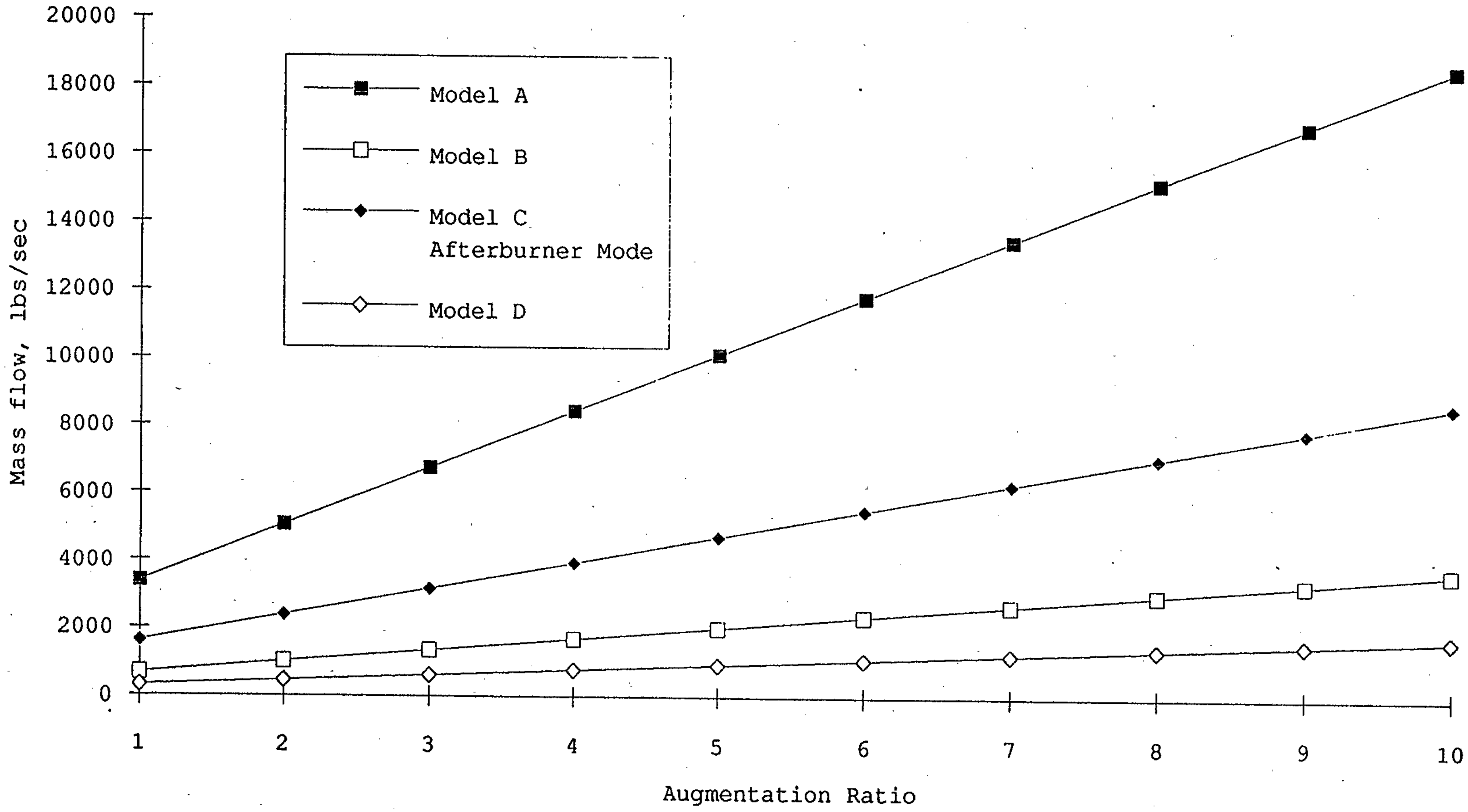

Figure 3-5. Predicted stack gas peak mass flow rate as a function of augmentation ratio.

TABLE 3-3. PREDICTED EMISSION CHARACTERISTICS FOR A TURBOJET/TURBOFAN MODEL TEST CELL

Augmentation Ratio = 5.0   Total Yearly Hours used per Model Test Cell = 200 hrs   Ambient Air Temperature = 80°F

Inputed Data				Calculated Characteristics					
Test Cell Model	Thrust lbf	Fuel lbs/min	NOx lbs/Mlbs fuel	Stack Gas Temperature, °F	Stack Gas lbs/second	NOx Flow lbs/second	NOx, Tons Per Year	Stack % O2, wet	Stack NOx ppmvd at 15% O2
Model A	48671	298.0	29.6	116.3	10123	0.147	13.2	20.84	373.1
	41370	249.3	26.6	112.0	9808	0.111	9.9	20.75	185.8
	14601	84.7	10.8	91.8	8924	0.015	1.1	20.91	85.6
	1723	19.8	3.4	88.4	2913	0.001	0.1	20.93	29.5
							24.4		
Model B	15084	167.9	19.7	203.0	2017	0.055	5.0	20.06	130.9
	13549	147.9	16.5	199.4	1820	0.041	3.7	20.09	110.0
	1869	25.9	4.4	114.6	974	0.002	0.1	20.73	30.9
	628	14.5	2.6	116.8	514	0.001	0.1	20.72	17.9
							8.8		
Model C *	17500	583.3	4.5	257.3	4728	0.044	0.8	19.66	29.8
	11248	166.7	10.3	246.9	1417	0.029	2.6	19.73	67.9
	9000	126.3	8.3	193.5	1512	0.017	1.3	20.13	55.0
	3381	57.0	4.2	153.3	1024	0.004	0.3	20.44	28.5
	265	20.8	1.3	141.9	439	0.000	0.0	20.52	9.0
							4.9		
Model D	8439	105.8	8.9	235.6	938	0.016	1.4	19.81	58.9
	7355	89.9	7.6	224.5	852	0.011	1.0	19.90	50.1
	3157	38.5	4.5	169.2	568	0.003	0.2	20.31	30.3
	511	11.9	2.7	147.1	231	0.001	0.1	20.48	18.0
							2.7		

NOTE:

Engine Emissions Data for Model Test Cells B, C, and D utilize the following reference:

Aircraft Environmental Support Office, "Summary Tables of Gaseous and Particulate Emissions from Aircraft Engines," AESO Report Number 6-90, San Diego California, June 1990, p.7, 15, 22.

Engine Emissions Data for Model Test Cell A are from the following reference:

U. S. Department of Transportaion, "FAA Aircraft Engine Emission Database (FAEED)," Office of Environment and Energy, Federal Aviation Administration.

* [=] Afterburner Mode

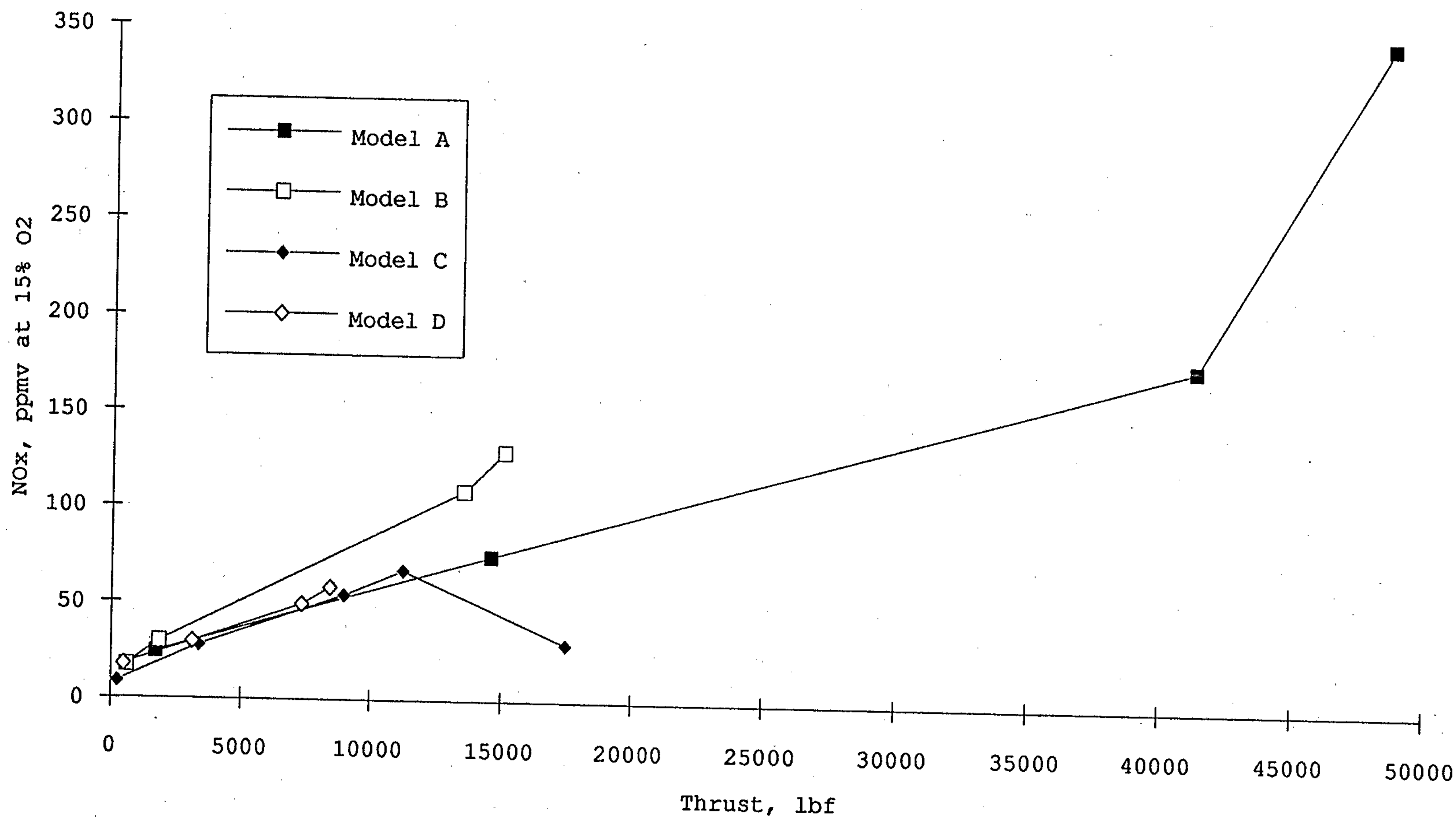

Figure 3-6. Predicted stack NO_x concentration by thrust corrected to 15 percent O_2.

non-catalytic reduction (SNCR), or other potential NO_x controls to the test cell are strongly influenced by these parameters. However, the feasibility and cost effectiveness of potential NO_x control strategies can also be affected by more detailed parameters than can be determined using the model test cells. Specifically, gas flow velocity, NO_x distribution and gas temperature distribution within the test cell can all have a significant impact on the feasibility of a particular NO_x control method.

In an effort to assess the viability of implementing SCR, a 1987 study was conducted to determine detailed gas characteristics in the exhaust of a test cell.[10] Detailed stack and augmenter tube measurements were conducted at the Navy facility in Lemoore, California, in test cell #3 (T10 Type design). The engine used in the study was a General Electric F404 military afterburning turbofan engine (maximum thrust of 17,000 lbs) and is similar in engine specific parameters to the J79-GE-10B used in Model Test Cell (C). Figure 3-7 presents a schematic diagram illustrating the components of the air flow through the augmenter tube. In addition, the static pressures associated with these flows are plotted as a function of position along the augmenter tube. This figure illustrates the mechanism for the air entrainment through the test cell, in addition to the potential for significant variations in velocity, temperature, and pollutant concentration that can occur in the augmenter tube region.

Figure 3-8 presents a plot of the measured gas temperature profiles at various locations within the augmenter tube with the engine operating at 89 percent of maximum power. The data illustrate the impact of the mixing process on reducing the engine exhaust gas temperatures. Using the engine data for a F404 in the test cell model (C), stack exit temperatures are predicted to be 180°F at an augmentation ratio of 7. The DoD has indicated that T-10 test cells operate at an augmentation ratio of 7. This corresponds with the fully mixed values of 180°F recorded 55 feet from the engine.

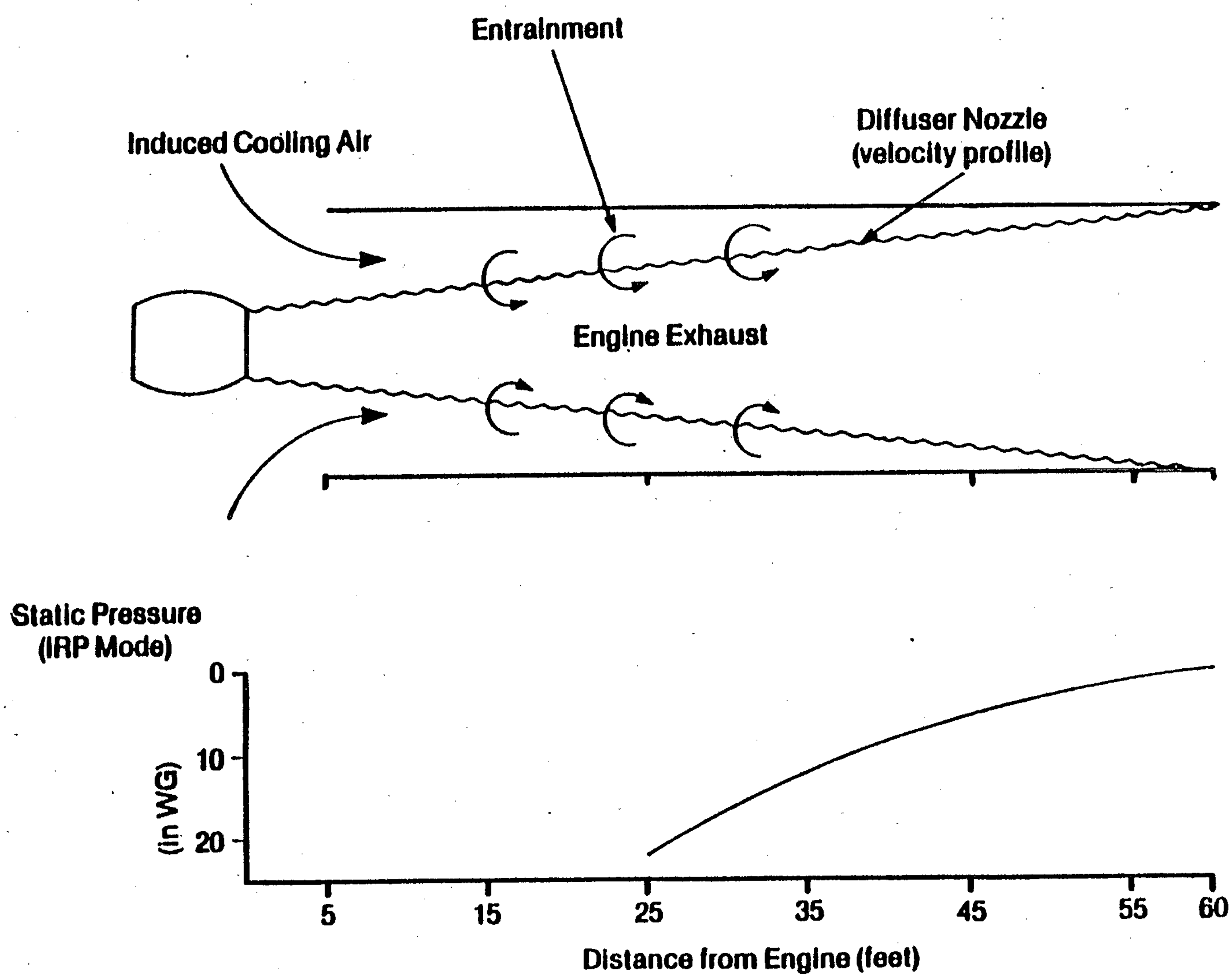

Figure 3-7. Jet engine test cell/augmenter flow and accompanying measured static pressure profile.

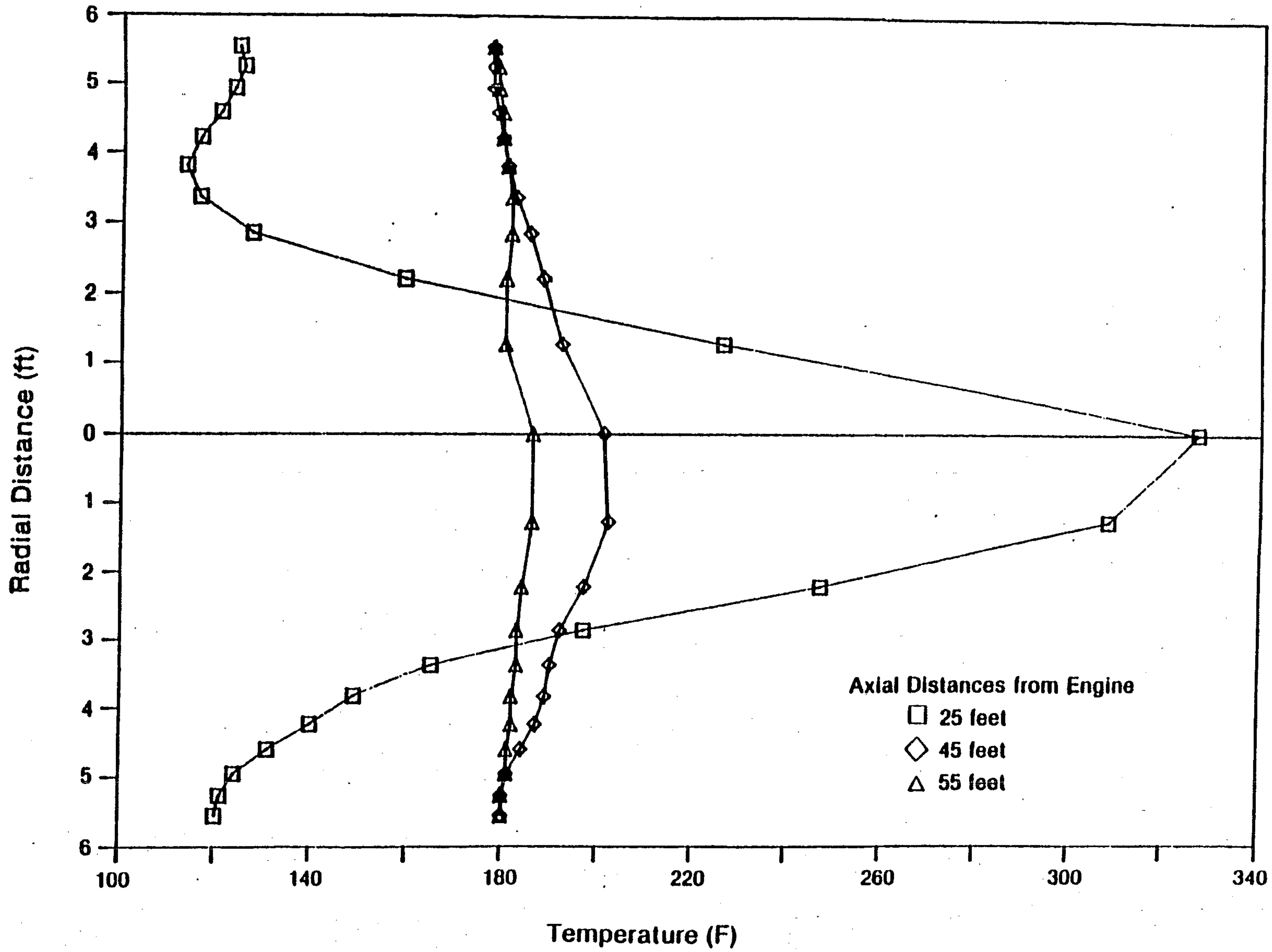

Figure 3-8. Measured gas temperature profiles at various axial distances from the engine at 89 percent power.

Figure 3-9 presents the measured NO_x concentrations at various locations within the augmenter tube. This graph displays similar profiles to the temperature plots (Figure 3-8) and illustrates the impact of mixing the entrained air with the engine air on the final stack exit NO_x concentrations. The slight skew in the data is attributed to asymmetries in the augmentation air flow.

The measured temperature and NO_x data are indicative of the large variations that exist within the gas stream as it passes down the augmenter tube. In the absence of fully mixed conditions, significant local variations in temperature and concentrations exist. The effectiveness of NO_x controls (for example, SNCR) within the augmenter tube itself would be significantly reduced by these variations. In addition, insertion of SNCR within the augmenter tube would have the potential to impact the pressure profile and resulting rate of air entrainment through the test cell.

3.5 TURBOPROP/TURBOSHAFT MODEL TEST CELL DESCRIPTION

Turboprop/turboshaft jet engines are distinguished in part from turbojet/turbofan engines in that the exhaust is a low energy, typically lower velocity gas stream. As discussed in Chapter 2, testing of these type engines within test cells typically involves extracting the engine power using a dynamometer. Figure 3-10 presents the schematic diagram of a representative test cell capable of testing turboshaft/turboprop engines, although other designs and locations of the dynamometer are possible. Because the exhaust is a low velocity gas stream, entrained augmentation air is significantly less than that found in test cells testing turboprop/turbojet type engines. A single model test cell has been developed to assist in determining the technical feasibility and costs of implementing NO_x control to test cells testing turboshaft/turboprop type engines.

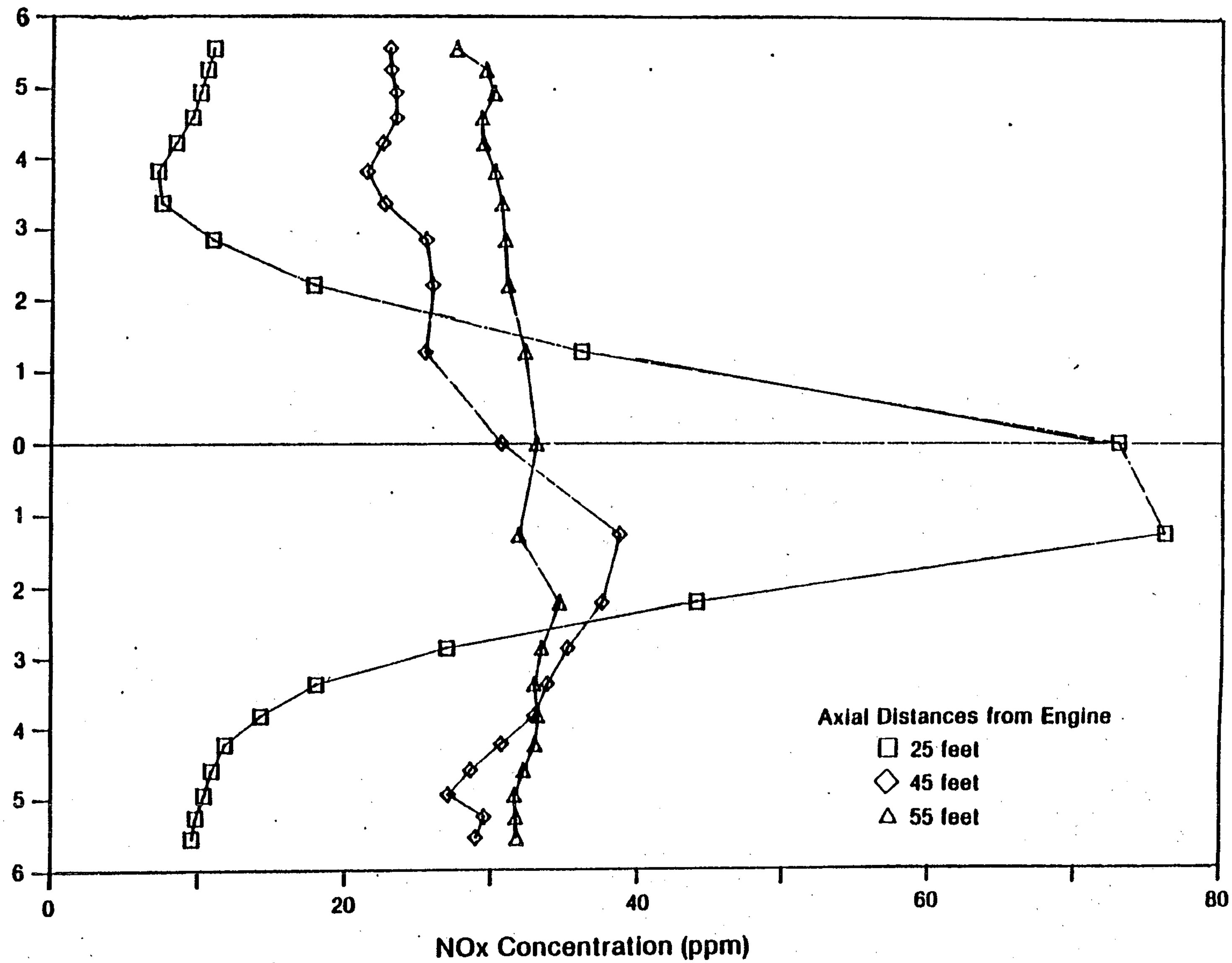

Figure 3-9. Measured NO_x concentration profiles at various axial distances from the engine at intermediate run power.

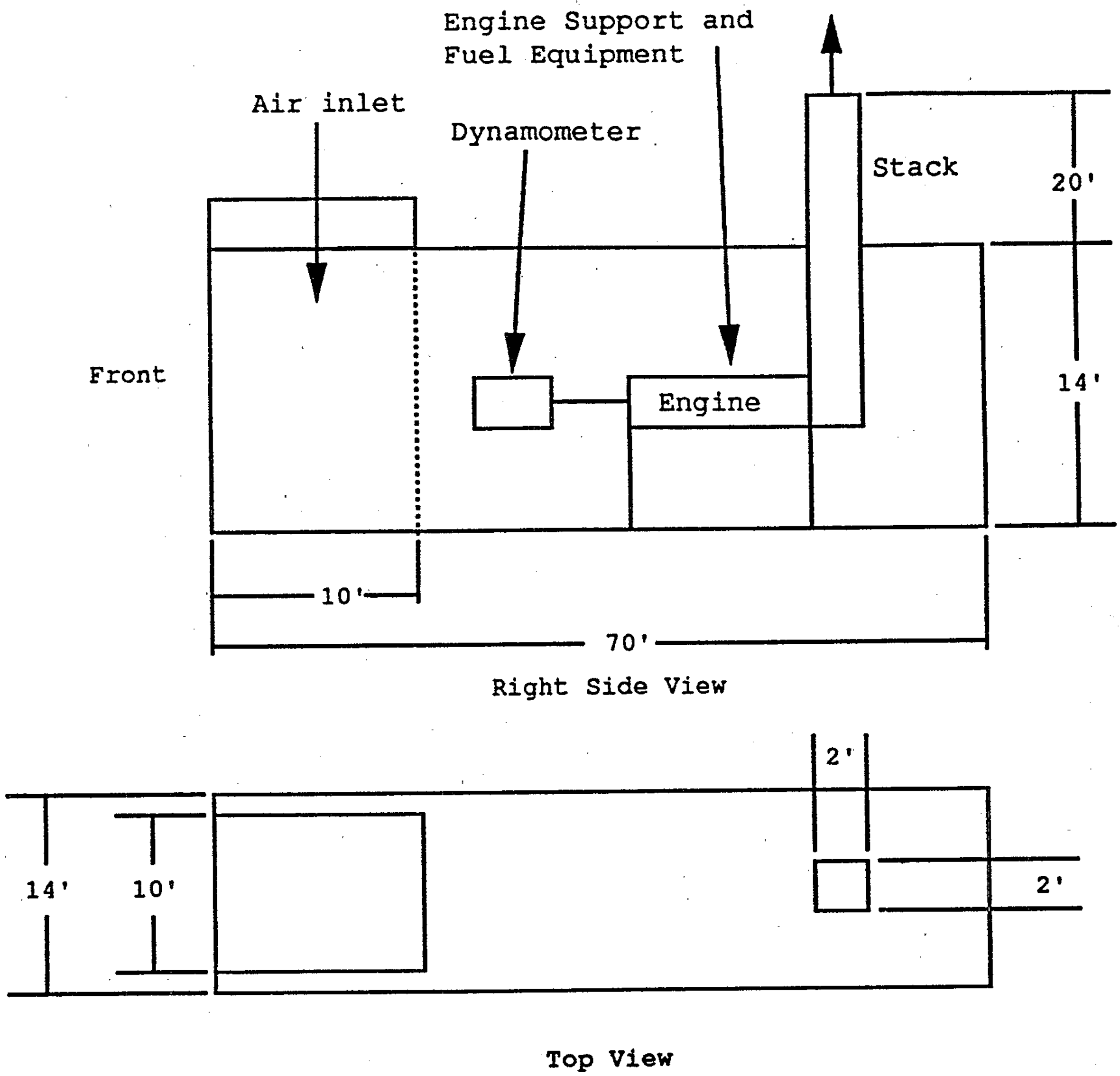

Figure 3-10. Schematic of turboprop/turboshaft model test cell (Relative dimensions for Model E Test Cell).

Model Test Cell (E): This model test cell uses the T58-GE-8F turboshaft engine. This engine is used in the Sea King Series helicopters and delivers approximately 1,400 peak shaft horsepower.

The engine core exhaust temperature is calculated using Equation 3-3 and the engine specific data.[11] The development of this equation is provided in Appendix C.

$$tc = ta + 1/Cp\ (LHV * FA - W/Me) \qquad \text{Eq. 3-3}$$

where:

tc: Engine core exhaust gas temperature (°F)
ta: atmospheric temperature (°F)
Cp: heat capacity (BTU/lb °F)
LHV: jet A lower heating value (18,500 BTU/lb)
W: horsepower of the engine (hp)
Me: engine exhaust mass flow (lb/sec)

Fully mixed stack temperatures are calculated using Equation 3-2. Annual NO_x estimates from the model test cell are based on 200 hours/year operation and a power schedule as shown in Table 3-2. This model test cell's annual utilization is consistent with the reported utilization of the current test cell population as reported in Chapter 6. Figure 3-11 presents the predicted stack gas exit temperatures and stack mass flow rates for the model test cell. A uniform (independent of thrust) augmentation ratio of 0.2 is assumed. Predicted peak gas temperatures are generally above those predicted for the turbofan/turbojet test capable model test cells and are in the range of 900°F. Stack NO_x emissions are plotted in Figure 3-12. Peak NO_x emissions are predicted to be 62 ppm at 15 percent O_2. Annual NO_x emissions of much less than 1 ton are predicted. Table 3-4 summarizes the emission estimates from Test Cell Model (E).

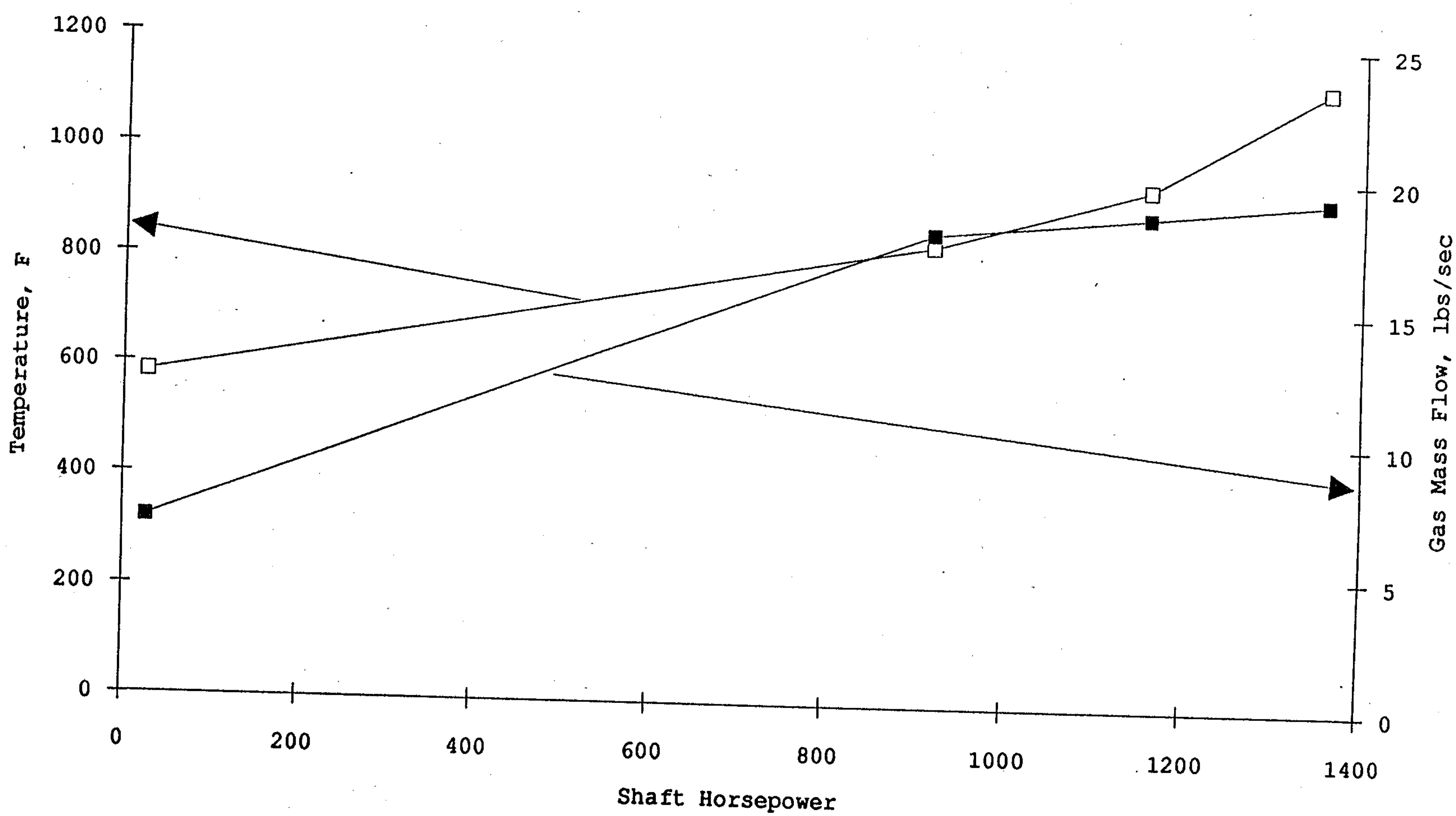

Figure 3-11. Predicted stack gas temperature and mass flow rate for Model E Test Cell at various horsepower settings and an augmentation ratio = 0.2.

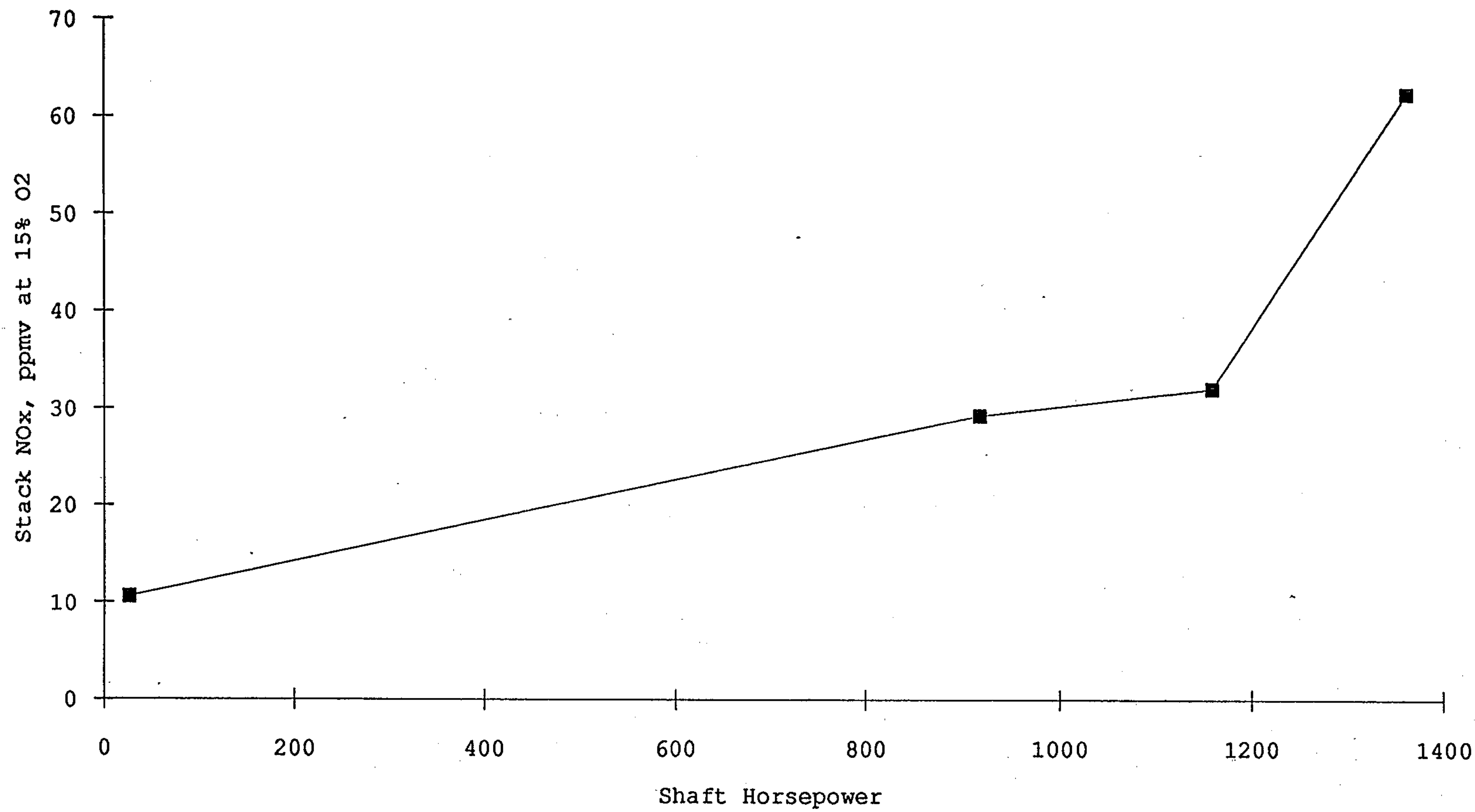

Figure 3-12. Predicted stack NO_x concentration by shaft horsepower.

TABLE 3-4. PREDICTED EMISSION CHARACTERISTICS FOR A TURBOPROP/TURBOSHAFT MODEL TEST CELL

Augmentation Ratio = 0.2 Total Yearly Hours used per Model EUAETC = 200 hrs Ambient Air Temperature = 80°F

Inputed Data				Calculated Characteristics					
Test Cell Model	Shaft Hp	Fuel lbs/min	NOx lbs/Mlbs fuel	Stack Gas Temperature, °F	Stack Gas lbs/second	NOx Flow lbs/second	NOx, Tons Per Year	Stack % O2, wet	Stack NOx ppmvd at 15% O2
Model E	1360	14.1	5.5	937.4	19.3	1.28E-03	.116	17.01%	62.4
	1159	11.4	4.9	943.9	18.6	9.48E-04	.084	15.07%	32.1
	918	9.7	4.5	833.8	17.9	7.33E-04	.052	15.76%	29.3
	27	2.5	1.6	583.3	6.7	6.77E-05	.007	17.41%	10.6
							.259		

NOTE:

Engine Emissions Data for Model Test Cell E are from the following reference:

Aircraft Environmental Support Office, "Summary Tables of Gaseous and Particulate Emissions from Aircraft Engines," AESO Report Number 6-90, San Diego California, June 1990, p. 30.

3.6 SUMMARY

Five model test cells have been developed to predict the stack gas characteristics necessary in evaluating the feasibility and cost of adding NO_x controls to those test cells capable of testing turbojet/turbofan and turboprop/turboshaft engines. These model test cells utilize measured data from engines representative of those evaluated and tested in the current population of test cells. Additionally, measured data have been presented to both illustrate the variability of gas temperatures and NO_x concentrations within the augmenter tube region of a test cell and verify the predictions of the model test cells. Comparison of the predicted stack gas temperatures with measured data indicates that the models are sufficiently accurate for the purpose of this study. As will be discussed in Chapter 4, these variations of gas temperature and NO_x concentrations within the test cell have a significant impact on determining the placement and the viability of flue gas NO_x controls.

3.7 REFERENCES

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3. International Civil Aviation Organization, Annex 16. Environmental Protection, Volume II. Aircraft Engine Emissions. June 1981.

4. United States Department of Defense. Software Users Manual for the Aircraft Engine Emission Database System. Aircraft Division, Naval Air Warfare Center. Trenton, New Jersey. August 1992.

5. Aircraft Environmental Support Office. Summary Tables of Gaseous and Particulate Emissions from Aircraft Engines. Prepared for the Aircraft Environmental Support Office, Naval Aviation Depot. North Island, San Diego, California. AESO Report No. 6-90. June 1990.

6. Ref. 5, pp. 7, 15, 22.

7. Ref. 5, p. 45.

8. Energy and Environmental Research Corporation. Delta Airlines Site Visit Report. Prepared for the U.S. EPA. Research Triangle Park, North Carolina. ESD Project No. 92/20. March 1993. p. 2.

9. Ref. 5, p. 53.

10. Stelling, J.H.E., P.A. May, and G.D. Jones (Radian Corporation). Pilot De-NO_x Test Facility for Jet Engine Test Cells. Prepared for the U.S. EPA. Research Triangle Park, North Carolina. Draft. September 1987.

11. Ref. 5, p. 30.

CHAPTER 4

FEASIBILITY OF REDUCING NO_x EMISSIONS FROM TEST CELLS

4.1 OVERVIEW

The technical feasibility of applying a variety of NO_x control technologies to test cells is examined in this chapter. Flue gas treatment methods, specifically selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR), are well established technologies for reducing NO_x emissions from a broad range of fossil fuel-fired systems. The feasibility of these methods for reducing NO_x emissions from test cells is examined in Sections 4.3 and 4.4. Reburn is a combustion modification NO_x control technology which has recently received considerable testing and validation on large utility-type boilers. The feasibility of reburn for NO_x control applied to test cells is examined in Section 4.5. Gas turbines used for power generation, including aeroderivative models, commonly incorporate either steam or water injection to reduce NO_x emissions. More recently, fuel emulsifiers have been investigated as a means of reducing NO_x emissions from stationary gas turbines. The feasibility of these NO_x control methods (steam/water injection, fuel emulsifiers) for test cells is examined in Section 4.6. There has been research conducted through a series of Small Business Innovation Research (SBIR) awards to develop a NO_x control method solely for test cell application. This research effort has resulted in development and testing of a low temperature magnesium-oxide, vermiculite-based sorbent for NO_x control which does not require chemical injection. Section 4.7 examines this technology for general applicability to full-scale test cell operation and also includes a discussion of low NO_x combustor design. As part of the feasibility assessment of NO_x control technologies, Section 4.8 examines potential effects of the NO_x control technologies on the engine and engine test.

The operational complexity of altitude simulating test cells, as well as the multitude of subsystems, further complicates the development of flue gas NO_x abatement techniques. Typically, the altitude facility will have less available plot space to install NO_x control reactors. Large temperature swings will place greater demands on flue gas conditioning, and potential failure in temperature control can result in catastrophic failure in downstream systems due to the thermal shock. Altitude facilities are less uniform in design, and site-specific factors will dominate potential reactor design. Therefore, the focus of this chapter is on the feasibility of applying NO_x control technologies to sea level test cells.

4.2 NO_x FORMATION MECHANISMS

The NO_x emissions from test cells are generated by the engines tested within the facility. The NO_x mass emission rate is determined solely by the test engine and is unaffected by the design of the test cell itself. Nitrogen oxides (NO_x) are products of all conventional combustion processes. NO_x is a collective term for nitric oxide (NO) and nitrogen dioxide (NO_2). NO is the predominate form of NO_x produced by aircraft engines, with lesser amounts of NO_2; however, once emitted to the atmosphere, NO converts to NO_2.

NO_x emissions from jet engines are generated in the primary combustion zone of the engine, located in the forward volume of the combustor where the fuel is injected. Within the combustor (Figure 4-1), localized regions of stoichiometric and near stoichiometric fuel/air mixtures exist at high engine power conditions, resulting in high flame temperatures. As will be discussed, these high flame temperatures are responsible for most of the NO_x emissions from jet engines.

The generation of NO_x from fuel combustion is a result of three formation mechanisms, namely thermal NO_x formation, prompt NO_x formation, and fuel NO_x formation. Thermal NO_x is produced by exposing the nitrogen contained in the combustion air (ambient air contains 79 percent nitrogen by volume) to the high temperatures of combustion. Prompt NO_x is formed from the oxidation of hydrogen cyanide, an intermediate product from the reaction of nitrogen with hydrocarbon. Fuel NO_x is formed when the nitrogen in the fuel is oxidized to NO.

The chemistry associated with formation of thermal NO_x is relatively well understood, especially under fuel-lean conditions. The controlling chemical reactions are referred to as the Zeldovich mechanism. The Zeldovich reaction set predicts a linear dependence between the rate of thermal NO_x formation and the local concentration of oxygen atoms. The main source of oxygen atoms is the disassociation of O_2, which is exponentially dependent on the flame temperature. The combined effect is that thermal NO_x formation is strongly dependent on flame temperature, with the rate of NO_x formation increasing by an order of magnitude with approximately every 100°C increase in peak flame temperature.

Fuel NO_x is formed when the fuel being burned contains nitrogen within its chemical structure. Jet fuel is a composite of light distillate oils. Typically, light distillate oil contains less than 0.015 percent by weight of

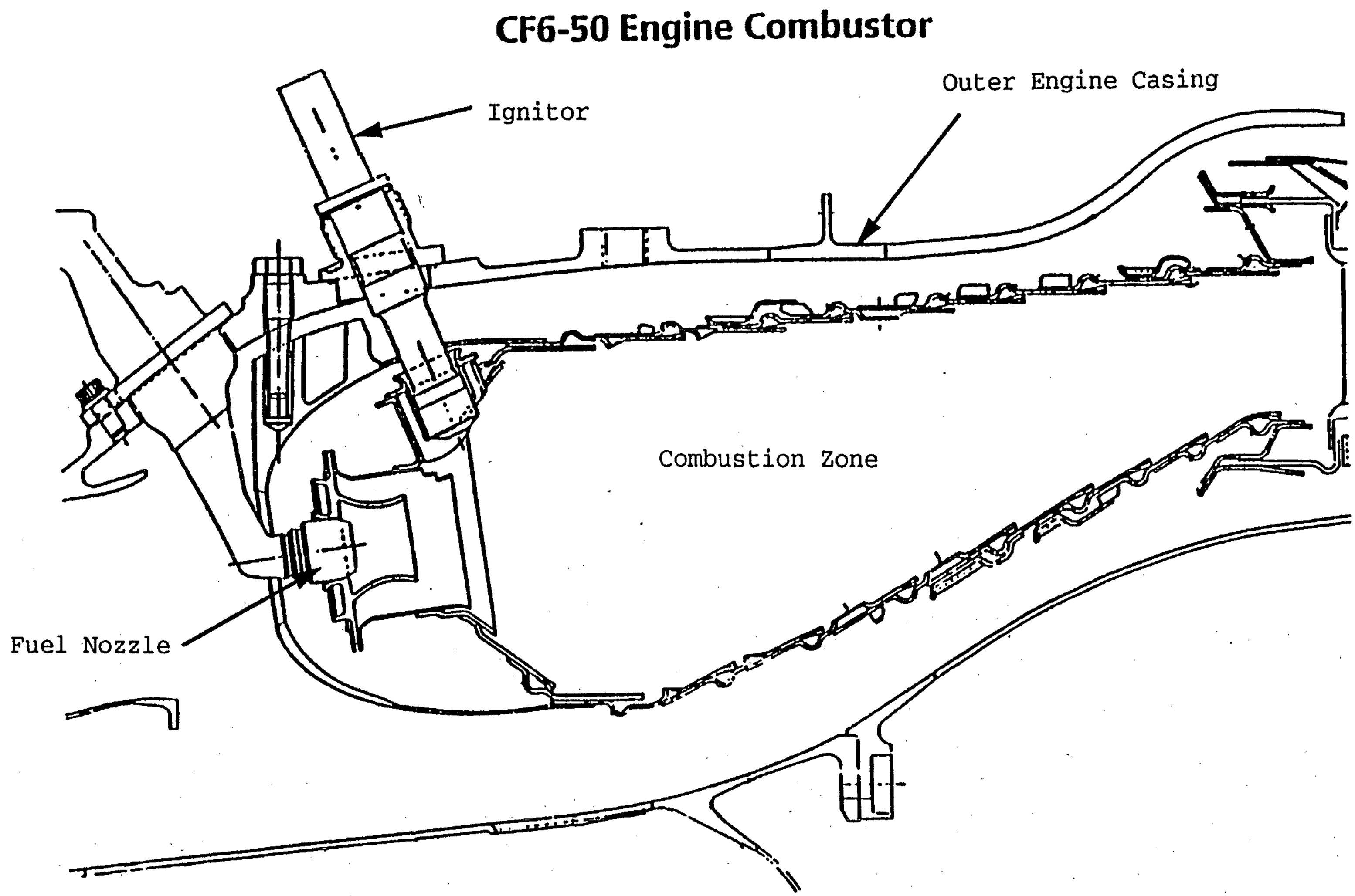


Figure 4-1. Typical annular combustor.

chemically-bound nitrogen. Chemically-bound nitrogen is the nitrogen that is bound to hydrogen atoms (such as amines) or to carbon atoms (such as cyano compounds).

The relative contributions of thermal and prompt NO_x versus fuel NO_x for turbines burning jet fuel are easily estimated. For a jet fuel containing 0.015 weight percent fuel-bound nitrogen, complete conversion of the bound nitrogen equates to an emission factor of 0.5 lb fuel NO_x/1,000 lbs fuel. Emission factors for engines used in the model test cells described in Chapter 5 range from 7.5 to 29.6 lbs NO_x/1,000 lbs fuel at 80 percent power. Emission factors during idle for these engines (where fuel NO_x would account for a more significant fraction due to low combustion temperatures) range from less than 1.3 to greater than 3 lbs NO_x/1,000 lbs fuel. At idle conditions, conversion of the fuel-bound nitrogen to NO_x accounts for a significant portion of the NO_x formed. However, at normal operating conditions where emission rates are significantly higher, thermal NO_x accounts for more than 95 percent of total NO_x emissions.

4.3 SELECTIVE CATALYTIC REDUCTION (SCR)[1, 2, 3]

SCR is a post-combustion NO_x control technology which employs a highly reaction-specific process to push the reaction of NO with ammonia towards a thermodynamic equilibrium:

$$NO + NH_3 + 1/4\ O_2 \leftrightarrow N_2 + 3/2\ H_2O$$

The products of the reaction under idealized conditions are nitrogen and water. However, under practical conditions, the reaction is not complete and results in some unreacted ammonia (NH_3 slip) and NO in the exiting flue gas.

The majority of SCR experience in the United States is with stationary gas turbine applications, primarily firing natural gas. The largest body of SCR experience with energy systems firing moderate sulfur oil and coal fuel is in Japan, where over 40,000 MW of electric power are generated using SCR as a NO_x control method. Catalyst technology is continuing to develop, and this will impact the viability of SCR as a NO_x control strategy for test cells. Early catalysts were typically designed to operate between 675 and 750°F, with space velocities (flue gas volumetric flow rate/catalyst volume) in the range of 15,000 to 20,000 hrs^{-1}. Currently, catalysts are available which can operate in the 475 to 550°F temperature range, with space velocities in excess of 40,000 hrs^{-1}. Demonstrated NO_x removal efficiencies range from 80 to 90 percent when applied to stationary gas turbines.

The NO_x reduction efficiency for an SCR system is influenced by the catalyst material and physical condition, the reactor operating temperature, the residence time of the gas within the catalyst reactor, and the molar ratio of ammonia to NO_x (NH_3/NO_x). Several catalyst materials are available, and each has an optimum NO_x removal efficiency range within a specified reaction temperature range. Proprietary formulations containing titanium dioxide, vanadium pentoxide, platinum, or zeolite are available to meet a wide range of operating temperatures.

The NO_x removal efficiency gradually decreases over the operating life of the SCR system due to catalyst masking, poisoning, or sintering. Catalyst masking involves the deposition of agents on the catalyst surface, forming a barrier between the active catalyst surface and the gas. The effects of the masking can typically be removed by vacuuming, using soot blowers, or superheated steam to clean the catalyst. Catalyst poisoning involves a chemical reaction between the catalyst and the flue gas. Typically, a poisoned catalyst cannot be regenerated to perform at design NO_x reduction efficiencies. Sintering results from a physical change due to overheating of the catalyst. Most catalysts have porous-type surfaces; sintering causes the surface of the catalyst to become non-porous and therefore not as effective.

The rate of catalyst performance degradation, either through masking or poisoning, depends on the flue gas characteristics and operation characteristics of the system, and is therefore site specific. However, natural gas-fired systems incorporating SCR have reported 5 to 10 years of catalyst life. Coal-fired or heavy fuel oil systems typically operate 3 to 4 years before significant catalyst performance degradation.

The space velocity for a particular SCR design is indicative of the gas residence time within the reactor. The lower the space velocity, the longer the residence time, and the higher the potential NO_x emission reduction. The distance between the plates or cells within a catalyst is referred to as the pitch and affects the overall size of the catalyst body. The smaller the pitch, the greater the number of rows or cells that can be placed in a given volume. Both the space velocity and pitch determine the physical space requirements necessary to house the catalyst volume required to achieve the desired NO_x reductions.

Ammonia handling, storage and injection grids are required in addition to the SCR reactor vessel required to house the catalyst in order to implement SCR. Both anhydrous and aqueous ammonia are used in SCR designs. Anhydrous ammonia (usually a liquid under pressure) results in the smallest storage tankage but represents a potential hazard through catastrophic tank failure. Aqueous ammonia (roughly 20 mole percent) storage requires approximately four times the tank volume but is safer. For both systems, a dilution system is required, typically air for anhydrous systems and water for aqueous ammonia systems.

4.3.1 Feasibility of SCR for Test Cell Application

Significant differences exist between the exhaust gas characteristics of power generating gas turbines and the stack gas characteristics of test cells. These differences impact both the SCR system requirements to implement SCR and the costs associated with the SCR system. As shown in Chapter 3, the stack gas temperature of test cells is generally below that suitable for SCR systems incorporating a proven catalyst material. In addition, the stack gas temperature will vary significantly with engine thrust. Furthermore, the NO_x mass emission rate will vary with engine thrust, causing the NO_x concentration entering the SCR reactor to vary. The ammonia injection system must track NO_x molar flow rates. If not, then NO_x reduction efficiencies will be reduced and/or excessive ammonia slip will occur. Engine testing (as shown in Chapter 2) requires rapid and frequent changes in engine output, thus the variations in temperature and NO_x emissions from test cells will place demands on the SCR controller not found in current SCR installations; and ammonia injection systems have not been applied to test cells.

The stack gas from test cells can be heated using a duct burner to elevate and maintain the stack gas temperature to the catalyst operating temperature. Duct burners are commonly used on power generation gas turbine installations to increase the temperature of the flue gas upstream of the heat recovery steam generator (HRSG) and increase the overall efficiency of the installation, but they have not been applied to test cells. However, the use of a duct burner will increase the

NO_x emissions entering the SCR system. The NO_x emissions from the duct burner can be minimized by firing the burner with natural gas. The operation of the duct burner must be tightly controlled to ensure a uniform, suitable temperature of the test cell exhaust gas entering the SCR reactor. This will require linking the operation of the duct burner to the test engine power setting, as well as the reactor inlet gas temperature. For facilities testing afterburning engines, an additional concern with the duct burner can arise. Afterburning engines introduce raw fuel downstream of the combustor. Should flame out or failure of the afterburner occur, the potential for ignition by the duct burner and flashback of this well mixed fuel exists.

In a previous examination of SCR for test cell application,[4] reduction in the level of augmentation air flow was considered as a means of elevating the exhaust gas temperature to levels suitable for the SCR catalyst. As discussed in Chapter 2, the required level of augmentation air flow is determined from the calibration and cooling requirements of the test cell; therefore, it is not feasible to introduce a system to automatically adjust the level of augmentation air flow to minimize reheat requirements, as well as maintain the engine test integrity, during the typically transient test schedule. For this reason, both the SCR and the SNCR system analysis in the next chapter use reheat to achieve the suitable exhaust gas temperature.

For an SCR system to effectively reduce NO_x emissions, it is necessary to ensure that the ammonia and NO are uniformly mixed at the design NH_3/NO_x molar ratio. As presented in Chapter 3, a uniform NO_x concentration does not occur until well downstream of the engine exhaust. Injection of the ammonia at rates based on mean flow NO_x levels in the presence of a NO_x concentration distribution will result in both a lower NO_x removal efficiency and excessive ammonia slip. In order to ensure adequate mixing and a uniform NO_x

concentration distribution, the injection grids will have to be placed either at the end of the augmenter tube or in the stack region of the test cell. For space-limited test cells, it may be necessary to force the mixing of the augmentation air with the engine exhaust to ensure a uniform NO_x concentration. However, this will increase the pressure drop downstream of the engine and therefore increase the back pressure on the engine tested within the test cell.

As discussed in Chapter 2, the augmentation air flow and the operation and calibration of the test cell is critically dependent on the back pressure experienced by the engine tested within the test cell. Changes in the pressure drop downstream of the test engine affect the air flow upstream of the engine and alter the calibration of test cell for that specific engine. Excessive back pressure will affect flow patterns upstream of the engine air inlet and can potentially lead to exhaust gas recirculation and possibly engine stall.[5] Additionally, these changed air flow patterns may cause non-representative test measurements and non-repeatable tests. However, modeling studies have shown that if an augmentation ratio of at least 0.8 is maintained, inlet air vortices may be avoided.[6,7] As a result of installing an SCR system to an existing test cell, the facility will need at a minimum to recalibrate the test cell for each engine tested at that test cell. In addition, the test cell facility may be downsized in thrust capability as a result of the decrease in augmentation air flow associated with the increase in engine back pressure generated by the SCR system. This effect can be minimized by designing an SCR system with a reduced pressure drop. Recent SCR installations for power generating gas turbines have been installed with between 1 and 2 inches of water gauge pressure drop across the reactor.[8] As will be shown in Chapter 5, lowering the back pressure impacts the cost of the SCR system.

Additionally, water vapor in the stack gas from test cells which incorporate water cooling may affect the SCR system. Water cooled test cells have exit moisture contents on the order of 10 percent. Stationary power generating gas turbine facilities use SCR in conjunction with water injection into the combustor. Water injection, as a NO_x control technology, is described in Section 4.6.1. The water-to-fuel mass ratio of stationary gas turbines which use water injection is on the order of 1 to 2 pounds of water per pound fuel. These SCR systems experience moisture on the order of 7 to 9 percent and experience no loss of NO_x reduction at these moisture levels. Therefore, if SCR is applied to a test cell that uses water cooling, the water vapor should not affect SCR performance.

The reheat portion of the system would need to be tightly controlled to ensure a uniform reactor inlet temperature independent of the rapidly varying engine exhaust gas temperature and exhaust gas flow rates. For test cells testing afterburning engines, cooling the gas stream may be required (most likely water quench) to ensure the integrity and maintain the appropriate operating temperature of the SCR system during afterburning operation. The SCR system would also require controllers to govern the ammonia injection to ensure adequate NO_x reductions without excessive ammonia slip. A waste heat recovery system may be part of the design to reduce stack exit gas temperatures and recover a portion of the energy used to reheat the stack gas. However, the waste heat and potential steam generated may not be needed by or easily incorporated into all test cell facilities. If stack gas cooling downstream of the SCR system is required, then a water quench system should be easily incorporated.

It is conceptually possible to design an SCR system using conventional catalyst materials that could be applied to test cells. A research and development and evaluation program would be required before decisions could be made on design characteristics for test cells incorporating such a NO_x control system. This would result in test cells which would control NO_x and not affect the safety or performance of the engines when tested or affect subsequent in-flight safety. Present-day test cells may require major structural modifications to meet these new design characteristics. Various considerations, such as site conditions, may limit the practicality of retrofit and necessitate test cell replacement.

4.4 SELECTIVE NON-CATALYTIC REDUCTION (SNCR) [9, 10, 11, 12, 13]

SNCR technology provides post-combustion reduction of nitrogen oxide emissions. Using SNCR technology, chemical agents are added to the combustion products where they react at elevated temperatures with NO_x to form molecular nitrogen. Typical agents which have broad industrial applications are ammonia (NH_3) and urea [$CO(NH_2)_2$]. However, small-scale studies have shown that other chemical compounds can also be used to provide effective NO_x control. The primary limiting factor restricting SNCR application is that it is only viable over a fairly narrow temperature range and there is the potential for the production of by-product emissions. For both ammonia and urea injection, incomplete reactions will result in ammonia emitted from the stack (referred to as ammonia slip). Additionally, recent studies have shown that nitrous oxide (N_2O) emissions can increase with urea injection.

Ammonia injection was developed and patented by Exxon in the late 1970s as the Exxon Thermal $DeNO_x$® process.

The overall chemistry for the process can be expressed by two competing reactions:

$$NO + NH_3 + 1/4\ O_2 \rightarrow N_2 + 3/2\ H_2O$$
$$NH_3 + 5/4\ O_2 \rightarrow NO + 3/2\ H_2O$$

The first reaction is the desired step causing the reduction of NO to molecular nitrogen. This reaction occurs in a narrow temperature range centered at approximately 1,800 to 2,000°F. If the temperature is more than 100 to 200°F over this range, the second reaction dominates and NO is created. At temperatures below the optimum range, the ammonia will be unreacted and will exit as ammonia slip. A variety of promoting agents or compounds have been developed which will shift the optimum temperature range down 100 to 300°F.

Urea injection for NO_x control was developed and patented by the Electric Power Research Institute (EPRI). When urea ($CO(NH_2)_2$) is injected into high temperature post-combustion gases, it decomposes to form ammonia and isocyanic acid (HNCO). The ammonia formed from the decomposition can then react with the combustion gas in the same manner as if ammonia had been injected directly into the gas stream. A key component of the process is what happens to the isocyanic acid formed from the decomposition process. This species reacts to form the NCO radical, which can then form NH or NO. Recent studies have shown that under certain process conditions, the NCO radical will react with NO to form N_2O. This species is not presently regulated, but there are growing concerns about N_2O since it may contribute to the greenhouse effect. Recent studies have identified several chemical agents which can be added to urea to extend the temperature range over which injection is effective at reducing NO_x emissions.

As with SCR, SNCR requires chemical injection into the flue gas stream. Chemical handling equipment, including storage tanks and injection grids, are required. Unlike SCR, however, a large reactor vessel housing the catalyst is not required, but the reactor vessel must be able to handle the increased temperatures associated with SNCR. This removes the pressure drop and elevated back pressures associated with this component.

4.4.1 Feasibility of SNCR for Test Cell Application

Many of the factors influencing the technical feasibility of SCR for application to test cells also apply to SNCR. Test cell stack gas exit temperatures are significantly below the reaction temperatures necessary for the application of SNCR, therefore stack gas reheat is required. In addition, a uniform NO_x concentration distribution and an ammonia or urea injection system are required to ensure maximum NO_x reduction and minimum ammonia or urea slip.

As with SCR, the temperature of the exhaust gas entering the SNCR system can be raised using a duct burner. However, because the reaction temperature of SNCR is significantly above test cell exit gas temperatures and the NO_x reduction potential using SNCR is less than SCR (50 to 60 percent versus 80 to 90 percent), a potential exists for a net increase in NO_x emissions from the test cell as result of the SNCR technology. This possibility for a net increase in NO_x emissions arises from the NO_x generated by the duct burners when reheating the gas stream. The reheat requirements are a function of the test cell operating characteristics and the engines tested within the facility. As such, the feasibility of SNCR strongly depends on the specific site. In Chapter 5, the cost of implementing SNCR is evaluated. In the analysis, the relative level of NO_x generated from the duct burner to that removed by the SNCR system is determined. This analysis indicates that SNCR is conceptually possible (reduces overall NO_x emissions) under a narrow range of test cell operational characteristics and will be discussed in Chapter 5. This narrow range severely restricts the use of SNCR technology for broad application to test cells. It is conceptually possible to design an SNCR system using conventional materials that could be applied to test cells. However, until the research and development and test and evaluation programs have been completed, the safety and performance issues cannot be fully addressed.

4.5 REBURN NO_x CONTROL TECHNOLOGY [14, 15, 16, 17]

Conventional gas reburning is a combustion modification emission control technique which reduces NO_x formed in the main combustion zone by firing natural gas in a second combustion zone under slightly fuel-rich conditions. NO_x is reduced by reactions with hydrocarbon fragments formed by the natural gas combustion. Typically, conventional gas reburn as applied to boilers involves injection of natural gas (at rates equal to about 15 percent of the total combustion load) into the region just above the main combustion zone. This is followed by the downstream introduction of the remainder of the combustion air. The injection of natural gas is ideally done with a nearly inert carrier, such as recirculated flue gas, to produce a slightly fuel-rich region. In that region, NO_x produced by the primary source is "reburned" and reduced to molecular nitrogen.

Depending on the initial NO_x level and the specific boiler design, NO_x emission control in the range of 60 percent may be achieved. Additional air is added following this "reburning zone" to complete combustion and return the excess air levels back to normal values. This transition region is also important for NO_x control since only a portion of the fixed nitrogen will be converted back to NO_x.

For conventional gas reburning to be effective, it is necessary to inject the natural gas into the flue gas stream and mix it rapidly with the combustion products from the primary combustion zone. Penetration of the natural gas into the flue gas stream can be improved by increasing the momentum of the injected natural gas stream via a carrier gas. The carrier gas should contain minimal oxygen since the objective of the natural gas injection is to produce a slightly fuel-rich zone. For boiler applications, flue gas is a convenient carrier because it typically contains only about 7 percent oxygen and does not require preheating.

For conventional gas reburning, the location, size and shape of the gas injectors are key to the overall effectiveness of the natural gas reburning process. These parameters are site specific and are selected as part of the process design. Typically, flow modeling (either computational or reduced scale) is required to reliably design this component.

As with the natural gas injectors, the location, size, and shape of the air injection ports are key to the overall effectiveness of the gas reburning process. The air must be injected far enough downstream of the reburn gas injectors to provide adequate residence time for the NO_x reduction reactions while still completing combustion. By adjusting the designs of the reburn gas injectors and overfire air ports, NO_x emission control, steam temperature, and CO burnout efficiency can all be balanced in boiler applications.

4.5.1 Feasibility of Reburning for Test Cell Application

As part of a series of exploratory studies of novel technologies to control NO_x emissions from engine test facilities, reburn was evaluated as a potential NO_x control technology for test cell application[16]. In the study, "lean reburn" was investigated using a laboratory scale rig to assess the likely performance and cost for application to a military test cell. Lean reburn involves utilizing a duct burner which consumes a portion of the excess oxygen available in the exhaust of the test cell. Unlike conventional reburn, burnout air is not added downstream of the burner. Figure 4-2 presents the schematic diagram of the test rig used to evaluate the technology. Figure 4-3 presents the possible configurations postulated for application of lean reburn to the test cell. Figure 4-4 presents the plot of the measured NO_x removal efficiency versus fuel equivalence ratio, where the fuel equivalence ratio is defined as the actual ratio of fuel to oxygen divided by the stoichiometric ratio of fuel to oxygen. Plotted in this fashion, values for the fuel equivalence ratio of less than 1 represent fuel-lean (excess oxygen) conditions. In the test rig, a 50 percent reduction in NO_x was observed at a fuel equivalence ratio of approximately 0.8. When the inlet NO concentration was lowered from 1,000 ppm to 550 ppm at the equivalence ratio of 0.8, the observed NO reduction efficiency was reduced to approximately 28 percent.

Using methane (CH_4) as the reburn fuel, a fuel equivalence ratio of 0.8 corresponds to an oxygen level of approximately 4.5 percent in the exhaust. Assuming an inverse linear relationship between the NO_x removal efficiency and the inlet NO_x concentration from Figure 4-4, this would yield a conservative estimate of a 10 percent NO_x reduction at an inlet NO_x concentration of 100 ppm. From Table 3-3, stack O_2 levels from the model test cells are in the range of 16 to 20 percent. Therefore, to achieve a 10 percent NO_x reduction,

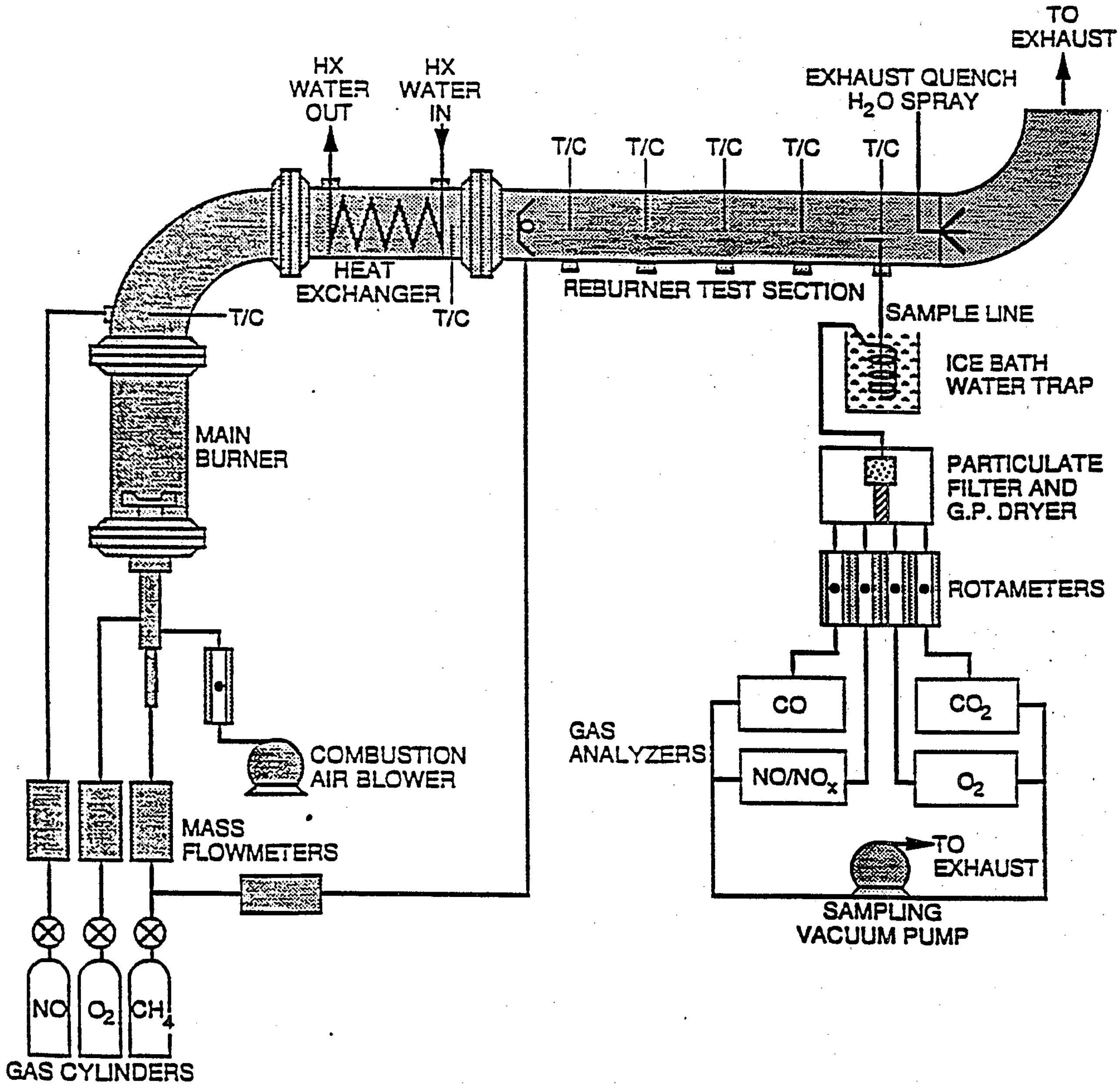
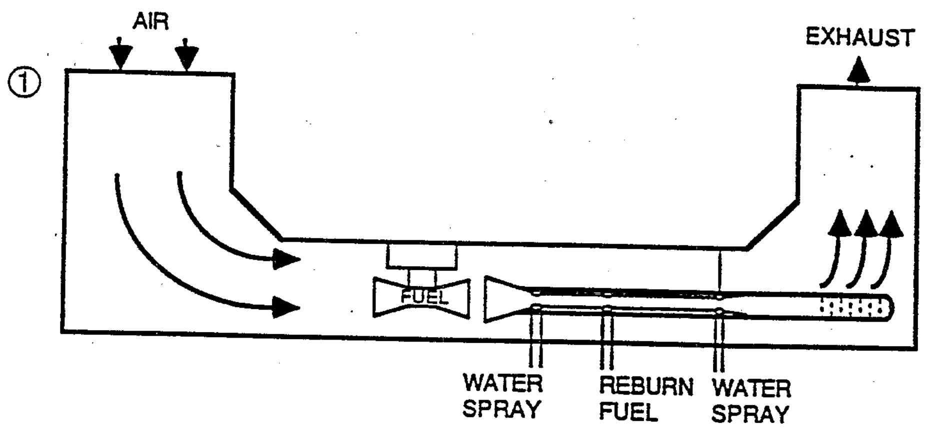
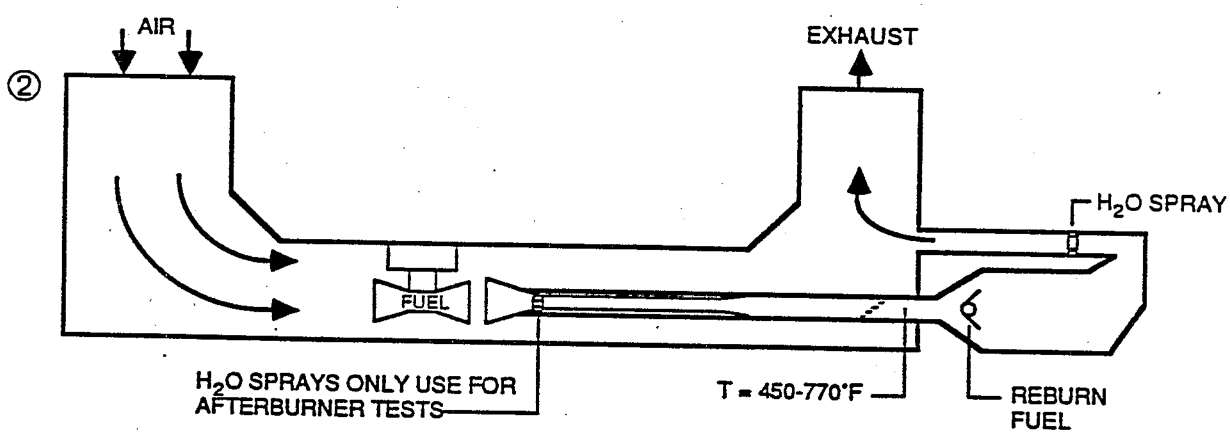


Figure 4-2. Reburn test apparatus.



- INCORPORATE REBURNING INTO AUGMENTER
- MAY REQUIRE REPLACING AUGMENTER WITH HIGH-TEMPERATURE ALLOY
- WORRY ABOUT VELOCITY/TURBULENCE



- INCORPORATE H_2O SPRAYS TO QUENCH VERY HIGH EXHAUST TEMPERATURES IN AUGMENTER
- BUILD EXTERNAL REBURN CHAMBER DOWNSTREAM OF EXISTING AUGMENTER TUBE
- ADJUST/CONTROL OF BACKPRESSURE?

Figure 4-3. Reburning options.

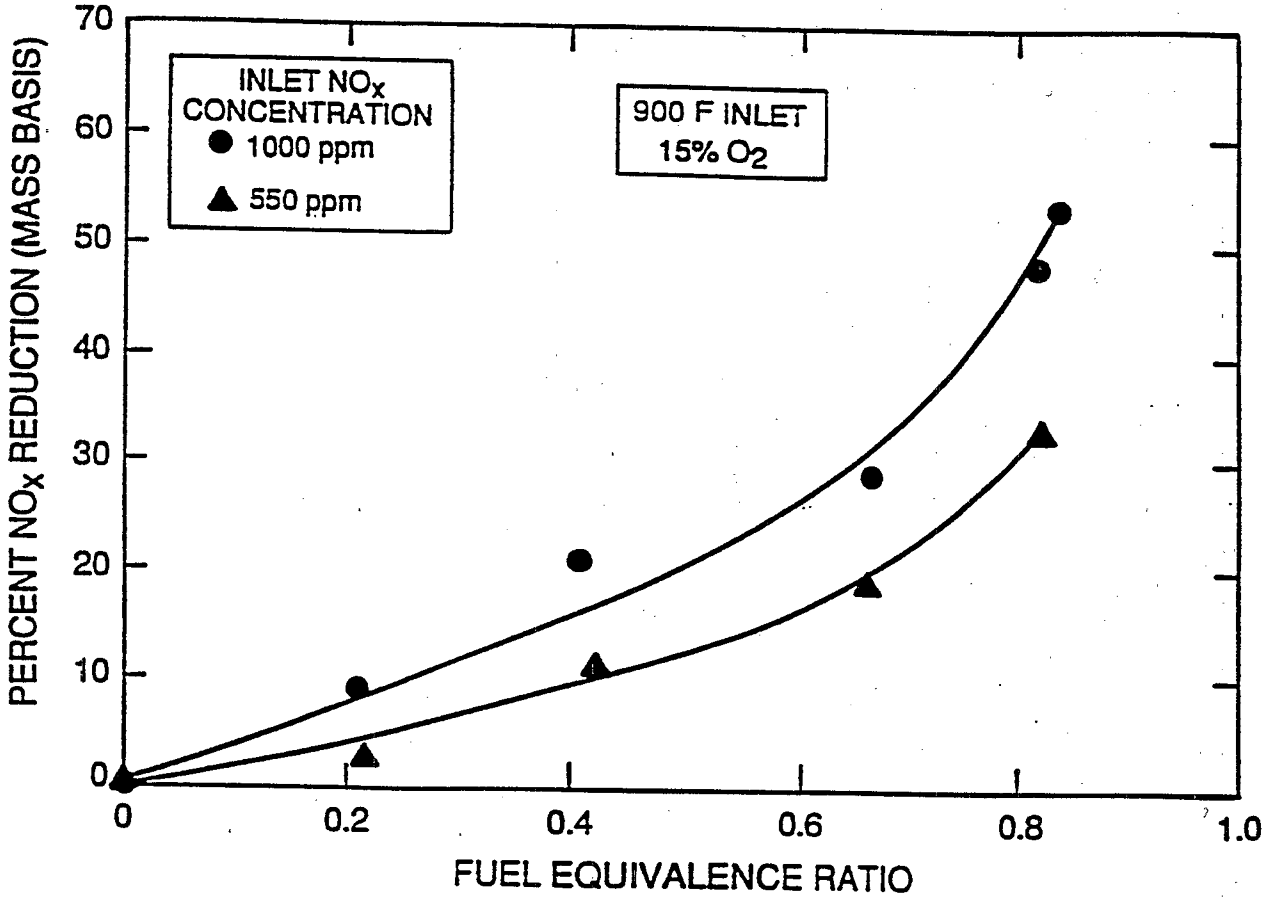


Figure 4-4. Effect of NO_x concentration on reburning NO_x reduction.

sufficient reburn fuel must be consumed to lower the oxygen level from between 16 and 20 percent to 4.5 percent. At stoichiometric conditions, 2 moles of oxygen are required for every mole of methane burned. At an equivalence ratio of 0.8, yielding the 10 percent reduction in NO_x, 2.5 moles of oxygen are required per mole of reburn fuel. The methane requirements necessary to reduce the stack O_2 levels to the required 4.5 percent and achieve the 10 percent reduction in NO_x emissions can be calculated as follows.

$$\text{Moles } (O_2) / \text{sec} = Ms / MWs * [O_2] \qquad \text{Eq. 4.1}$$

where:

Ms = Test cell stack gas flow rate (lbs/sec)
MWS = Test cell stack gas molecular weight
$[O_2]$ = Test cell stack gas oxygen concentration

The volumetric flow rate of methane required to achieve the 10 percent reduction in NO_x is given by:

$$CH_4(ft^3/sec) = 379(Moles/ft^3)*(Moles\ (O_2)/sec)/2.5 \qquad \text{Eq. 4.2}$$

Using the above equations and the stack conditions summarized in Tables 3-3 and 3-4, the methane consumption necessary to reduce the NO_x emissions 10 percent from the model test cells discussed in the previous chapter is summarized in Table 4-1. The methane consumption is based on 25 hours per year of test cell operation at maximum engine thrust. Under this condition, stack exit temperatures are highest and oxygen levels are lowest, with conditions favorable for reburn application.

Also provided is an estimate of the cost in \$/ton NO_x removed, assuming a methane cost of \$3/MSCF. These estimates

TABLE 4-1. COST EFFECTIVENESS FOR REBURN NO_x CONTROL APPLIED TO MODEL TEST CELLS

	Upstream of Reburn System						
Test Cell	Stack % O2	Stack Flow	NOx Emitted	Methane Flow	Annual Methane	NOx Removed	Cost Effectiveness
		(lbs/sec)	(tons/yr)	(Cubic ft/sec)	(MMSCF)	(tons/yr)	($1000/ton NOx)
A	20.5	35990	13.3	46279	4165	1.330	$9,395
B	18.3	2017	5.0	2313	208	0.500	$1,249
C	17.4	4728	2.6	5158	464	0.260	$5,356
D	17.6	938	1.4	1036	93	0.140	$1,998
E	17.0	19	0.12	21	2	0.012	$479

NOTES:

- Cost effectiveness estimate includes reburn fuel consumption only
- Stack flow rates based on maximum engine thrust and an augmentation ratio of 5 for Test Cells A, B, C, and D
- Stack flow rates based on maximum engine shaft horsepower and an augmentation ratio of 0.2 for Test Cell E
- Test cell emissions computed using 25 hours/year at maximum thrust
- NOx removal efficiency of 10% based on 100 ppm inlet concentration and an 0.8 fuel equivalence ratio
- Methane costs of $3 / 1000 cubic feet assumed
- MMSCF = million standard cubic feet

range from a low of approximately $480,000 per ton NO_x removed to a high of over $59 million per ton. These estimates do not reflect any costs beyond those associated with the methane gas consumption. In addition, an optimistic 10 percent reduction in NO_x was assumed based on an estimate of mean stack NO_x concentration levels of 100 ppm. Actual stack NO_x concentrations are a function of the augmentation air flow and can be less than 100 ppm.

The assumption that lean reburn can achieve even a 10 percent reduction in NO_x emissions has not been proven at inlet conditions similar to those found in test cells. For this reason, lean reburn cannot be considered a proven technology for test cell application. It is conceptually possible to design a reburn system using conventional materials that could be applied to test cells. However, until the research and development and test and evaluation programs have been completed, the safety and performance issues cannot be fully addressed. In the event that the lean reburn technology would achieve this level of NO_x reduction performance, the methane consumption alone drives the cost effectiveness in $/ton NO_x removed above those anticipated for SCR (Chapter 5).

4.6 ENGINE MODIFICATION APPROACHES TO NO_x EMISSION REDUCTIONS

Temporarily modifying the engine during the test to reduce engine NO_x emissions is a potential approach to reducing NO_x emissions from test cells. However, as will be discussed in Section 4.6.3, the engine modifications necessary to reduce the NO_x emissions significantly alter the engine performance characteristics.

4.6.1 Steam/Water Injection Process Description[18, 19]

Steam or water injected into the primary combustion zone of a gas turbine engine provides a heat sink which lowers the flame temperature and thereby reduces thermal NO_x formation. This injection is described by the water-to-fuel ratio (WFR) evaluated on a mass basis (lb water or steam injected per lb fuel consumed). For water injection, the control system would require a water purification system, pump(s), water metering valves and instrumentation, turbine-mounted injection nozzles, and any necessary interconnecting piping. A steam injection system would require the same items except a steam generator would replace the pump(s).

The WFR is the most important factor affecting the performance of steam or water injection. The injection rate is directly related to the NO_x abatement potential. The higher the WFR, the higher the possible NO_x abatement. For the gas turbine industry, WFR's range from 0.46 to 2.28 to achieve controlled NO_x emission levels for oil-fired units ranging from 42 to 110 ppmv, corrected to 15 percent oxygen. Water-based WFR's are usually lower than the steam WFR for the same NO_x abatement. The latent heat associated with water injection increases the heat sink capability of water injection and therefore lowers the required WFR for a given NO_x reduction level. From available stationary gas turbine data, steam/water injection is used to achieve NO_x removal efficiencies of 70 to over 85 percent from uncontrolled levels.

The type of fuel burned in the turbine affects the performance of steam or water injection. In general, lower controlled NO_x emission levels may be achieved with gaseous fuels than with oil fuels. For turbines firing distillate oil fuels, steam/water injection has the effect of increasing the conversion of fuel-bound nitrogen to NO_x (Figure 4-5). This would not be anticipated to affect the engines tested within test cells which burn fuels with fuel-bound nitrogen levels of typically less than .015 percent.

4.6.2 Fuel Emulsion Process Description [20, 21]

The use of a water-in-fuel emulsion is a more recent NO_x control technique developed for stationary gas turbines. The process reduces NO_x by lowering the peak flame temperature in precisely the same manner as steam/water injection discussed in the previous section. The water-in-fuel suspension allows a more ideal heat absorption to occur due to both the homogeneous nature of the emulsion and the ideal location of the water in close vicinity to the burning fuel droplet. Additionally, the process creates the emulsion prior to injection and combustion. In contrast, the steam/water injection fluid forms a heterogeneous post-combustion mixture where fuel predominates in some areas of the flame and the steam/water predominates in others.

The fuel emulsion homogeneous mixture allows for a lower WFR than in traditional steam/water injection. The emulsion WFR ranges from 20 to 50 percent and is stabilized with chemical additives to maintain the emulsion at the high temperature and pressure associated with injection. The process uses similar hardware as water injection with additional equipment for the emulsification, chemical stabilizer, storage, and injection systems (including metering valves and instrumentation). This system can be retrofitted onto existing fuel delivery systems.

Nalco Fuel Tech has developed an emulsion technology for distillate oil-fired stationary gas turbines. The technology has been tested in both short-term and long-term tests.

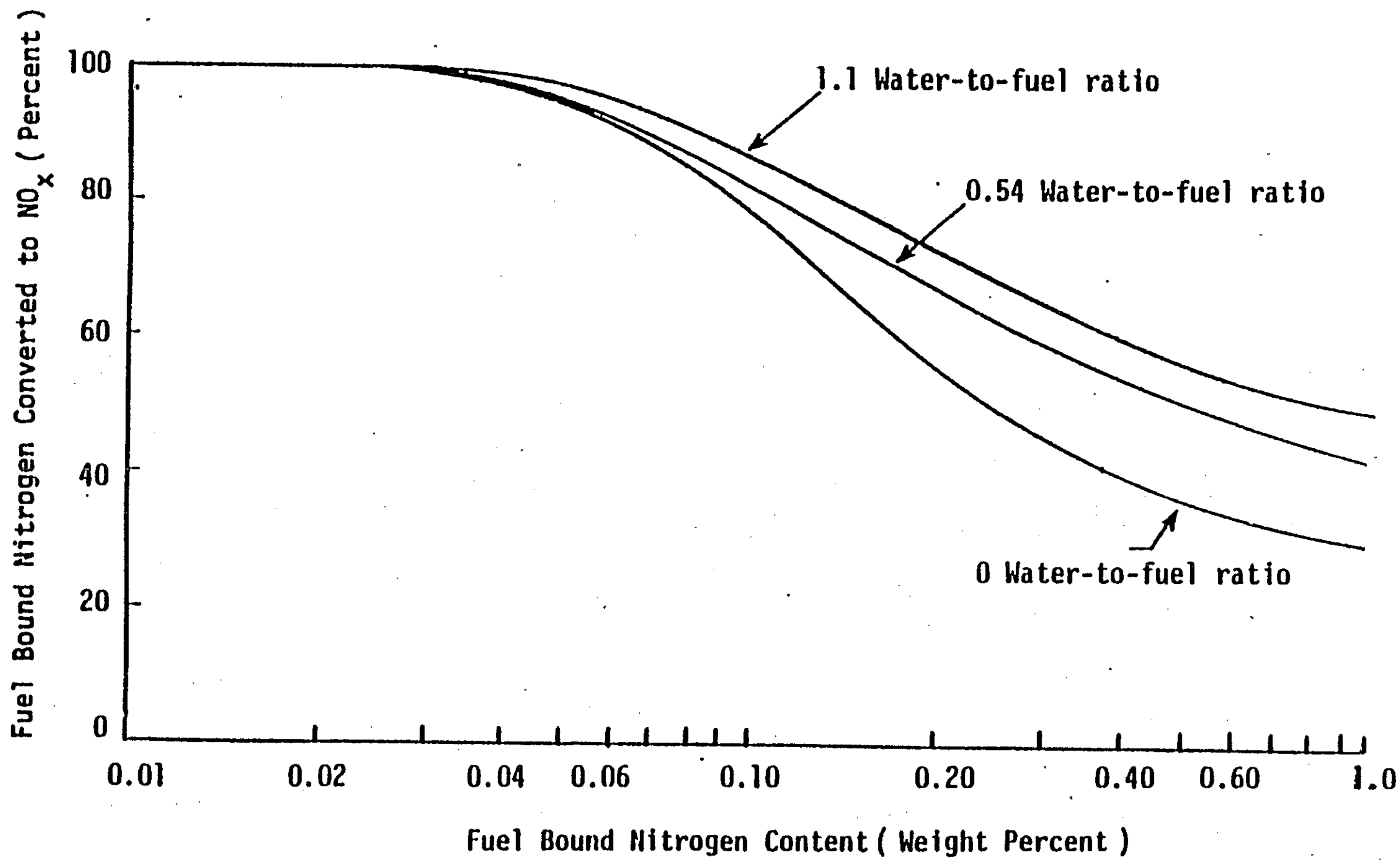


Figure 4-5. Percentage fuel-bound nitrogen converted to NO_x vs. fuel-bound nitrogen content and water-to-fuel ratio.

The short-term tests were conducted at Public Service and Gas Company's (PS&G) Kearney Generating Station on a single TP&M A4 engine operated as part of a twinpak consisting of two gas turbine engines and one generator. NO_x emission reductions ranging from 8 to 68 percent, with water weight percents of 4.4 to 36, respectively, were achieved. The short-term emulsion tests caused no observable detrimental effects to the gas turbine engine.

A long-term demonstration of the Nalco Fuel Tech NO_x emissions reduction process was later conducted on PS&G Edison Station Unit #1. The unit consists of four twinpaks for a combined unit output of 76 MW. The twinpak engines are FT4 A-9 aeroderivative gas turbines and are dual-fuel capable. Four separate emulsification systems were installed, one to service each twinpak. Tests were conducted over a 60-day period on one of the four engines with emission measurements of NO_x, CO, O_2, and unburned hydrocarbon (UHC). During the testing, the water content of the emulsion varied from 0 to 0.65 water/oil weight ratio. With the ratio at 0.65, a reduction in NO_x emissions of close to 70 percent was observed.

Water-in-fuel emulsion lowers the flame temperature and therefore is an effective thermal NO_x control for gas turbine engines. This approach has the initial apparent advantage over the more traditional steam/water injection method in that injection nozzles mounted within the combustor are not required. However, for both water in fuel emulsion and steam/water injection, the impact on engine performance will be similar, and hardware modifications to the engine under test would be required that would not be used during in-flight service.

4.6.3 Feasibility of Water/Steam Injection and Fuel/Water Emulsion for NO_x Control of Test Cells

As described in Chapter 2, the owner/operators of test cells utilize the facilities for either engine development or certification and evaluation following engine repair. The use of either water/steam injection or water-in-fuel emulsion would require temporary engine modifications and would significantly alter the performance characteristics of the engine under test. These modifications would result in the evaluation of an engine within the test cell which would require further modification before being returned for in-flight service. Additionally, the operating characteristics of the modified engine will be significantly different in all of the critical areas used to evaluate the performance of the engine within the test cell. The use of either water/steam injection or water-in-fuel emulsion will impact the engine under test as follows.

- For a given turbine inlet temperature, there will be an increase of fuel usage related directly to the latent and sensible heat of the water.
- The increased fuel flow and water flow will cause increased mass flow through the turbine, which will increase turbine rotor speed and engine thrust.
- An increase in turbine speed will increase compressor speed and result in increased air flow through the compressor and an increase in engine pressure ratio.
- Increased air flow drives conditions in the combustor more fuel-lean.

- Engine tests to a specific thrust condition can be reached at lower turbine inlet temperatures due to increased mass flow through the turbine.

- Engine tests to a specific thrust condition can be reached at reduced fan speeds. This would limit information regarding blade failures, vibration, and tip clearance variations.

- The change in specific gravity from as little as a 10 percent water emulsion may require modification to some engines' fuel control system (i.e., pump and fuel lines).

- Changes to fuel flow and pressure drop across fuel nozzles would greatly impact fuel atomization and the details of the burning process. This might impact the relight capability, blow-out performance, and flame stability.

All of the changes arising as a result of the NO_x controls applied to the engine will affect performance parameters which are critical in assessing engine integrity, including fuel efficiency, thrust, and temperature calibration. Engine testing with either steam/water injection or fuel emulsion installed following repair would require subsequent alterations to the engine before returning the engine to service. These additional alterations and modifications would raise air-worthiness concerns.

The use of temporary modifications to the engines tested within test cells would result in engines tested with performance characteristics which are not representative of the engine when prepared for in-flight service. This condition alone defeats the purpose of certification and validation testing following engine repair. For engine development related test cell operation, critical component testing and engine performance determination would be invalid or provide data for unrealistic or non-representative engines and operating conditions. For these reasons, as well as safety concerns that would certainly be raised, water/steam injection and water-in-fuel emulsion technology for test cell applications should not be considered technically viable options.

4.7 EMERGING TECHNOLOGIES

4.7.1 NO_x Sorbent Technology [22, 23, 24, 25, 26, 27]

The Air Force has directed a series of efforts focused on developing a control technology to reduce NO_x emissions from test cells. Phase I and Phase II investigations involved laboratory screening of 25 variations of a coated vermiculite substrate sorbent, bench-scale testing of the most promising options, slipstream tests, and finally prototype development for testing on a test cell.

The NO_x control technology selected for prototype testing was a magnesium oxide-coated (MgO) vermiculite bed preceded by either another uncoated vermiculite or an activated carbon bed. As the exhaust gas passed through the sorbent beds, the NO_x was adsorbed onto the bed material, which effectively acted as a NO_x "filter". Two engines, one a 2,200 lbf thrust and the other 930 lbf thrust, were tested in the facility. Temperatures at the filter inlet fluctuated between 170 and 210°F at 80 percent engine thrust. The system was designed such that the filter could be exposed to the entire exit gas flow from the facility. However, due to excessive pressure drop across the NO_x control system, only a small portion of the gas stream was subjected to the sorbent beds. The data suggest that only 10 percent of the exit gas stream passed through the sorbent beds, while the remaining gas flow went through slot doors placed adjacent to the NO_x control system. A NO_x removal efficiency ranging from 40 to 75 percent was reported using the upstream bed of virgin vermiculite. A slight improvement in NO_x removal efficiency was reported when incorporating the activated carbon bed.

The vermiculite sorbent technology operates in a temperature region more suited for test cell application than either SCR or SNCR. However, insufficient testing of this technology on either test cells or other NO_x emission sources has been completed to document the performance of the technology for extended operation. There is an approved proposal to further evaluate this approach on a test cell. It is conceptually possible to design a vermiculite sorbent bed that could be applied to test cells. However, until the research and development and test and evaluation programs have been completed, the safety and performance issues cannot be fully addressed.

4.7.2 Low NO_x Combustor Technology [28]

As described in Chapters 2 and 3, the NO_x emission rates from test cells are a direct function of the engine under test. Jet-type aircraft engines designed and installed in the 1970s burned cooler and less completely than the current generation of aircraft engines. This resulted in lower NO_x emission factors and higher carbon monoxide (CO) and total hydrocarbon (THC) emission factors (emission factor is defined as lbs of pollutants per lbs fuel burned). Engine and combustor development focused on improving engine performance and efficiency has altered these characteristics considerably. Current jet-type aircraft engines have relatively lower CO and THC emission factors and higher NO_x emission factors at full and flight power. Presently, there is a considerable effort being made to lower the NO_x emission factors from aircraft engines while still maintaining the reduced CO and THC emission factors.

Dry low NO_x combustor technology has been developed for stationary gas turbine applications. In this technology, combustors are designed to minimize NO_x production without the use of steam/water injection. Stationary gas turbines incorporating dry low NO_x combustors primarily fire natural gas, whereas aircraft engines burn liquid fuel. The combustion characteristics of liquid fuels are significantly different than those of gaseous fuels and typically result in higher NO_x emissions. Aircraft engines require rapid transient operation with a low risk of flame out. When flame out does occur, easy restart is required. These requirements place further demands on the combustor technology which are not required in stationary gas turbines. Currently, there are two basic aircraft engine low NO_x combustor designs under research by manufacturers and NASA. They are the lean pre-mixed/prevaporized(LPP) and the rich-burn/quick-quench/lean-burn (RQL).

The development of low NO_x combustion technology for aircraft engines may ultimately reduce NO_x emissions from the test cell population. The development and sale of aircraft engines with reduced NO_x emission rates will be followed by a transition period as these engines progress onto their aircraft fleet.

4.8 EFFECTS OF TEST CELL NO_x CONTROL TECHNOLOGIES ON AIRCRAFT ENGINE SAFETY, DESIGN, STRUCTURE, OPERATION AND PERFORMANCE TESTING [6,7]

Subparts 4 and 5 of §233(a) of the CAAA pertain to the effects that NO_x control technologies might have on the safety, design, structure, operation and performance of aircraft engines and the impact on the effectiveness and accuracy of aircraft engine safety design and performance tests conducted at test cells. All of the known potential effects that the various control technologies may have on the engine or the engine test are addressed in the following sections. However, until the research and development and test and evaluation programs have been completed, the safety and performance issues on testing cannot be fully addressed.

4.8.1 Effects of Water or Steam Injection

As discussed previously, water or steam injection and fuel/water emulsion would directly affect the engine and engine test by altering the performance characteristics during testing. These modifications would result in the evaluation of an engine within the test cell which would require further modification before being returned for in-flight service. Also, this type of NO_x control would result in engines tested with performance characteristics which are not representative of the engine when prepared for in-flight service. This alone defeats the purpose of certification and validation testing following engine repair. For engine development-related test cell operation, critical component testing and engine performance determination would be invalid or provide data for unrealistic or non-representative engines and operating conditions.

4.8.2 Effects of Back Pressure

Back pressure resulting from add-on NO_x controls may also affect the engine or engine test. The back pressure associated with the post-combustion NO_x control technology equipment, such as catalyst and sorbent beds, and duct burners would impede the air flow through the test cell. Using conventional technology, designs can limit back pressure to 0.1 inch water for a duct burner and 1 to 2 inches of water for a catalyst bed.

The aerodynamics of the test cell can affect the performance of the engine being tested. In turn, an increase in back pressure, as would occur with an add-on NO_x control technology, would affect the aerodynamics of the test cell. Air flow recirculation, causing temperature and pressure distortion of the engine inlet air, can lead to uncertainty about engine performance measurements. Engine performance may become unstable and unrepeatable, leading to test rejection and possibly unnecessary engine rebuild. Recirculation of air within the test cell will also affect engine thrust measurement. In extreme cases, engine inlet air flow distortion may result in compressor stall and cause severe engine damage.

An increase in back pressure downstream of the test engine may reduce the augmentation ratio (an indicator of the amount of test cell dilution air which bypasses the engine). This would make it necessary to recalibrate the test cell for each engine model tested in that test cell. In addition, the increase in back pressure may make it necessary to decrease the maximum thrust capability of a test cell to compensate for the decrease in augmentation air flow. This resultant decease in thrust capability would effectively limit the size of engines that can be tested in the cell. Continued testing of these engines would require a major modification of the test cell or construction of a new test cell that would use NO_x controls and not affect the safety or performance of the engine.

One modeling study indicated that vortices in the test chamber may be avoided if the augmentation ratio is kept above 0.8. New test cells are designed so that augmentation ratios are typically greater than 0.8, and in practice, augmentation ratios are normally between 1 and 10. Therefore although the add-on NO_x control technology may lead to a reduced augmentation ratio, there is some indication that if the new augmentation ratio remains greater than 0.8, inlet air vortices may be avoided. However, for low bypass ratio engine testing and engine core testing, the minimum augmentation ratio is determined by the cooling requirement on the aft portion of the engine. Subsequently, low bypass ratio engine testing and engine core testing augmentation ratios must be maintained much higher than 0.8 to provide sufficient cooling.

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CHAPTER 5

COSTS OF IMPLEMENTING NO_x CONTROL TECHNOLOGIES

5.1 OVERVIEW

The costs of implementing selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) NO_x controls to the model test cells developed in Chapter 3 are presented in this chapter. As discussed in Chapter 3, these model test cells are representative of the current population of test cells within the United States. As discussed in Chapter 4, SCR and SNCR are well-established control technologies for other fossil fuel-fired NO_x sources; as such, many of the cost components associated with implementing each of these methods are readily defined. However, due to the unique nature of test cell operation, there are several aspects of the costs associated with implementing SCR and SNCR which would typically not be found for other more traditional SCR/SNCR installations.

Section 5.2 describes the methodology used in the cost analysis. Section 5.3 describes the components of the SCR cost model as applied to the five model test cells developed in Chapter 3. In Section 5.4, the cost estimates of implementing SCR to the five model test cells are presented. The costs of implementing SCR are strongly dependent on several parameters, including the desired level of NO_x emission reduction. In Section 5.5, the sensitivity of the cost projections to changes in this value, as well as the other major cost elements, are examined. The cost components of implementing SNCR are described in Section 5.6. The cost estimates of implementing SNCR to the five model test cells are presented in Section 5.7.

5.2 COST ESTIMATION METHODOLOGY

The costs of implementing both SCR and SNCR NO_x controls to test cells can be divided into two major cost categories -- capital investment costs and annual operating and maintenance (O&M) costs. Capital costs consist of the total investment necessary to purchase, construct, and make operational a control system. Operating and maintenance costs are the total annual costs necessary to operate and maintain the control system.

Capital costs of NO_x controls include both direct and indirect cost components. Direct capital costs are expenses required to purchase equipment for the control system as well as those expenses required for installing the equipment. Indirect capital costs are those costs entailed in the development of the overall control system.

Annual O&M costs are also classified as either direct or indirect annual costs. For this analysis, O&M costs are considered to be costs resulting from the operation of the NO_x control equipment and do not include the annual O&M costs of operating the test cell without NO_x controls.

Using the Office of Air Quality Planning and Standards (OAQPS) EPA costing methodology, total capital investment and annual O&M costs may be combined to give a total annualized cost.[1] Total capital investment is converted to a uniform annual capital recovery cost by multiplying the total capital investment by the capital recovery factor given by:

$$CRF = i(1+i)^n/((1+i)^n-1) \qquad \text{Eq. 5.1}$$

where:

n : Economic life (years).
i : Pretax marginal rate of return on private investment.

For the analysis presented in this chapter, a 20-year life expectancy is used. This is combined with a value of 7 percent for the pretax marginal rate of return (i) and results in a cost recovery factor of 0.094.

As described in Chapter 4, selective catalytic reduction of NO_x utilizes a catalyst whose reactivity decreases over time. This loss of catalyst activity has the effect of reducing the performance of the SCR system. Typical vendor guarantees of the reactor catalyst life when applied to gas fired boilers, heaters and power generating turbines range between 3 and 5 years, although actual data indicate that little reduction in reactor performance occurs before 6 to 10 years. Traditional SCR systems have never been implemented on test cells; therefore, actual life expectancy data are unavailable. However, it is likely that the thermal cycling associated with the operation of test cells will have a detrimental effect on the life of the reactor catalyst. Additionally, due to the low sulfur content of Jet A (the fuel primarily burned by the engines tested within the test cells), it is unlikely that catalyst "poisoning" will occur, and in the absence of other factors an extended catalyst life on the order of 6 to 10 years would be expected. Because of these two competing conditions, a life expectancy of 5 years has been chosen for the reactor catalyst.

The cost effectiveness of implementing SCR and SNCR can be determined by dividing the total annualized cost by the anticipated NO_x emission reduction (in tons) to generate a $/ton NO_x removed ratio. The calculation of the cost effectiveness ($/ton) not only allows comparison of cost effectiveness between SCR and SNCR when applied to test cells, but can be used to compare the cost effectiveness of implementing NO_x controls to sources other than test cells within a specific geographical region. As discussed in Chapter 4, the application of SCR and SNCR to test cells requires significant reheating of the stack gas to the operating temperature range of the control technology. This reheating has the effect of increasing the amount of NO_x entering the control system. In the cost analysis presented in this chapter, the tons of NO_x removed used in the cost effectiveness calculation is taken as the difference between the uncontrolled model test cell NO_x emissions and the NO_x emissions following application of the NO_x control system. The removal of NO_x generated by reheating of the test cell gas is not credited in the cost-benefit calculation. Additionally, the cost effectiveness calculation for both SCR and SNCR predicted negative cost effectiveness values at some operating conditions. A negative cost effectiveness results from the control technology forming more NO_x than it can remove.

5.3 SELECTIVE CATALYTIC REDUCTION COST COMPONENTS

The SCR cost model is based on the SCR system described in Chapter 4 applied to the model test cells described in Chapter 3. The cost elements are derived from a conceptual design of the system, supported with typical costs of SCR when applied to other gas-fired systems. As described in Chapter 4, the SCR reactor would be located in the stack region of test cells. The main components of any SCR NO_x control system include: the ammonia tank, the ammonia vaporization system and injection grids, the catalyst reactor vessel, catalyst, and a controller. In addition to these elements, application of SCR to the model test cells requires the use of duct burners to reheat the gas stream to the operating temperature of the catalyst material. Conceptually, the duct burners must be located upstream of the ammonia injection grid, either at the base of the stack or at the end of the augmenter tube region of the test cell. The catalyst vessel can be located within or on top of the stack, either in place of the exit baffles or within the exit baffles if they exist.

Typically, the primary cost element of an SCR NO_x control system is the catalyst. Final selection of both the catalyst material and the desired NO_x emission reduction impacts other costs associated with installing and operating an SCR system, including those related to the reactor vessel, construction and contingency (indirect capital costs), reheat fuel requirements, and chemical costs. Cost elements which have not been included in the cost analysis are system design/development costs and the cost of recalibrating the engine/test cell combination following retrofit to account for the change in air flow characteristics through the cell. It is not anticipated that these components will significantly alter the cost effectiveness estimates. Using the cost analysis methodology outlined in Section 5.2, every $1 million of capital investment increases the cost effectiveness estimates by $4,000 per ton NO_x removed (cost recovery factor of 0.094 and 24 tons NO_x per year).

There are a variety of catalyst materials commercially available for use in SCR NO_x control systems. Selection of a particular catalyst material defines the required operating temperature range of the reactor vessel. Selection of a pressure drop across the reactor vessel combined with a desired level of NO_x emission reduction are the principle elements in determining the space velocity of the catalyst material. The space velocity is defined as the volumetric gas flow rate divided by the catalyst volume ($ft^3/hr/ft^3$) and has units of hrs^{-1}. The space velocity is inversely related to the residence time required for the stack gas to remain over the catalyst material in order to achieve the desired level of NO_x emission reduction. Early SCR NO_x systems were developed using a titanium/vanadium-based (TiO_2/V_2O_5) system. For gas-fired systems, space velocities were typically on the order of 15,000 hrs^{-1} to 20,000 hrs^{-1}. Currently, for the same level of NO_x emission reduction, gas-fired boilers, heaters, and power generating turbines are using titanium/vanadium-based SCR systems with space velocities in the 30,000 hrs^{-1} to 50,000 hrs^{-1} range. More recently, platinum-based catalysts have been developed with operating temperatures significantly below those found in the titanium/vanadium-based systems. In applying SCR to the model test cells of Chapter 5, several catalyst systems were considered. The catalyst materials and their operating characteristics are summarized in Table 5-1. The costs per cubic foot of catalyst presented in Table 5-1 are derived from recent vendor quotes of catalyst systems to be installed in a variety of natural gas-fired industrial boilers and process heaters. These gas-fired systems were operating with stack NO_x conditions on the order of 33 ppm (at 15 percent O_2). The space velocities summarized in Table 5-1 are based on NO_x emission reductions of 80 percent for all catalyst materials.

As previously discussed, the operating characteristics of the individual catalyst material affects the costs of installing SCR to test cells beyond the purchase cost of the

TABLE 5-1. SUMMARY OF CATALYST MATERIAL PARAMETERS USED IN SCR COST ANALYSIS

Catalyst Material	Back Pressure, inches water gauge	Operational Temperature, °F	Space Velocity, hr^{-1}	Volume Cost, $/ft^3	NOx Reduction, %
Platinum	1	490	27000	$4,100	80
Platinum	2	490	52673	$3,500	80
TiO_2/V_2O_5	1	650	35324	$1,200	80
TiO_2/V_2O_5	2	650	56651	$1,200	80

catalyst itself. The platinum catalyst, which has the lowest operating temperature (490°F), will require less reheat fuel to elevate the stack gas temperature to the catalyst operating temperature than required for the titanium/vanadium-based SCR systems. Additionally, this reduction in reheat fuel consumption reduces the ammonia requirements necessary to maintain the prescribed NO_x emission reduction since the duct burners will contribute less to the NO_x load entering the SCR reactor. However, as will be presented in the next section, these benefits of the reduced operating temperature associated with the platinum catalysts do not exceed the increase in catalyst purchase cost.

The required catalyst volume necessary to achieve the target NO_x emission reductions is determined by the space velocity for the individual catalyst system and the stack gas volume flow rate from the model test cells. As described in Chapter 3, the stack gas volume flow rate is a function of the specific engine used in the model test cell and the augmentation ratio.

Table 5-2 presents a copy of a portion of the spreadsheet used to calculate the costs associated with implementing SCR to the turbofan/turbojet model test cells using the titanium/vanadium-based catalyst. The required catalyst volume is computed using the stack gas flow rate and the required space velocity for the particular catalyst material from Table 5-1. The cost of purchasing the catalyst is calculated using the required catalyst volume and cost per cubic foot (Table 5-1). As discussed in Section 5.2, the catalyst is modeled with a 5-year life expectancy and annualized using the cost recovery factor of 0.24 (5 years, 7 percent).

The capital cost of the reactor vessel used to house the catalyst is estimated at 10 percent of the catalyst cost.

TABLE 5-2. TURBOFAN/TURBOJET MODEL TEST CELL SCR COST MODEL

AR= 5				
SCR Catalyst Type	TiO2/V2O5	TiO2/V2O5	TiO2/V2O5	TiO2/V2O5
Model Test Cell	A	B	C	D
Pressure Drop of Catalyst Bed, " wg	2	2	2	2
Temperature of Catalyst, °F	650	650	650	650
Space Velocity of Catalyst Bed, hr^-1	56651	56651	56651	56651
Peak Gas Flow, lbs/sec	10123	2017	4728	938
Peak ACFS at Catalyst Operating Temp.	273808	54548	127878	25373
Required Catalyst Volume, ft3	17400	3466	8126	1612
Catalyst Cost, $/ft3	$1,200	$1,200	$1,200	$1,200
Direct Capital Costs (5 years, 7%)				
SCR Catalyst Cost	$20,879,601	$4,159,667	$9,751,490	$1,934,841
Cost Recovery Factor	.243	.243	.243	.243
Annualized Cost	$5,073,743	$1,010,799	$2,369,612	$470,166
Direct Capital Costs (20 years, 7%)				
SCR Reactor Vessel (10% Cat. Costs)	$2,087,960	$415,967	$975,149	$193,484
Ammonia Tank	$14,000	$14,000	$14,000	$14,000
CEM/Contol Systems	$175,000	$175,000	$175,000	$175,000
Duct Burners	$20,000	$20,000	$20,000	$20,000
Ammonia Vaporization System	$15,000	$15,000	$15,000	$15,000
Total	$2,311,960	$639,967	$1,199,149	$417,484
Indirect Capital Costs (20 years, 7%)				
Contingency (3% Direct Capital Cost)	$69,359	$19,199	$35,974	$12,525
Constuction (20% Direct Capital Cost)	$462,392	$127,993	$239,830	$83,497
Total	$531,751	$147,192	$275,804	$96,021
Total Capital Costs (20 Years, 7%)	$2,843,711	$787,159	$1,474,953	$513,505
Cost Recovery Factor	0.094	0.094	0.094	0.094
Annualized Cost	$267,309	$73,993	$138,646	$48,270
Total Installed Cost	**$23,723,312**	**$4,946,826**	**$11,226,444**	**$2,448,347**
Total Annualized Capital Cost	**$5,341,052**	**$1,084,792**	**$2,508,258**	**$518,436**
Annual Operating				
Ammonia, ($200/ton 25% wt sol.)	$19,707	$4,466	$2,917	$1,630
Reheat (NG), ($3.5/MMBtu)	$2,958,091	$439,059	$344,503	$197,296
Labor (10% Operating Costs)	$297,780	$44,352	$34,742	$19,893
Total	$3,275,578	$487,877	$382,163	$218,818
Total Annual Cost	**$8,616,630**	**$1,572,669**	**$2,890,420**	**$737,254**
Cost Effectiveness				
Engine NOx Emissions, tons/yr	24.397	8.832	4.946	2.695
Duct Burner NOx Emissions, tons/yr	42.258	6.272	4.921	2.819
Total Tons NOx Emitted per year	66.656	15.104	9.867	5.513
Total Tons NOx Removed (80%) per year	53.32	12.08	7.89	4.41
Net Tons Emitted per year	13.33	3.02	1.97	1.10
Net Tons Removed per year	11.07	5.81	2.97	1.59
Total ($/Net ton NOx removed)	**$778,655**	**$270,636**	**$972,379**	**$463,068**

The contingency and construction costs (indirect capital costs) are based on a percentage of those direct capital costs which are annualized over 20 years. The contingency costs are estimated to be 3 percent of the direct capital costs. The construction costs are estimated to be 20 percent of the direct capital costs. As discussed in Section 5.2, the annualized capital costs are determined using the cost recovery factor computed using a 20-year life and an interest rate of 7 percent. The total installed cost is calculated as the cost of purchasing the catalyst plus the direct and indirect capital costs.

The annual operating costs are dependent on both the catalyst material and the individual model test cell operating characteristics. The temperature difference between the operational temperature of the catalyst (Table 5-1) and the model test cell stack temperature is used to estimate the heat input required from the duct burner. The annual heat input estimate incorporates the engine power schedule for the model test cells and the total operating hours of the model test cell as described in Chapter 3. The costs of reheating the stack gas is based on a natural gas cost of $3.50/MMBtu. The duct burner contributes additional NO_x loading on the SCR reactor. A NO_x emission factor of 0.1 lbs NO_x per million Btu[2] is used in the calculation, which is consistent with the performance of natural gas-fired burners. The required ammonia flow rate is then calculated using the NO_x mass flow rate determined in the model test cell and the additional NO_x from the duct burners and a NH_3/NO_x molar ratio of 1. The cost of the ammonia is based on the use of an aqueous ammonia solution (25 wt percent NH_3) with a price of $250/ton of solution.

The cost effectiveness of SCR in $/ton NO_x removed is determined by summing the annual operating costs and the annualized capital costs (including the catalyst cost) and dividing by the total annual tons of NO_x removed by the SCR system. As discussed in Section 5.2, the NO_x removed by the SCR system originating from the duct burner is not included in this calculation.

A complete sample calculation of the costs associated with implementing SCR is presented in Appendix D.

5.4 COST ESTIMATES FOR IMPLEMENTATION OF SCR TO MODEL TEST CELLS

Figure 5-1 and Table 5-3 present the cost effectiveness estimates for installing SCR to the turbofan/turbojet model test cells. For each model test cell there is a significant range in the predicted cost effectiveness estimates arising from the catalyst material and the test cell operating characteristics. For all model test cells, the most cost effective installation of SCR uses the titanium/vanadium catalyst with the 2-inch pressure drop across the reactor vessel (2" $\Delta P, TiO_2/V_2O_5$). The highest costs are predicted using the platinum-based catalyst with the 1-inch pressure drop across the reactor vessel. The most cost-effective installations of SCR on the turbofan/turbojet model test cells range from a low of $270,000/ton NO_x removed for Model Test Cell B to a high of $972,000/ton NO_x removed for Model Test Cell C at an augmentation ratio of 5 (an augmentation ratio of 5 was chosen as the median of the augmentation ratios examined). The EPA has estimated the cost effectiveness of implementing SCR to land-based, gas-fired power generating turbines of similar size to those engines used in the model test cells to be in the range of $6,000 to $10,000 per ton of NO_x removed.[3] This large difference in cost effectiveness is a direct result of significantly lower annual NO_x emissions from the model test cells with similar peak gas volume flow rates.

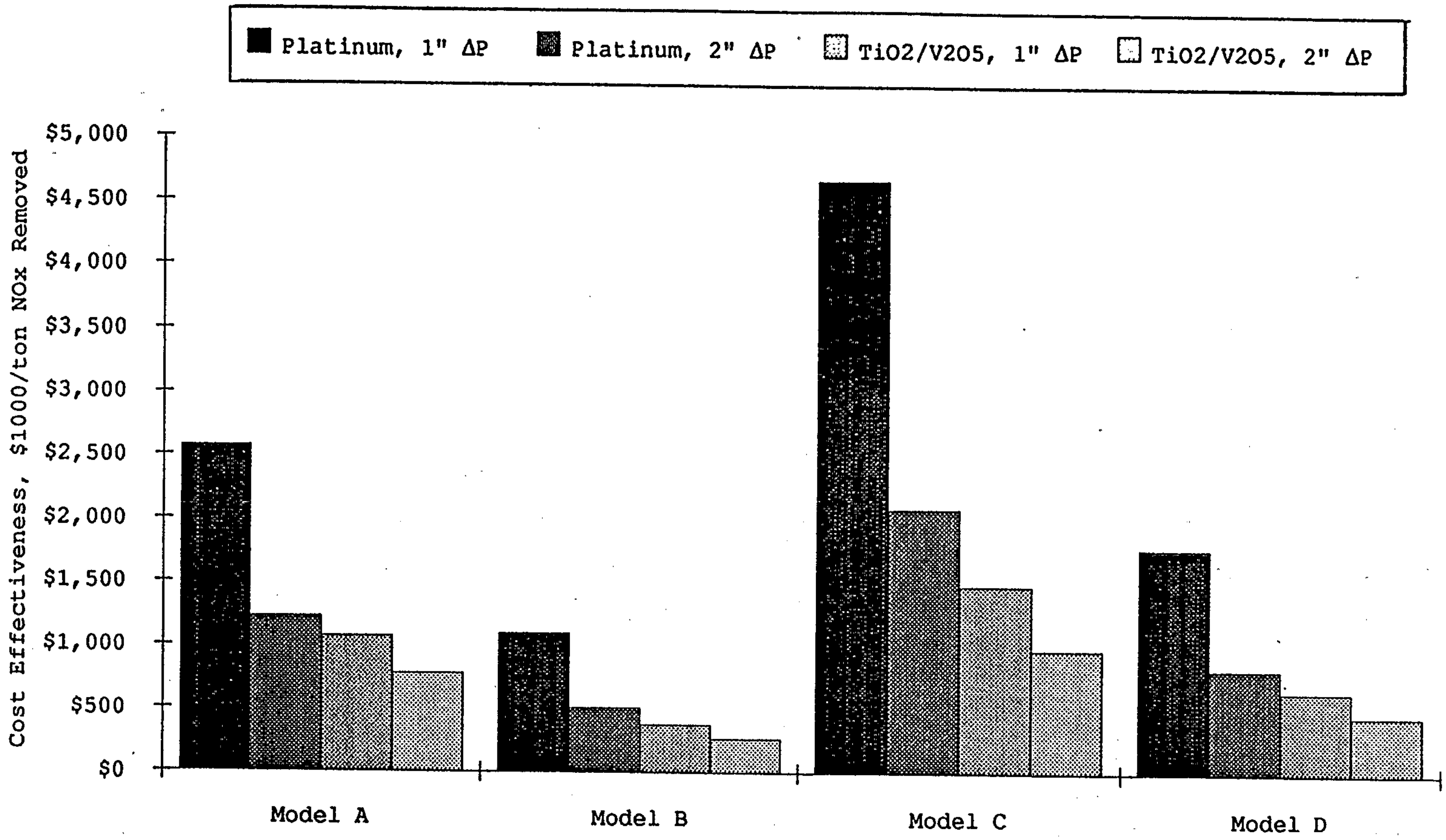

Figure 5-1. Cost effectiveness of SCR for turbofan/turbojet model test cells as a function of catalyst material (augmentation ratio = 5)

TABLE 5-3. COST EFFECTIVENESS ($ Per ton NO_x removed) OF SCR FOR THE MODEL TEST CELLS AND EACH CATALYST (Augmentation ratio = 5)

Catalyst	Model A	Model B	Model C	Model D
Platinum 1" ΔP	$2,576,000	$1,097,000	$4,667,000	$1,772,000
Platinum 2" ΔP	$1,224,000	$511,000	$2,089,000	$827,000
TiO2/V2O5 1" ΔP	$1,069,000	$380,000	$1,477,000	$650,000
TiO2/V2O5 2" ΔP	$779,000	$270,000	$972,000	$463,000

As discussed in Chapter 3, the augmentation ratio is the independent parameter in the model test cells and affects the volume flow rate of stack gas. Figure 5-2 presents the predicted cost effectiveness of installing the most cost effective SCR system (2" $\Delta P, TiO_2/V_2O_5$) to the turbofan/turbojet model test cells as a function of the augmentation ratio. The increase in the predicted cost effectiveness ($/ton) with the augmentation ratio results from the increased volume flow rate of gas entering the SCR system and the associated increase in catalyst volume and reheat fuel consumption.

Figure 5-3 presents the predicted total installed cost of applying the most cost effective SCR system (2" $\Delta P, TiO_2/V_2O_5$) to the turbofan/turbojet model test cells as a function of the augmentation ratio. Total installed costs range from $1,012,000 for Model Test Cell D at an augmentation ratio of 1 to $43,000,000 for Model Test Cell A at an augmentation ratio of 10. The total capital cost for a recently designed test cell capable of evaluating large turbofan type engines (80,000 lbs thrust) ranges from $18 to $20 million. The total installed cost to incorporate SCR to this test cell is estimated at $14 million.[4]

Figure 5-4 presents the predicted annual operating cost of the most cost effective SCR system (2" $\Delta P, TiO_2/V_2O_5$) to the turbofan/turbojet model test cells as a function of the augmentation ratio. Annual operating costs are predicted to range from $10,000 for Model Test Cell D at an augmentation ratio of 1 to $6,000,000 for Model Test Cell A at an augmentation ratio of 10.

The turboprop/turboshaft model test cell differs from the four turbofan/turbojet model test cells primarily in the reduced level of volume flow of stack gas and the total annual NO_x emissions. The reduced stack gas volume flow decreases

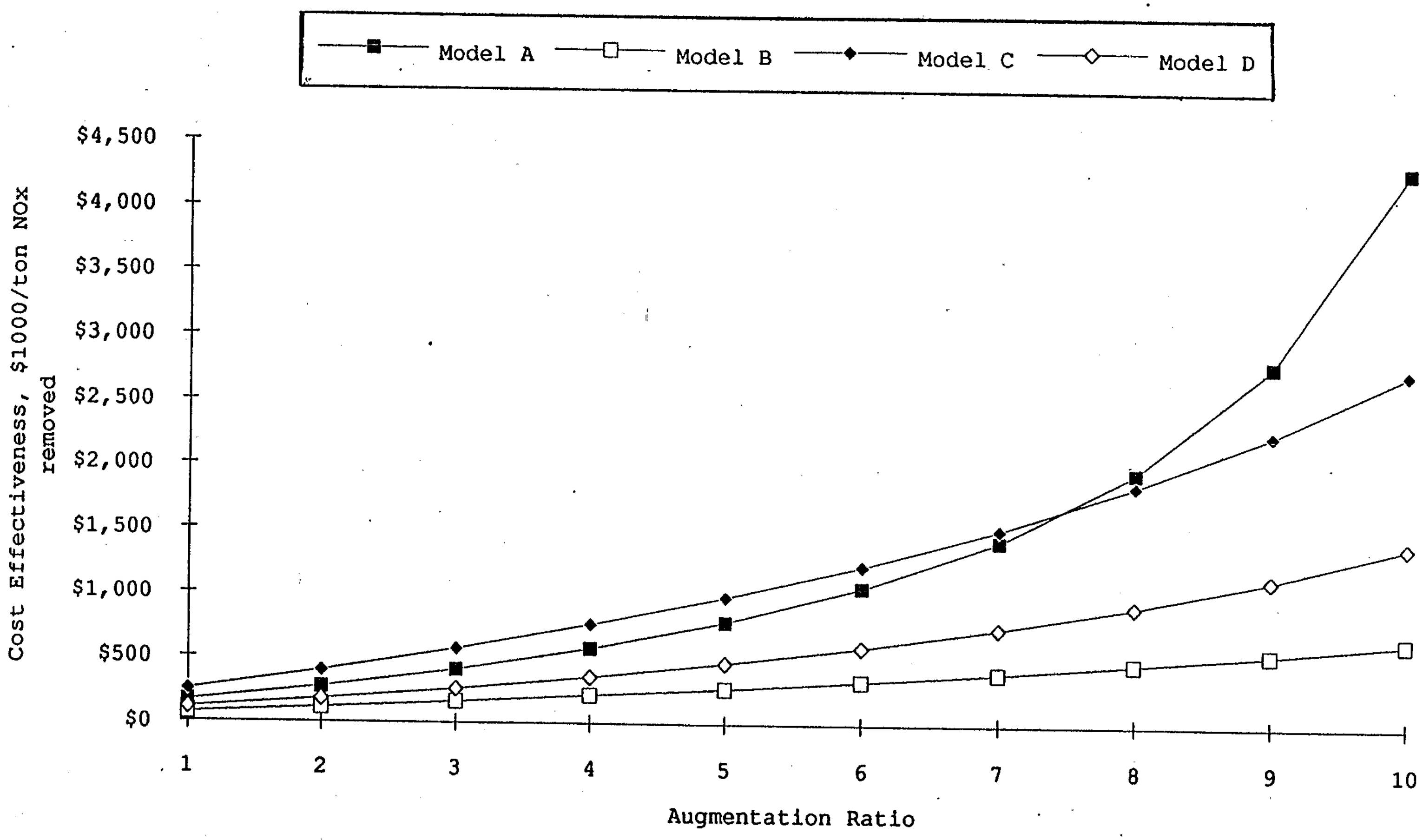

Figure 5-2. Cost effectiveness of SCR for the turbojet/turbofan model test cells as a function of augmentation ratio (2" ΔP TiO_2/V_2O_5 catalyst).

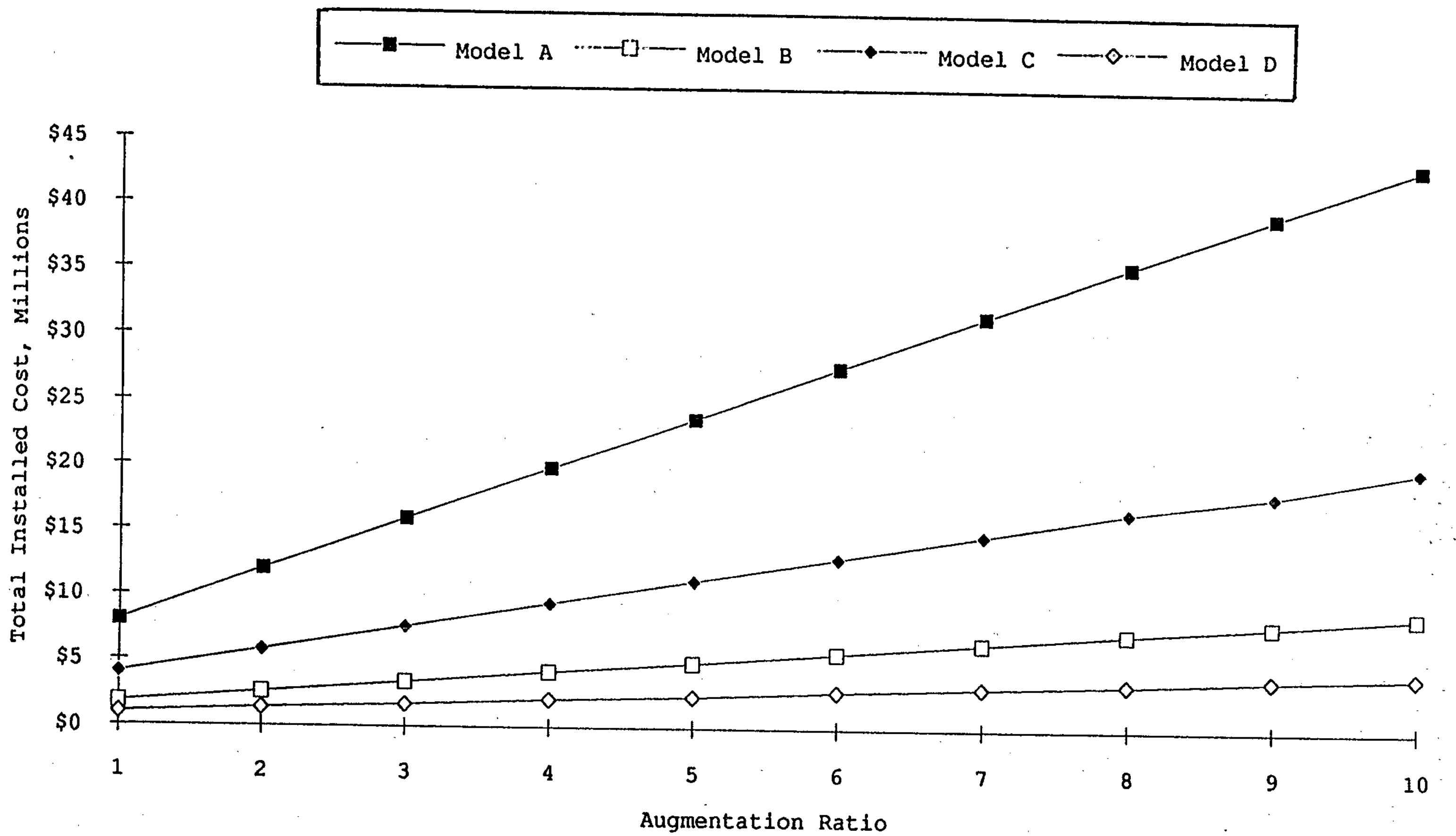

Figure 5-3. Total installed cost of SCR for the turbojet/turbofan model test cells as a function of augmentation ratio (2" ΔP TiO_2/V_2O_5 catalyst).

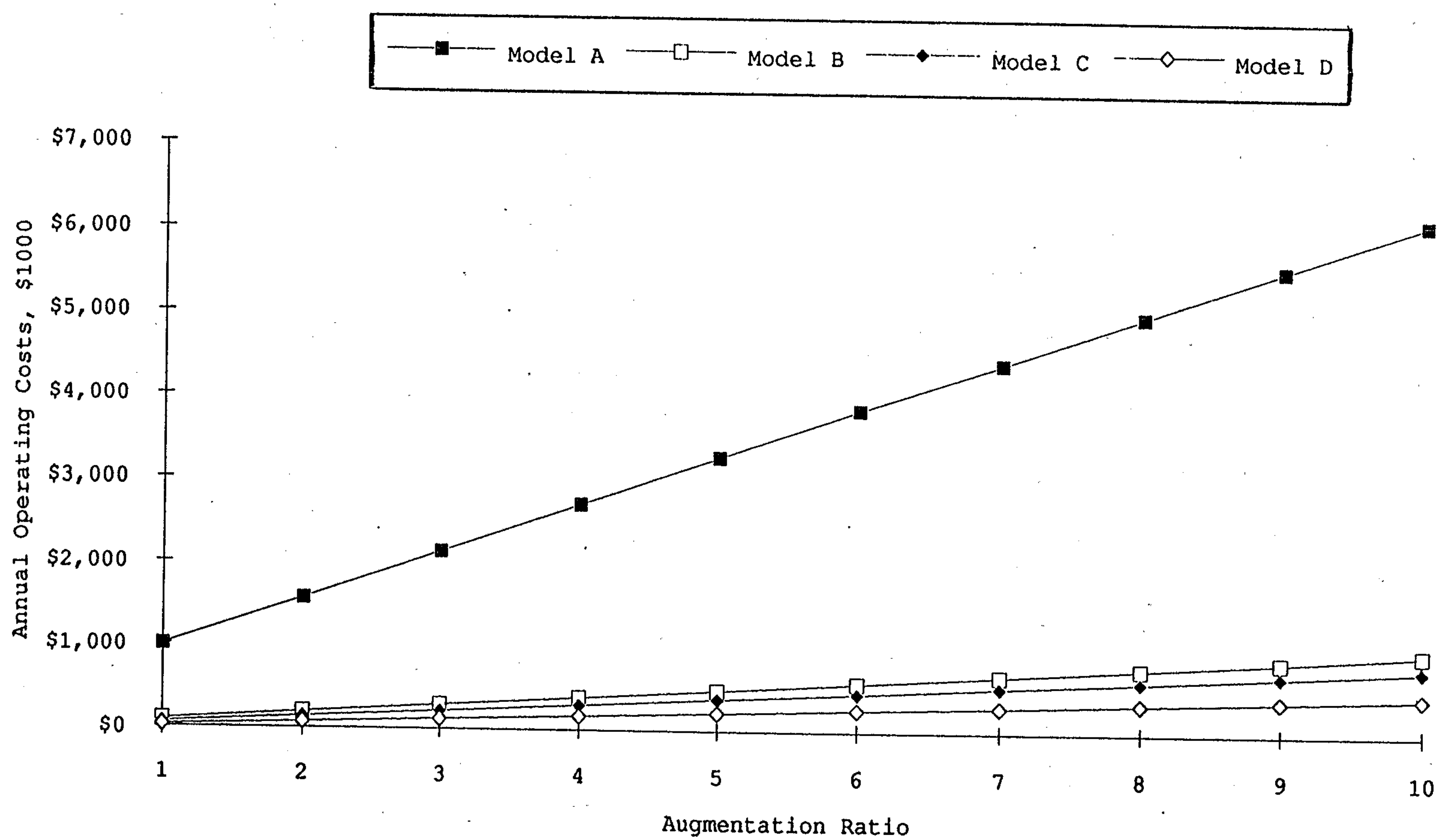

Figure 5-4. Annual operational costs of SCR for the turbojet/turbofan model test cells as function of augmentation ratio (2" ΔP TiO_2/V_2O_5 catalyst).

the catalyst volume requirements and the resulting capital costs. This is offset in the cost effectiveness calculation by a reduction in annual NO_x available for removal by the SCR NO_x control system.

Figure 5-5 presents the cost effectiveness estimates of applying the four SCR catalyst systems to the turboprop/turboshaft model test cell. The cost effectiveness ranges from a low of $167,000/ton to a high of $425,000/ton, for an augmentation ratio equal to 0.2 (an augmentation ratio of 0.2 is representative of turboprop/turboshaft test cell operation). The titanium/vanadium SCR system with the 2-inch pressure drop across the reactor vessel (2" $\Delta P, TiO_2/V_2O_5$) is predicted to be the most cost effective SCR installation.

Figure 5-6 presents the cost effectiveness and total installed costs of installing the (2" $\Delta P, TiO_2/V_2O_5$) SCR system to Model Test Cell E as a function of the augmentation ratio. For augmentation ratios between 0 and 1, total installed costs range from $313,000 to $348,000, while cost effectiveness estimates range from $167,000 to $219,000 per ton NO_x removed.

Figure 5-7 presents the corresponding predicted annual operating costs as a function of the augmentation ratio. Annual operating costs are predicted to be less than $2,000 under all conditions. This significant reduction in the annual operating costs over the turbojet/turbofan test cells is a direct result of the elevated exhaust gas temperatures, lower exhaust flow, and low NO_x emissions associated with the operation of the turboprop/turboshaft test cell.

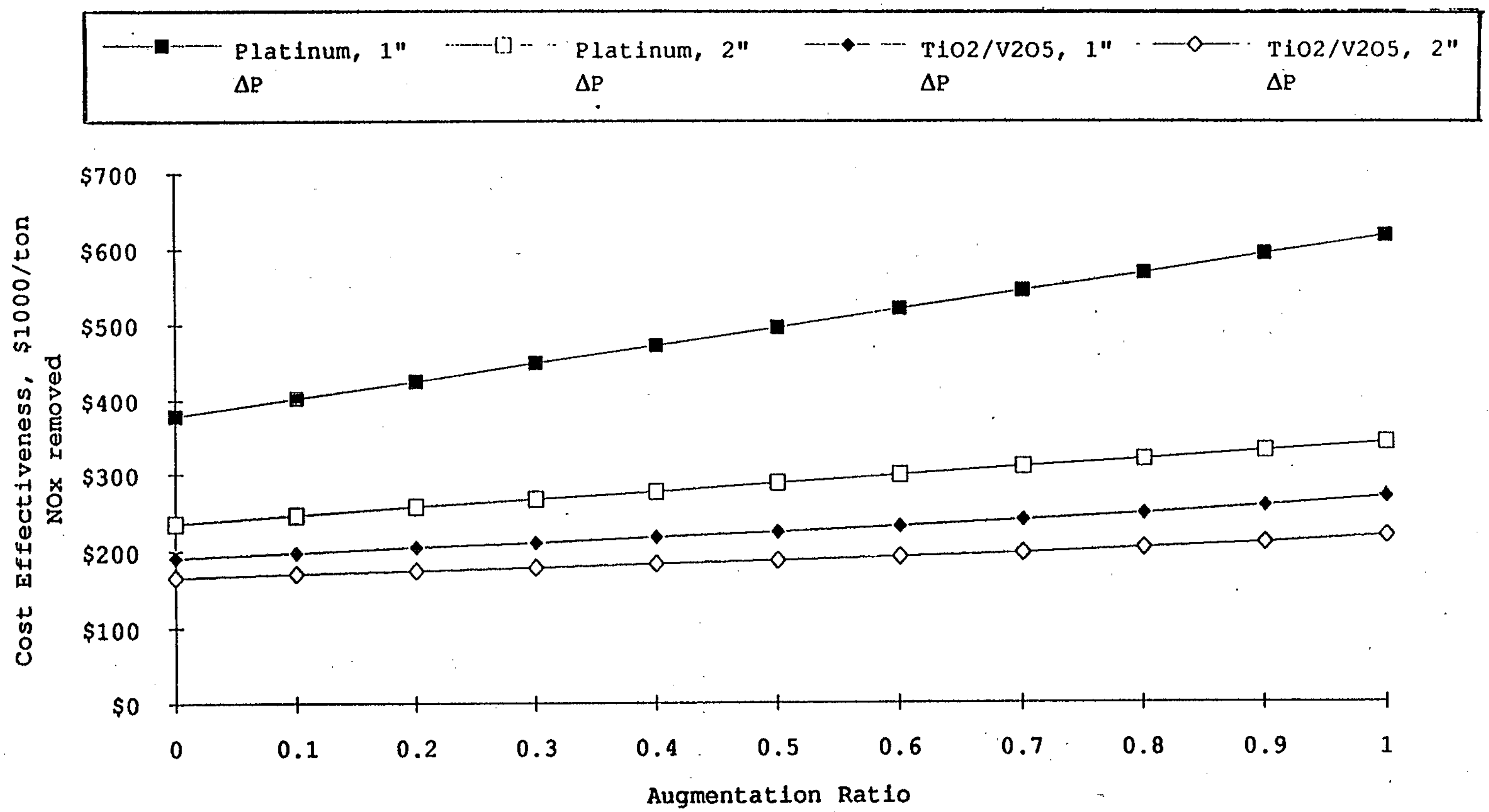

Figure 5-5. Cost effectiveness of SCR for turboprop/turboshaft Model E Test Cell.

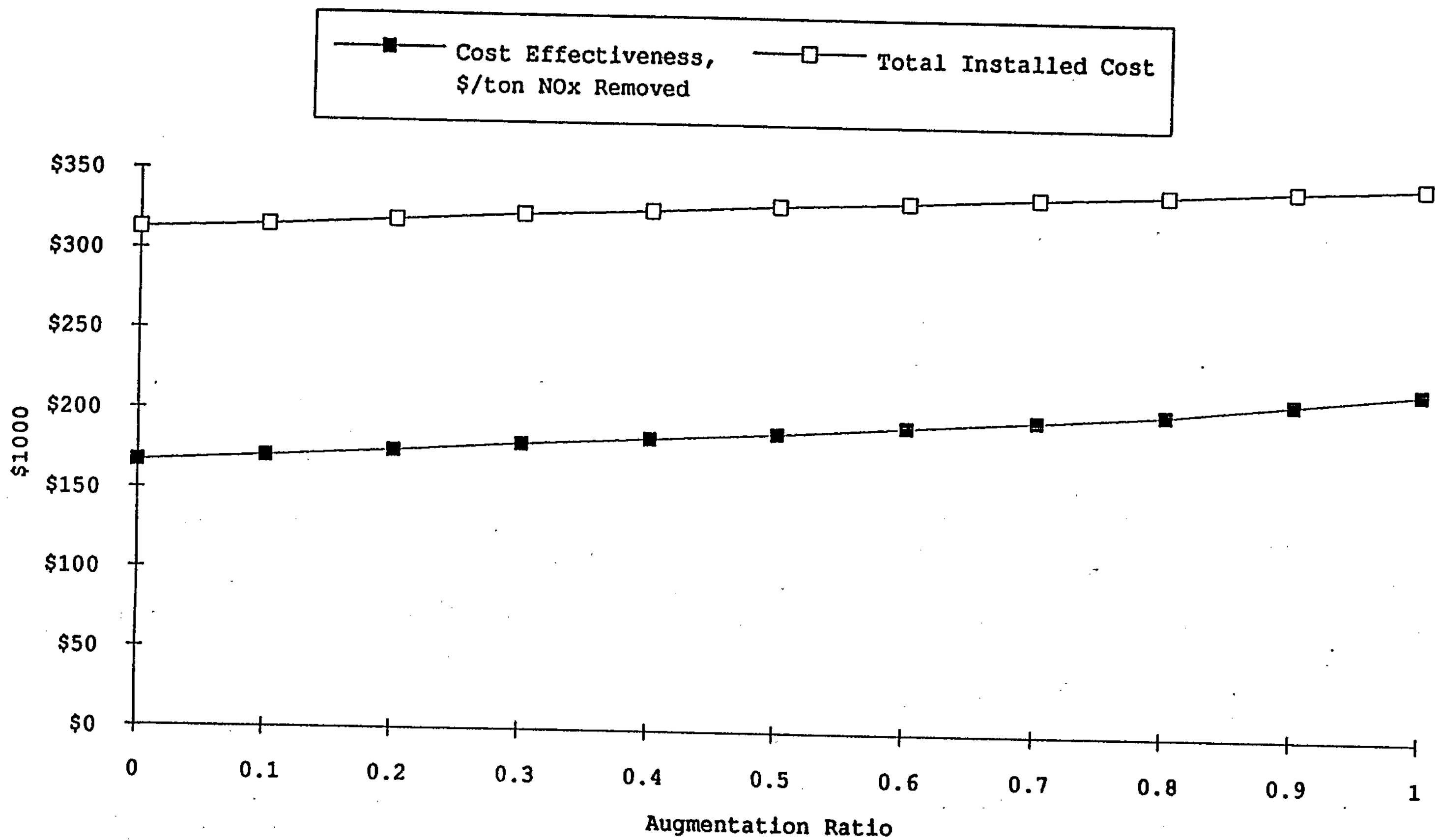

Figure 5-6. Cost effectiveness and total installed cost for turboprop/turboshaft Model E Test Cell (2" ΔP TiO_2/V_2O_5 catalyst).

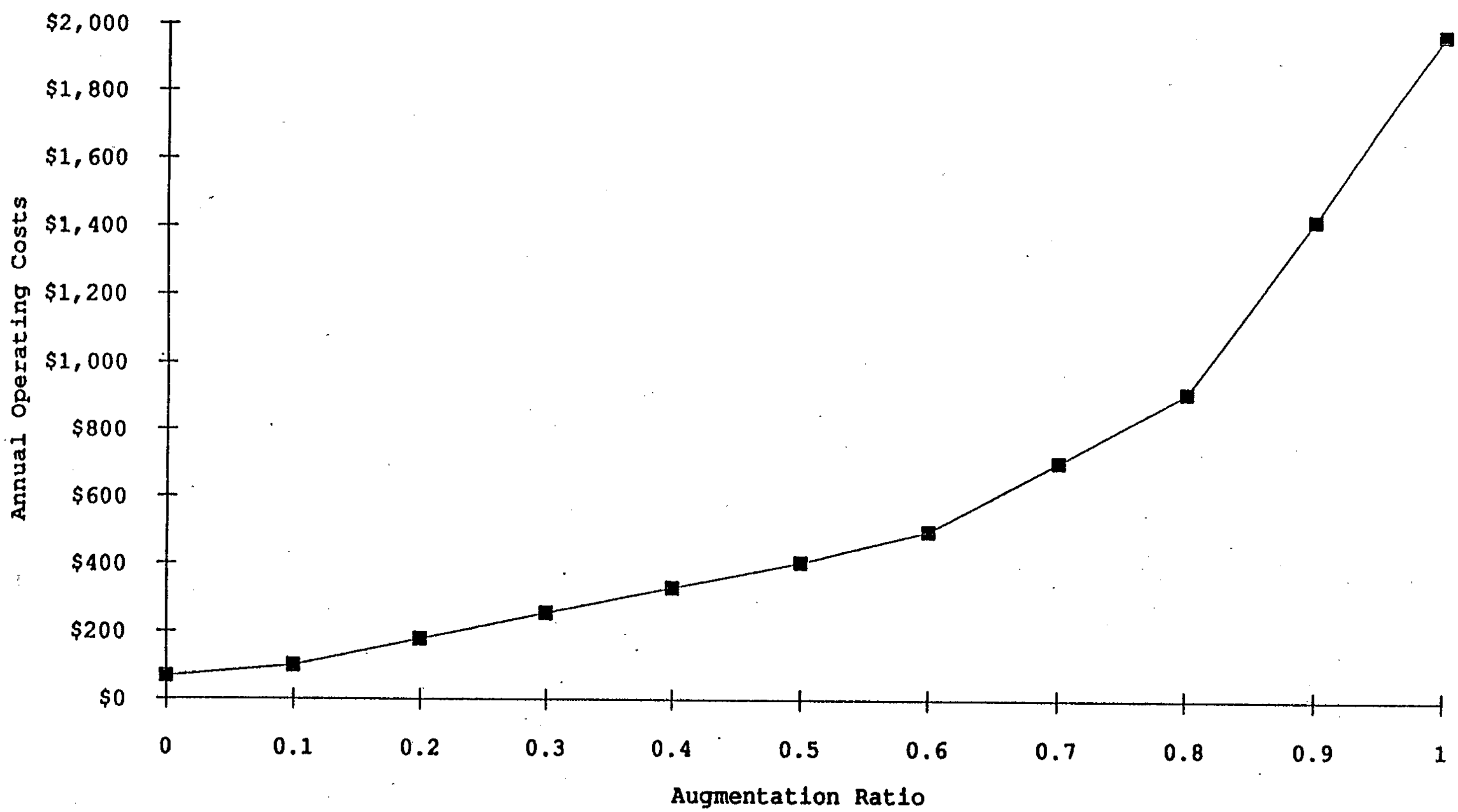

Figure 5-7. Annual operating cost of SCR for turboprop/turboshaft model test cell as a function of augmentation ratio (2" ΔP TiO_2/V_2O_5 catalyst).

5.5 SENSITIVITY OF SCR COST PROJECTIONS

As discussed in Section 5.3, the cost of implementing SCR to the model test cells is strongly dependent on both the life of the catalyst material and the level of NO_x emission reduction required from the SCR system. The cost effectiveness ($/ton) is driven by both the total annualized costs and the total tons of NO_x removed. Table 5-4 summarizes the results of a sensitivity analysis examining the costs of implementing SCR to the five model test cells to changes in these cost elements. The cost effectiveness of installing the titanium/vanadium-based SCR system with 2 inches of water pressure drop across the reactor is provided as the baseline case. As presented in the last section, this SCR system represents the lowest cost (in $/ton NO_x removed) solution of installing SCR to the model test cells as defined in Section 5.3. As expected, the sensitivity analysis indicates that increasing the catalyst life from 5 to 10 years lowers the predicted cost effectiveness estimates. This reduction in the cost effectiveness is approximately 30 percent from baseline for Model Test Cells A, B, C, and D, and a reduction in the cost effectiveness is approximately 10 percent from baseline for Model Test Cell E.

Increasing the model test cell hours of operation from 200 to 400 hours doubles the total annual NO_x emissions from the model test cells. Peak gas flow rates remain unchanged, and total capital costs remain constant from the baseline case; however, the increase in test cell utilization increases the annual ammonia and reheat gas requirements to achieve the same 80 percent NO_x emission reduction. The resulting cost effectiveness ($/ton NO_x removed) of installing the SCR system under these conditions is reduced by approximately 40 percent from baseline for all model test cells.

TABLE 5-4. SCR COST SENSITIVITY FOR LOWEST COST SOLUTION CATALYST ($/ton NO_x removed for the 2" ΔP TiO_2/V_2O_5 catalyst)

Varied Caharacteristic	Model A	Model B	Model C	Model D	Model E
Baseline	$779,000	$270,000	$972,000	$463,000	$175,000
40% NOx Reduction	NCE	NCE	NCE	NCE	$303,000
Increase operational hours to 400 hours per year	$537,000	$177,000	$550,000	$300,000	$88,000
Increase catalyst life to 10 years	$558,000	$199,000	$641,000	$340,000	$156,000

NOTE: NCE = Negative cost effectiveness

A decrease in the target NO_x emission reduction level from 80 to 40 percent reduces the volume of catalyst required in the SCR system by 50 percent, thereby reducing the catalyst costs by the same amount. However, the other fixed capital costs (including ammonia tank, controller, and duct burners) are not reduced as significantly. The change in capital costs is combined with the reduction by 50 percent in annual tons of NO_x removed. As a result of the drop in SCR effectiveness, the cost sensitivity analysis predicted negative cost effectiveness values for Model Test Cells A, B, C, and D, meaning that the NO_x emitted by the duct burner exceeded the total NO_x removed by the SCR system. The cost sensitivity analysis for Model Test Cell E, however, predicted a 73 percent increase in the cost effectiveness of SCR from the baseline case.

5.6 SELECTIVE NON-CATALYTIC REDUCTION COST COMPONENTS

The SNCR cost model is based on the SNCR system described in Chapter 4 applied to the model test cells outlined in Chapter 3. As with the SCR cost model, the cost elements of SNCR are derived from a conceptual design of the system, supported with typical costs of SNCR when applied to other gas-fired systems. As discussed in Chapter 4, the SNCR system would be located in the stack region of the model test cells.

The main cost elements of the system are the duct burners required to heat the stack gas to the suitable temperature range, and the ammonia injection and vaporization system. As with the SCR system, the duct burners would be located near the bottom of the stack and the ammonia injection grid would be located just downstream of the duct burners. The capital cost components of the SNCR system are the ammonia storage, vaporization and injection system, duct burners and the control system.

As discussed in Section 5.3, the principal cost element of implementing SCR to the model test cells is the catalyst. In the absence of the catalyst material (which is not used for SNCR), the principle cost element is the annual usage of reheat fuel required to elevate the stack gas temperature to the required reaction temperature (1700°F). The increase in reheat fuel consumption over that used by the SCR system is associated with an increase in the NO_x which must be removed by the SNCR system. The annualized costs for SNCR are determined in precisely the same manner used in the SCR analysis. Total capital costs are annualized using the cost recovery factor and combined with annual operating costs. Design and development costs have not been included in the cost effectiveness estimates. It is not anticipated that these cost components will significantly alter the cost effectiveness of SNCR. Using the cost analysis methodology outlined in Section 5.2, every $1 million of capital investment increases the cost effectiveness estimates by $4,000 per ton NO_x removed (cost recovery factor of 0.094 and 24 tons NO_x per year). A 50 percent reduction in the NO_x level entering the SNCR system is used to estimate the cost effectiveness. This is consistent with those reductions found on industrial applications of SNCR to other fossil fuel-fired systems.

5.7 COST ESTIMATES FOR IMPLEMENTATION OF SNCR TO MODEL TEST CELLS

Table 5-5 summarizes the cost model and resulting cost estimates for implementing SNCR to the five model test cells (augmentation ratio = 5 for Models A, B, C, and D and 0.2 for Model E). Note that for Model Test Cells A through D, the annual tons of NO_x per year emitted by the duct burner exceed the total NO_x eliminated by the SNCR controls. This is indicated as a negative cost effectiveness. As a result, application of SNCR under these conditions increases the net

TABLE 5-5. MODEL TEST CELL SNCR COST MODEL

Model Test Cell	A	B	C	D	E
SNCR Operating Temperature, °F	1700	1700	1700	1700	1700
Augmentation Ratio	5	5	5	5	0.2
Direct Capital Costs (20 years, 7%)					
Ammonia Tank	$14,000	$14,000	$14,000	$14,000	$14,000
CEM/Contol Systems	$175,000	$175,000	$175,000	$175,000	$175,000
Duct Burners	$20,000	$20,000	$20,000	$20,000	$20,000
Ammonia Vaporization System	$15,000	$15,000	$15,000	$15,000	$15,000
Total	$224,000	$224,000	$224,000	$224,000	$224,000
Indirect Capital Costs (20 years, 7%)					
Contingency (3% Direct Capital Costs)	$6,720	$6,720	$6,720	$6,720	$6,720
Constuction (20% Direct Capital Costs)	$44,800	$44,800	$44,800	$44,800	$44,800
Total	$51,520	$51,520	$51,520	$51,520	$51,520
Total Installed Cost	$275,520	$275,520	$275,520	$275,520	$275,520
Cost Recovery Factor	.094	.094	.094	.094	.094
Annualized Capital Cost	$25,899	$25,899	$25,899	$25,899	$25,899
Annual Operating					
Ammonia, ($200/ton 25% wt sol.)	$44,334	$8,678	$6,011	$3,659	$115
Reheat (NG), ($3.5 MMBtu)	$8,789,016	$1,436,491	$1,323,153	$677,610	$9,031
Labor (10% of operating Costs)	$883,335	$144,517	$132,916	$68,127	$915
Total	$9,716,685	$1,589,686	$1,462,080	$749,396	$10,061
Total Annual Cost	$9,742,584	$1,615,585	$1,487,979	$775,295	$35,959
Cost Effectiveness					
Engine NOx Emissions, tons/yr	24.397	8.832	4.946	2.695	0.259
Duct Burner NOx Emissions, tons/yr	125.557	20.521	15.386	9.680	0.129
Total Tons NOx Emitted per year	149.955	29.353	20.332	12.375	0.388
Total Tons NOx Removed (50%) per year	74.977	14.677	10.166	6.187	0.194
Net Tons Emitted per year	74.977	14.677	10.166	6.187	0.194
Net Tons Removed per year	-50.580	-5.845	-5.220	-3.493	0.065
Total ($/Net ton NOx removed)*	($192,617)	($276,418)	($285,042)	($221,976)	$554,857
*Values in parenthesis are negative					

NO_x emissions from the model test cells. Model E predicted a cost effectiveness of over a half of a million dollars per ton NO_x removed. The NO_x generated in the reheat of the stack gas is a direct function of both the volume flow rate of stack gas and the temperature rise required across the duct burner.

Model Test Cells A, B, C, and D are predicted to have negative cost effectiveness values at augmentation ratios of 2 or higher. At an augmentation ratio of 1, Model Test Cells B and C are predicted to have cost effectiveness values of \$350,000 and \$1.5 million/ton NO_x removed, respectively. Model Test Cells A and D are predicted to have negative cost effectiveness values at an augmentation ratio of 1. However, turbofan/turbojet test cells (Model Test Cells A through D) would typically be run with an augmentation ratio above 1.

Model Test Cell E would typically be run with an augmentation ratio of around 0.2. Under these conditions, the predicted cost effectiveness is just over \$550,000/ton NO_x removed. Table 5-6 summarizes the predicted cost effectiveness of implementing SNCR to Model Test Cell E as a function of augmentation ratio. Where the SNCR controls would result in a negative cost effectiveness, it is indicated in the table as NCE.

5.8 SUMMARY

Cost models for SCR and SNCR have been developed and applied to the model test cells described in Chapter 3. Several catalyst materials with a wide range of operating characteristics were incorporated into SCR cost projections. The most cost effective implementation of SCR to the model test cells would utilize a titanium/vanadium-based catalyst incorporating a 2-inch water gage pressure drop across the SCR reactor vessel. The cost effectiveness of installing this SCR

TABLE 5-6. PREDICTED COST EFFECTIVENESS OF SNCR AS A FUNCTION OF AUGMENTATION RATIO

Augmentation Ratio	Model E
0.0	$384,000
0.1	$458,000
0.2	$555,000
0.3	$688,000
0.4	$881,000
0.5	$1,188,000
0.6	$1,752,000
0.7	$3,132,000
0.8	$11,695,000
0.9	NCE
1.0	NCE

NOTE: NCE = Negative cost effectiveness

system to the five model test cells ranged from \$167,000 to \$972,000 per ton NO_x removed, operating Model Test Cells A through D at an augmentation ratio of 5 and Model Test Cell E at an augmentation ratio of 0.2.

A brief sensitivity analysis was conducted to determine the impact of changes in the principle cost components of SCR to the predicted cost effectiveness. This analysis indicated that reductions of approximately 30 percent in the cost effectiveness (\$/ton) estimates would result from extension of the catalyst life from 5 to 10 years. Reductions in the cost effectiveness estimates of approximately 40 percent from the baseline value were predicted with an annual utilization increase from 200 to 400 hours in the model test cells. The effect of decreasing the target NO_x emission reductions from 80 percent to 40 percent was also investigated. At 40 percent NO_x removal efficiency, the cost effectiveness (\$/ton)of installing SCR is predicted to be negative for Models A, B, C, and D. For Model E, the cost effectiveness is predicted to increase 73 percent from the baseline conditions.

The technical analysis of installing SNCR on five model test cells indicates that SNCR reduces NO_x emissions from the model test cells only under limited operating conditions. In most cases, it is predicted that the NO_x emissions from the duct burner used with SNCR would exceed the NO_x removed by SNCR. For Model Test Cell E, the predicted cost effectiveness values range from \$384,000 to \$11,700,000 ton/NO_x removed depending on the augmentation ratio. Model Test Cells B and C have predicted cost effectiveness values of \$350,000 and \$1,500,000 ton/NO_x removed, respectively, at an augmentation ratio of 1 and a net increase in NO_x emissions for augmentation ratios of 2 or higher. Model Test Cells A and D are predicted to have a net increase in NO_x emissions at all augmentation ratios.

5.9 REFERENCES

1. Office of Air Quality Planning and Standards. OAQPS Control Cost Manual. United States Environmental Protection Agency. Research Triangle Park, North Carolina. EPA 450/3-90-006. January 1990.

2. Office of Air Quality Planning and Standards. Alternative Control Techniques Document -- NO_x Emissions from Stationary Gas Turbines. Research Triangle Park, North Carolina. EPA-453/R-93-007. January 1993. pp 5-76 and 5-77.

3. Ref. 2, p. 6-27.

4. Letter from Sumner, J., General Electric Aircraft Engines, to Wood, J.P., EPA/ESD, February 10, 1994. Capital costs of a new test cell.

CHAPTER 6
TEST CELL NO_x EMISSION INVENTORY ESTIMATE

In this chapter, total annual NO_x emissions attributed to test cell operation are categorized by owner/operator group and by their location within ozone attainment or ozone non-attainment areas. The distribution of NO_x emissions from test cells within ozone non-attainment areas is further subdivided by non-attainment classifications. In addition, the NO_x emissions from test cells within ozone non-attainment areas are compared to both total stationary source NO_x emissions, as well as to combined total stationary and total mobile source NO_x emissions within that area.

6.1 INFORMATION COLLECTION BACKGROUND

6.1.1 Owner/Operator Information

The information presented in this chapter, as well as the owner/operator summary presented in Chapter 2, was compiled from information provided by test cell owners and operators.

The following is a list of companies and organizations that provided information for the study.

Engine Manufacturers:

- United Technologies, Pratt & Whitney
- General Electric Aircraft Engines

- Allied Signal Aerospace
- Textron Lycoming
- Allison Gas Turbines

Repair Facilities:

- Williams International
- Ryder Aviall Inc.
- Airwork
- Pacific Airmotive Corporation

Airlines:

- American Airlines
- United Airlines
- USAir
- Delta Airlines
- Northwest Airlines

Organizations:

- National Aeronautics & Space Administration (NASA)
- Department of Defense (DoD)
- AIA

Total annual NO_x emission estimates for each facility operating test cells were provided by the owner/operators. In addition, information related to fuel consumption, hours of operation, number of test cells, and test cell physical arrangement was obtained.

6.1.2 Summary of State and Local Regulations

State and local air pollution control agencies were contacted to obtain information on emission regulations and current permitting practices for test cells. Information requested of the state or local regulatory agencies included permitting practices for test cells and identification of any specific regulations pertaining to test cells. Table 6-1 presents a listing of all state and local regulatory agencies which were contacted in this effort.

None of the state or local air pollution control agencies contacted have specific regulations concerning NO_x emissions from test cells. Several agencies indicated that the permitting of test cells would use a maximum allowable emission standard to regulate atypical point sources. Emissions from jet aircraft engines are currently regulated by the EPA Office of Mobile Sources. Pollutants covered by the standards include total hydrocarbons and particulate emissions. Oxides of nitrogen from aircraft engines are currently not regulated. In addition, these regulations do not apply to the testing and maintenance of jet engines.

Without specific regulatory guidelines, several agencies were found to use worst-cases scenarios to determine the maximum allowable NO_x emissions of the test cell. For example, test cells that actually operate 200 to 400 hours per year are permitted based on 8,760 hours of operation. Several agencies were found to regulate other operational characteristics of the test cell. Maximum operational hours per year or per day and fuel type are the most common regulated characteristics. More than 50 percent of the military test cells located in the survey, all of the commercial, and two-thirds of the engine manufacturers' facilities are permitted with operational restrictions.

TABLE 6-1. STATE AND LOCAL REGULATORY AGENCIES CONTACTED

Regulatory agency	Contact and Phone Number
California, Bay Area Air Quality Management District	Ellen Linder (451) 771-6000
California, San Diego County Air Pollution Control District	Kim Cresencia (619) 694-3307
California, San Jaoquin Valley Unified Air Pollution Control District	Dave Warner (209) 497-1000
California, South Coast Air Quality Management District	Ranjit Vishwanath (714) 396-2000
Connecticut, Bureau of Air Manangement	Ernest Bouffard (203) 566-8230
Florida, Duval County Air Quality Division	Ronald Roberson (904) 530-3660
Georgia, Air Protection Branch	Ronald Methier (404) 656-4713
Indiana, Ciy of Indianapolis Air Quality Management District	Matt Mosier (317) 327-2270
Maine, Department of Environmental Protection	Rick Creswell (207) 289-2437
Maryland, Department of the Environment	Craig Holdefer (410) 631-3215
New York, Department of Environmental Conservation	Randy Orr (518) 457-7230
North Carolina, Air Quality Division	Charles Yirka (919) 733-3340
Ohio, Sate of Ohio Environmental Protection Agency	Jim Braun (614) 644-3617
Oklahoma, Tulsa City County Health Department	Ray Bishop (918) 744-1000
Pennsylvania, Bureau of Air Quality Control	George Mentzer (717) 787-9256
Pennsylvania, Department of Environmental Resources	Tom McGinley (215) 832-6224
Pennsylvania, Alleghany County Health Department	Mark Schooley (412) 578-8117
Tennessee, Air Pollution Control Division	Greg Forte (615) 741-3931
Texas, Air Control Board	Mike Coldiron (512) 908-1260
Texas, Air Control Board	Kevin Bloomer (512) 908-1514
Virginia, Department of Air Pollution Control	Art Escobar (804) 786-5783
Washington, Department of Ecology, Air Program	Sally Otterson (206) 459-6256
Washington, Northwest Air Pollution Authority	Jamie Randles (206) 428-1617

6.2 RESULTS OF TEST CELL INVENTORY

The compilation of data indicates that annual NO_x emissions from the current test cell population total approximately 2,830 tons. Approximately 67 percent of the test cells (249 out of a total of 368) are located in ozone non-attainment areas, with these test cells emitting 74 percent of the total test cell annual NO_x emissions.

Figure 6-1 presents a distribution of annual NO_x emissions by owner/operator group and by attainment or non-attainment status. Engine manufacturers operating test cells emit the majority of NO_x in ozone non-attainment areas, while test cells operated by the DoD emit the majority of NO_x in attainment areas. Total annual NO_x emissions from test cells owned and operated by aircraft engine manufacturers in ozone non-attainment areas are approximately 1,650 tons. Annual NO_x emissions from the DoD test cells are more evenly split between non-attainment and attainment areas, with approximately 513 tons out of a total of 845 tons produced in non-attainment areas. Figure 6-2 presents the corresponding test cell population distribution. The data indicate that engine manufacturers operate nearly 140 test cells in ozone non-attainment areas, while the DoD operates just over 100 test cells in ozone attainment areas and nearly 80 in non-attainment areas.

Figure 6-3 presents the NO_x emissions distribution for test cells located in ozone non-attainment areas. Within the ozone non-attainment areas, moderate and serious non-attainment areas account for 90 percent of the total NO_x emitted by test cells.

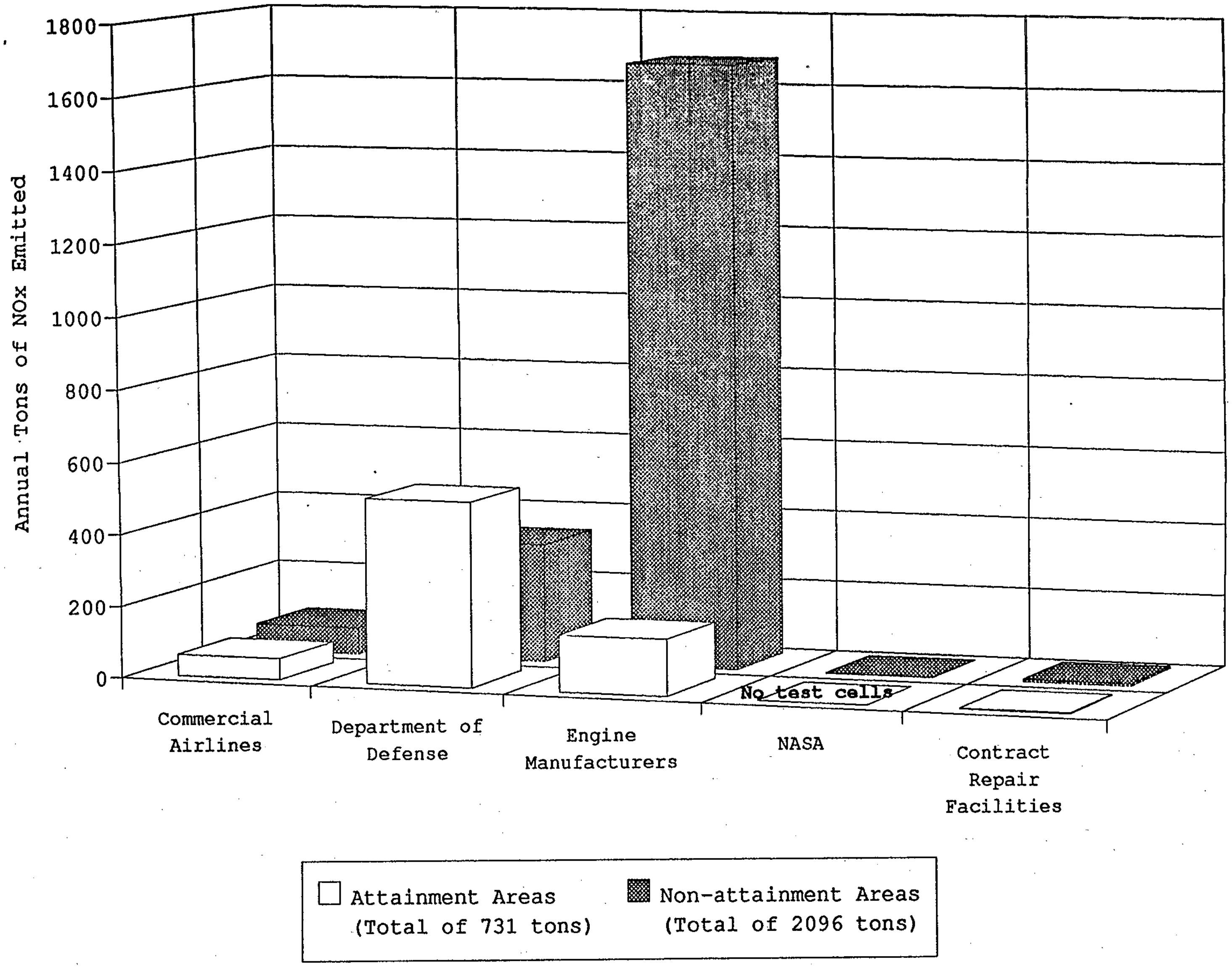

Figure 6-1. Annual NO_x emission distribution by ozone attainment status and test cell owner/operator group.

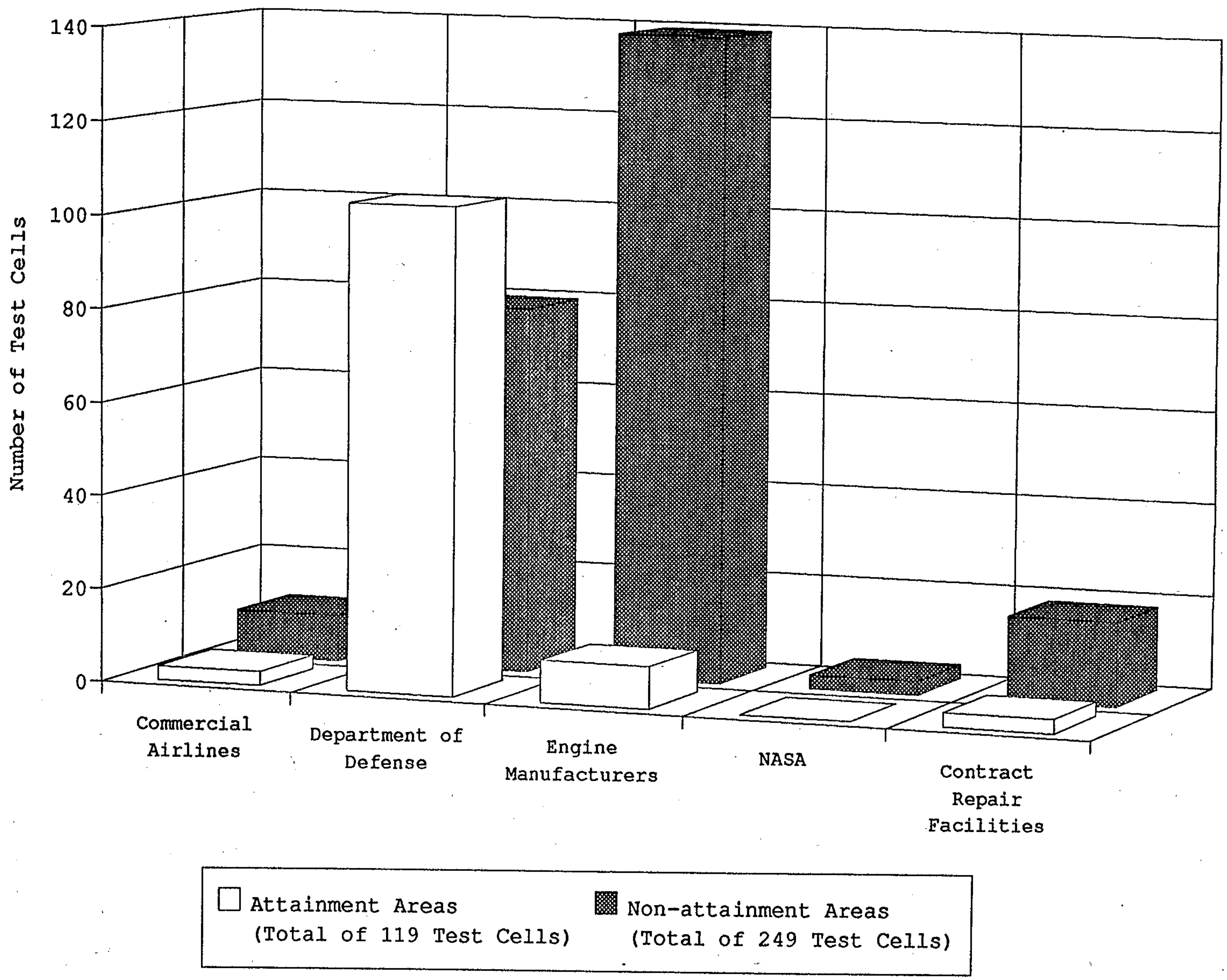

Figure 6-2. Test cell distribution by ozone attainment status and by owner/operator group.

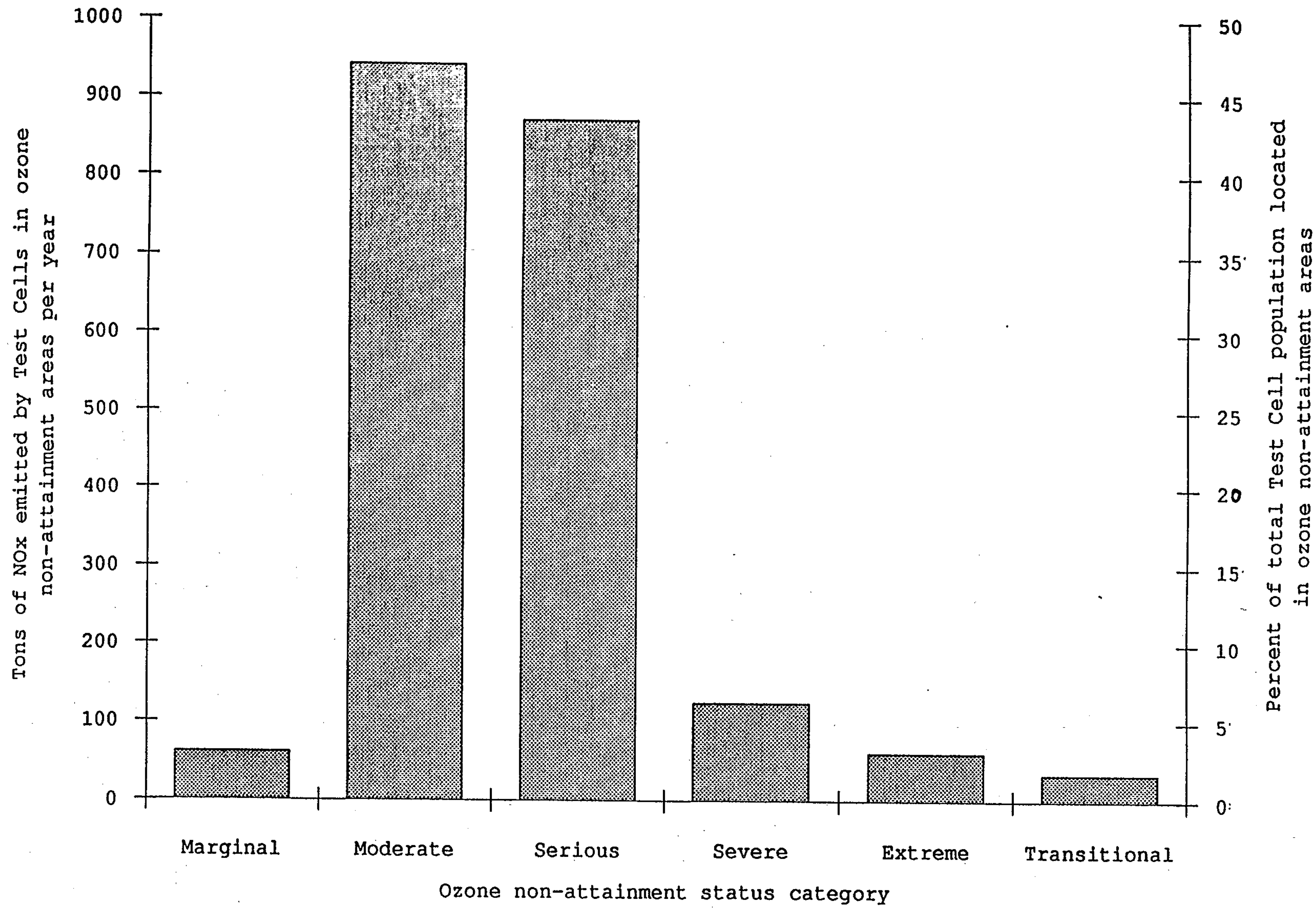

Figure 6-3. Annual test cell emissions by ozone non-attainment status category for test cells located in ozone non-attainment areas.

Figure 6-4 presents a distribution of average annual test cell NO_x emissions. The Model Test Cells A through E described in Chapter 3 emit 25, 10, 5, 2, and 0.3 tons of NO_x per year, respectively. These model test cell emission levels correspond well with the distribution of average annual test cell emissions identified in this survey.

The impact of not controlling NO_x emissions from test cells can be examined by comparing annual NO_x emissions from test cells to the total annual NO_x emissions in the area. Table 6-2 presents the relative contribution of NO_x emissions from test cells to the total stationary source NO_x emissions and the combined total stationary source and mobile source NO_x emissions for those test cells located within ozone non-attainment areas.

Total annual stationary source and mobile source NO_x emissions used in generating Table 6-2 were extracted from recent EPA compilations of NO_x source emissions.[1,2] The majority of the test cell facilities located within ozone non-attainment areas have less than a 1 percent contribution to the stationary source NO_x totals. Only two non-attainment areas have a contribution from test cell operation of more than 1 percent of the stationary source NO_x emissions. These areas are Phoenix, Arizona, at 2.66 percent, and the greater Connecticut area at 2.49 percent. None of the ozone non-attainment areas have NO_x contributions from test cells which are greater than 0.7 percent for the total NO_x emitted into that area, and only two locations are greater than 0.07 percent of the total NO_x contributed to an ozone non-attainment area.

Test cells contribute only slightly to the total NO_x emissions within non-attainment areas. Total annual NO_x emitted from test cells located in non-attainment areas is

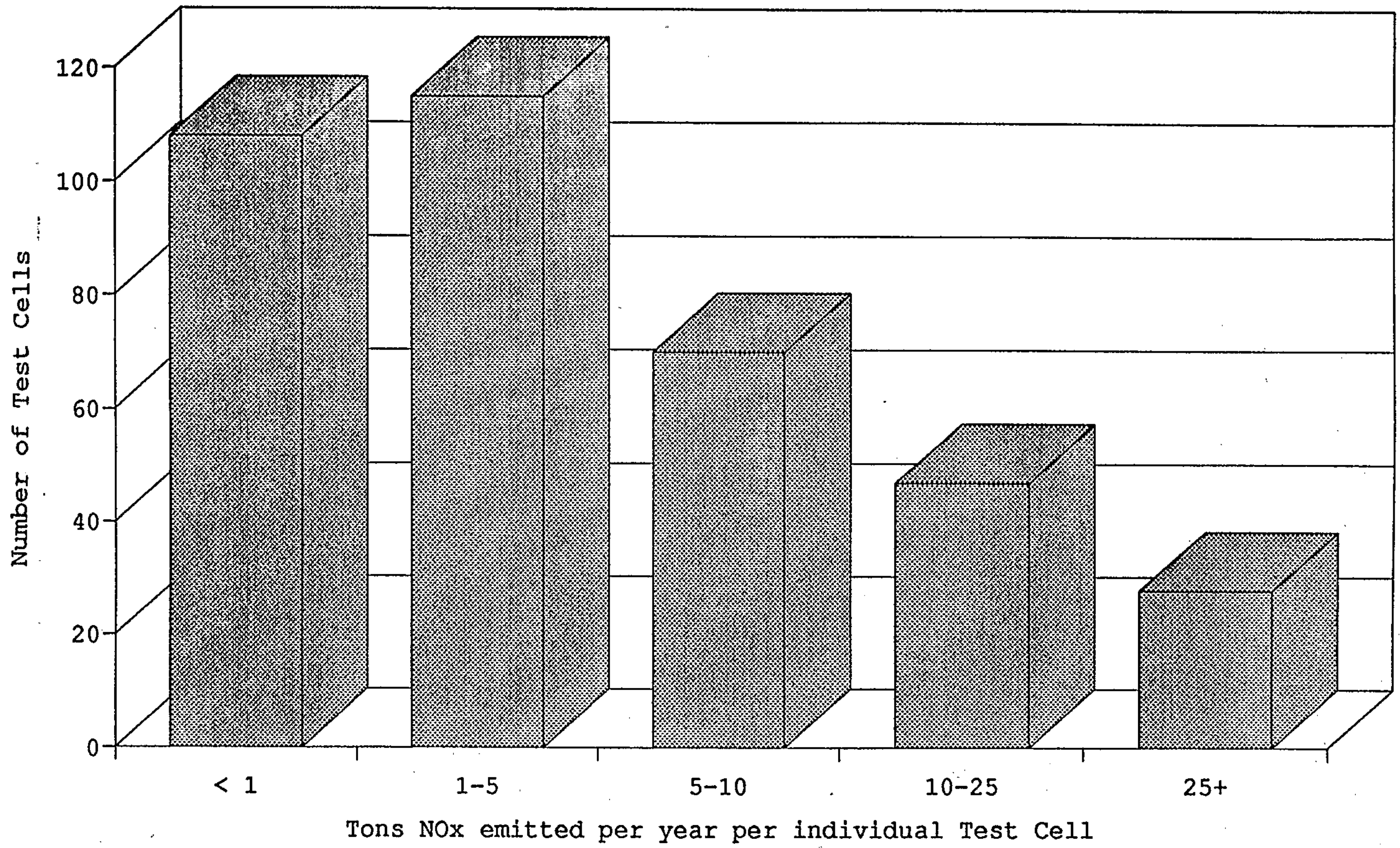

Figure 6-4. Average annual NO_x emission per test cell for all reported test cells.

TABLE 6-2. TEST CELL RELATIVE CONTRIBUTION TO OZONE NON-ATTAINMENT AREA STATIONARY SOURCE AND TOTAL ANNUAL NO_x EMISSIONS

Ozone non-attainment area (greater area)	Number of test cells	Test cell NOx (tons per year)	Total stationary source NOx (tons per year)		Total NOx, stationary & mobile sources (tons per year)	
			(tons per year)	(%) test cells	(tons per year)	(%) test cells
Phoenix, AZ	20	58.6	2,200	2.664	130,000	0.045
Greater Connecticut	49	672	27,000	2.489	101,000	0.665
Cincinnati, OH	13	716	77,000	0.930	155,000	0.462
Sacremento, CA	5	21.3	6,100	0.349	82,000	0.026
Norfolk, VA	6	52.5	18,000	0.292	77,000	0.068
Salt Lake City, UT	3	6.69	2,800	0.239	45,900	0.015
San Diego, CA	8	28.5	16,000	0.178	121,000	0.024
Boston, MA	24	178	100,000	0.178	263,000	0.068
Portland, OR	1	5.3	3,200	0.166	80,100	0.007
Brunswick, ME	1	0.22	147	0.150	3,600	0.006
San Francisco, CA	10	81.3	59,000	0.138	360,000	0.023
Indianapolis, IN	35	30.8	24,000	0.128	76,000	0.041
Dayton-Springfield, OH	1	5.97	6,500	0.092	46,300	0.013
Atlanta, GA	7	30.86	35,000	0.088	167,000	0.018
Atlantic City, NJ	1	8.63	11,600	0.074	25,300	0.034
Los Angeles, CA	9	62.22	123,000	0.051	552,000	0.011
San Joaquin Valley, CA	3	26.95	60,000	0.045	197,000	0.014
Phiadelphia, PA-Wilmington, DE	14	44.7	110,000	0.041	292,000	0.015
Ventura Co., CA	2	3	9,800	0.031	36,700	0.008
Seattle-Tacoma, WA	1	3.32	11,000	0.030	140,000	0.002
Dallas-Forth Worth, TX	5	8.74	48,000	0.018	377,000	0.002
Richmond, VA	1	3.35	24,700	0.014	59,500	0.006
Pittsburgh, PA	2	7.03	139,000	0.005	246,000	0.003
St. Louis, MO	1	5.08	147,000	0.003	260,000	0.002
Cleveland-Akron, OH	3	2.16	67,000	0.003	189,000	0.001
Washington, DC	5	2.44	76,000	0.003	205,000	0.001
Detroit. MI	9	3.2	237,000	0.001	441,000	0.001
Tampa-St. Petersburg, FL	3	0.78	95,000	0.001	157,000	0.000
Miami, FL	1	0.19	34,000	0.001	259,000	0.000
TOTAL	243	2069.83	1,570,047	0.132	5,144,400	0.040

just under 2,100 tons. These NO_x emissions account for less than 0.14 percent of the total stationary source NO_x emissions and 0.04 percent of the total NO_x emitted into those ozone non-attainment areas.

6.3 REFERENCES

1. United States Environmental Protection Agency. Regional Interim Emission Inventories, Volume II. Research Triangle Park, North Carolina. Publication No. EPA-454/R-93-021b. May 1993.

2. United States Environmental Protection Agency. Development of an Interim 1990 Emission Inventory -- Ozone Non-Attainment Area Summary Table. Prepared by E.H. Pechan and Associates, Inc., for EPA/OAQPS/TSD/SRAB. July 1993.

APPENDIX A: DEVELOPMENT OF EQUATION 3.1

The first law of thermodynamics can be applied to a control volume surrounding the engine mounted in the test cell. The resulting energy equation neglecting heat transfer from the surroundings to the control volume is given by:

$$dm/dt\ (h_i + V_i^2/2) = -dE/dt + dm/dt\ (h_e + V_e^2/2) + dW/dt$$

where :

dm/dt	:	Rate of mass addition to the control volume.
h_i	:	Enthalpy of gas entering control volume.
V_i	:	Velocity of gas entering the control volume.
h_e	:	Enthalpy of gas leaving the control volume.
V_e	:	Velocity of gas leaving the control volume.
dW/dt	:	Shaft power removed from the control volume.
$-dE/dt$	:	Rate of change of energy within the control volume.

For the turbojet/turbofan engines, the work extracted is zero. Assuming the exit velocity is significantly greater than the inlet velocity, the change in enthalpy through the control volume can be expressed as:

$$(h_e - h_i) = (dmf/dt)/(dm/dt) * LHV - (1/2)V_e^2$$

where :

dmf/dt	:	Fuel flow rate per unit time.
LHV	:	Lower heating value.

Assuming a constant heat capacity value across the control volume gives:

$$(t_e - t_i) = (1/Cp)\ [\ FA * LHV - (1/2)(Tc/(dm/dt))^2\ ]$$

where :

Cp : Heat capacity.

Tc : Engine core thrust.

LHV : Fuel lower heating value.

te : Temperature of gas leaving the control volume.

ti : Temperature of gas entering the control volume.

FA : Fuel-to-air-ratio.

If the inlet temperature is at atmospheric conditions, then the engine core exit temperature can be expressed as:

$$tc = ta + (1/Cp)[\ FA * LHV - (1/2)(Tc/(dm/dt))^2\ ]$$

where:

tc: Engine core exhaust temperature.

Tc: Engine core thrust.

ta: Atmospheric temperature.

APPENDIX B: DEVELOPMENT OF EQUATIONS GOVERNING NO_x ESTIMATES

The governing ideal combustion equation is given by:

$$CH_2 + (a)(3/2)(O_2 + (79/21)N_2) \rightarrow CO_2 + H_2O + (a)(3/2)(79/21)N_2 + (a-1)(3/2)O_2$$

where :

$a = EA + 1$

and :

EA is the excess air level defined as:

EA = (total air - theoretical air)/theoretical air

The excess air level is related to the engine air to fuel ratio (AF) by:

$$EA = (AF-14.7)/14.7$$

The moles of combustion products (MCP) per mole of fuel burned is given by:

$$MCP = (7.14)(a) + 0.5$$

The moles of bypass air flow (MB) per mole fuel burned is given by:

$$MB = (BP)(a)(3/2)(1 + 79/21)$$

$$MB = (7.14/14.7) * (AF)(BP)$$

where the bypass ratio (BP) is defined as the volume of air entering the front of the engine which does not pass through the combustor divided by the volume of air used in combustion.

The moles of augmentation air (MA) are equal to the augmentation ratio (AR) times the sum of the total air flow entering the front of the test engine.

$$MA = (AR)[(BP)(AF)(7.14/14.7) + (a)(7.14)]$$
$$MA = (AR)(AF)(7.14/14.7)(BP + 1)$$

Total stack mole flow per mole fuel combusted (TSM) is given as the sum of the augmentation mole flow and total engine exhaust flow:

$$TSM = MA + MB + MCP$$

The moles of NO_x (as NO_2) per mole of fuel burned (MNX) is given by:

$$MNX = EF * (14/46)$$

where :
EF : Engine NO_x emission factor (lbs NO_x/lb fuel)

The NO_x concentration in ppm at the stack exit is given by:

$$ppm\ NO_x = 1e6 * (EF)(14/46)/(TSM)$$

The percent oxygen concentration at the stack exit is given by:

$$O_2\ (\%) = 100 * [\ 0.21 * (MA + MB) + (a-1)(3/2\ ]/(TSM)$$

The NO_x concentration in the stack corrected to 15 percent O_2 is given by:

$$ppm\ NO_x\ (@\ 15\%\ O_2) = (ppm\ NO_x) * (20.98-15)/(20.98-O_2\%)$$

Sample Calculation:

Consider the emissions from a model test cell operating the CF6-80A2 at maximum thrust:

AF = 55 (from engine specific data)

EF = 29.6 lbs NO_x per 1000 lbs fuel

The moles of combustion products (MCP) is given by:

MCP = (7.14)(a) + 0.5

MCP = 27.2

where:

a = AF/14.7

a = 3.74

The moles of bypass (MB) air flow with a bypass ratio (BP = 5.17)is given by:

MB = (7.14/14.7) * (AF)(BP)

MB = 138.1

The moles of augmentation air at an augmentation ratio (AR) of 5 is given by:

MA = (AR)(AF)(7.14/14.7)(BP + 1)

MA = (5)(55)(7.14/14.7)(5.17 + 1)

MA = 824.1

The stack NO_x concentration is given by:

ppm NO_x = 1e6 * (EF)(14/46)/(TSM)

ppm NO_x = 1e6 *(29.6/1000)(14/46)/(27.2 + 138.1 + 824.1)

ppm NO_x = 9.1

The stack oxygen concentration is given by:

$$O_2\ (\%) = 100 * [\ 0.21 * (MA + MB) + (a - 1)(3/2)]/(TSM)$$

$$O_2\ (\%) = 100 * (0.21 * (160.3 + 133.6) + (55/14.7 - 1)(3/2))/989.4$$

$$O_2\ (\%) = 20.84$$

The NO_x concentration corrected to 15% O_2 is given by:

$$ppm\ NO_x\ (@\ 15\%\ O_2) = (ppm\ NO_x) * (20.98-15)/(20.98-O_2\%)$$

$$ppm\ NO_x\ (@\ 15\%\ O_2) = 28.05 * (20.98-15)/(20.98-20.84)$$

$$ppm\ NO_x\ (@\ 15\%\ O_2) = 373.1$$

APPENDIX C: DEVELOPMENT OF EQUATION 3.3

The first law of thermodynamics can be applied to a control volume surrounding the engine mounted in the test cell. The resulting energy equation neglecting heat transfer from the surroundings to the control volume is given by:

$$dm/dt\ (h_i + V_i^2/2) = -dE/dt + dm/dt\ (h_e + V_e^2/2) + dW/dt$$

where :

dm/dt	:	Rate of mass addition to the control volume.
h_i	:	Enthalpy of gas entering control volume.
V_i	:	Velocity of gas entering the control volume.
h_e	:	Enthalpy of gas leaving the control volume.
V_e	:	Velocity of gas leaving the control volume.
dW/dt	:	Shaft Power removed from the control volume.
$-dE/dt$	:	Rate of change of energy within the control volume.

For the turboprop/turboshaft engines, the work is extracted using a dynamometer, resulting in the exhaust energy which is significantly reduced relative to the turbojet/turbofan type engines. Assuming the exit velocity is zero, the change in enthalpy through the control volume can be expressed as:

$$(h_e - h_i) = (dmf/dt)/(dm/dt) * LHV - (dW/dt)/(dm/dt)$$

where :

dmf/dt	:	Fuel flow rate per unit time.
LHV	:	Lower heating value.

Assuming a constant heat capacity value across the control volume gives:

$$(t_e - t_i) = (1/Cp) [FA * LHV - (dW/dt)/(dm/dt)]$$

where :

Cp	:	Heat capacity.
dW/dt	:	Shaft power extracted from the engine.
LHV	:	Fuel lower heating value.
te	:	Temperature of gas leaving the control volume.
ti	:	Temperature of gas entering the control volume.
FA	:	Fuel-to-air-ratio.

If the inlet temperature is at atmospheric conditions, then the engine core exit temperature can be expressed as:

$$tc = ta + (1/Cp)[FA * LHV - (dW/dt)/(dm/dt)]$$

where :

tc	:	Engine core exhaust temperature.
Tc	:	Engine core thrust.
FA	:	Fuel-to-air-ratio.
ta	:	Atmospheric temperature.

APPENDIX D: SAMPLE COST CALCULATIONS OF SCR INSTALLATION

Basic Catalyst Parameters (Table 5-1):

Material:	Platinum
Pressure Drop:	1" water gauge
Space Velocity:	27,000 hrs^{-1}
Temperature (TC):	490 °F
Cost:	4,100 $\$/ft^3$

Model Test Cell (A) parameters extracted from Chapter 3 data:

Thrust (%)	Stack Temp °F	% Utilization	Stack Flow (lbs/sec)
100	116.3	25	10123
80	112.0	25	9808
30	91.8	20	8924
Idle	88.4	30	2913

Annual NO_x emissions: 24.4 tons/year

The catalyst volume is calculated using the peak stack volume flow rate at the catalyst operating temperature, and the catalyst space velocity as:

Peak stack actual ft^3/sec (acfs) (@490 °F) = (Max. test cell lbs/sec)/(ρ_s)

where:

ρ_s = Gas density at catalyst operating temperature

and: $\rho_s = (0.076) * (540/(460 + Tc))$

where:

Tc = 490 °F (from Table 5-1 and above)

Peak Stack ACFS (@ 490 °F) = 10123/0.0432

Peak Stack ACFS (@ 490 °F) = 234,340 ft^3/sec

The required catalyst volume (CV) is computed using the peak stack acfs at the catalyst temperature and the catalyst space velocity as:

$$CV\ (ft^3) = 234{,}340\ acfs * 3{,}600\ sec/hr\ /27{,}000\ hrs^{-1}$$
$$= 31{,}245\ ft^3$$

The catalyst cost is given by:

$$\text{Catalyst Cost} = 31{,}245\ ft^3 * 4{,}100\ \$/ft^3$$
$$\text{Catalyst Cost} = \$128{,}105{,}933$$

The reheat fuel flow rate is calculated using the temperature difference between the catalyst operating temperature and the test cell stack gas temperature, the heat capacity of the gas stream, and the heating value of the fuel (natural gas). The reheat fuel flow rate is given by:

$$mf = (ms)(Cp)(\Delta T)/[(Cp)(Tc) - LHV]$$

where:

- mf = Reheat fuel flow rate (lbs/sec)
- ms = Model test cell stack gas flow rate (lbs/sec)
- Cp = Stack gas heat capacity (Btu/lb/F)
- (ΔT) = Catalyst temperature - test cell stack temp. (°F)
- LHV = Lower heating value of reheat fuel (Btu/lb)
- Tc = Catalyst temperature

At 100% thrust, the reheat fuel flow rate is given by:

$$mf = (10{,}123) * (0.28) * (116.3-490)/[(0.28) * (490) - 21{,}500]$$
$$mf = 178{,}600\ lbs/hr$$

At 80% thrust, the reheat fuel flow rate is given by:

mf = (9808) * (0.28) * (112.0-490)/[(0.28) * (490) - 21,500]

mf = 174,900 lbs/hr

At 30% thrust, the reheat fuel flow rate is given by:

mf = (8924) * (0.28) * (91.8-490)/[(0.28) * (490) - 21,500]

mf = 167,700 lbs/hr

At idle, the reheat fuel flow rate is given by:

mf = (2,913) * (0.28) (88.4-490)/[(0.28)(490) - 21,500]

mf = 55,200 lbs/hr

The thermal input is given by the product of the fuel flow and the heating value of the reheat fuel. The calculation utilizes the power schedule of the test cell and is given by:

total BTU's = (total hours/year) * LHV * [(mf(100%) * 0.25 + mf(80%)* 0.25 + mf(30%) * 0.2 + mf(idle) * 0.3]

Total Btu's = $5.95 * 10^5$ MMBTU's

The cost of reheat is estimated at the natural gas price of $3.5/MMBtu[4].

Reheat Costs = Total Btu's * 3.5 $/MMBtu

= $5.95 \times 10^5 * 3.5$

= $2,084,000

The NO_x generated by the duct burner is given by:

NO_x (duct burner) = (MMBtu's reheat) * 0.1 lbs NO_x/MMBtu)

= $5.95 * 10^5 * 0.1$

NO_x (duct burner) = 29.7 tons/yr

The ammonia used by the SCR system is determined from the annual NO_x emission per year and the molar ratio of ammonia to NO_x (1). The annual consumption of ammonia (NH_3) is given by:

Tons Ammonia = Tons NO_x * (molecular wt. NH_3/molecular wt. NO_2)

= (29.7 + 24.4) * 17/46

= 20

The annual requirement of 25% weight ammonia solution is 4 times the tons of ammonia or 80 tons of a 25% solution. The annual chemical cost is then:

Ammonia Cost = 80 tons * 200 $/ton

= $16,000

TECHNICAL REPORT DATA

(Please read Instructions on reverse before completing)

1. REPORT NO. EPA-453/R-94-068	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Nitrogen Oxide Emissions and Their Control From Uninstalled Aircraft Engines in Enclosed Test Cells Joint Report to Congress on the Environmental Protection Agency - Department of Transportation Study		5. REPORT DATE September 1994 (date of submittal to Congress) 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Environmental Protection Agency Office of Air Quality Planning and Standards Emission Standards Division Industrial Studies Branch Research Triangle Park, NC 27711		10. PROGRAM ELEMENT NO. Emission Standards Division 92-20 11. CONTRACT/GRANT NO. Radian 68-D1-0177
12. SPONSORING AGENCY NAME AND ADDRESS Director Office of Air Quality Planning and Standards Office of Air and Radiation U.S. Environmental Protection Agency Research Triangle Park, NC 27711 Department of Transportation Federal Aviation Administration (FAA) Office of Environment and Energy 800 Independance Av SW Washington DC 20591		13. TYPE OF REPORT AND PERIOD COVERED Final - Report to Congress 14. SPONSORING AGENCY CODE EPA/200/04

15. SUPPLEMENTARY NOTES

EPA project manager: Joseph Wood (919) 541-5446. FAA Contact: Edward McQueen (202) 267-3560
Subcontractor for Radian Corp. was Energy and Environmental Research Corp.

16. ABSTRACT

This report was submitted to the Congress under mandate of Section 233 of the Clean Air Act Amendments of 1990. The report provides a characterization of aircraft engine test cells and their emissions. The majority of the test cells in the U.S. are owned and operated by the Department of Defense, aircraft engine manufacturers, and the airlines. There are 368 enclosed aircraft engine test cells in the U.S. No technologies to control NOx emissions have been applied to full-scale test cells. Various NOx control technologies that have been applied to combustion sources other than test cells are examined in the report for their applicability to test cells. The effectiveness of NOx controls applied to test cells is uncertain. It is estimated that the costs of applying conventional NOx controls to test cells would range from $167,000 to over $2.5 million per ton NOx reduced. Effects of NOx controls on the aircraft engine and aircraft engine test are also addressed. Finally, annual emissions from test cells are estimated and compared to total NOx emissions in the applicable ozone non-attainment areas.

17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Aircraft engine test cells nitrogen oxide emissions NOx emission control Costs for NOx emission controls	Air Pollution control	
18. DISTRIBUTION STATEMENT Release Unlimited	19. SECURITY CLASS *(Report)* Unclassified	21. NO. OF PAGES 195
	20. SECURITY CLASS *(Page)* Unclassified	22. PRICE

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