CONS/9416-1
NASA CR-135132

(NASA-CR-135132) DURABILITY TESTING AT ONE ATMOSPHERE OF ADVANCED CATALYSTS AND CATALYST SUPPORTS FOR AUTOMOTIVE GAS TURBINE ENGINE COMBUSTORS, PART 1 Final Report (Engelhard Minerals and Chemicals Corp.) N77-29519
Unclas
G3/37 40829

DURABILITY TESTING AT ONE ATMOSPHERE OF ADVANCED CATALYSTS AND CATALYST SUPPORTS FOR AUTOMOTIVE GAS TURBINE ENGINE COMBUSTORS

Part 1

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ENGELHARD INDUSTRIES
A DIVISION OF ENGELHARD MINERALS & CHEMICALS CORPORATION

June 1977

Prepared for the
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Cleveland, Ohio 44135

Contract NAS 3-19416

As a part of the
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Transportation Energy Conservation
Heat Engine Highway Vehicle Systems Program

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1. Report No.	2. Government Accession No.	3. Recipient's Catalog No
NASA CR-135132		

4. Title and Subtitle	5. Report Date
Durability Testing at One Atmosphere of Advanced Catalysts and Catalyst Supports for Automotive Gas Turbine Engine Combustors - Part I	June 1977
	6. Performing Organization Code
7. Author(s) R. M. Heck, M. Chang, H. Hess, and R. Carrubba	8. Performing Organization Report No
	10. Work Unit No
9. Performing Organization Name and Address Engelhard Industries, a Division of Engelhard Minerals & Chemicals Corporation Menlo Park, Edison, New Jersey 08817	11. Contract or Grant No NAS 3-19416
12. Sponsoring Agency Name and Address Energy Research and Development Administration Division of Transportation Energy Conservation Washington, D. C. 20545	13. Type of Report and Period Covered Contractor Report
	14. Sponsoring Agency ~~Code~~ Report No. CONS/9416-1

15. Supplementary Notes Final Report. Prepared under Interagency Agreement EC-77-A-31-1011. Project Manager, Ted Mroz, Power Generation and Storage Division, NASA Lewis Research Center, Cleveland, Ohio 44135.

16. Abstract

Studies were conducted under a NASA contract funded by ERDA to experimentally demonstrate the durability of CATCOM* catalysts and catalyst supports in a combustion environment. A test of 1000 hours duration was completed with two catalysts, using #2 diesel fuel and operating at catalytically supported thermal combustion conditions. This atmospheric pressure durability test was conducted, using an air preheat temperature of about 640° K and a reference velocity of about 14 meters/second. The adiabatic flame temperature of the fuel/air mixture was 1527° K. The performance of the catalysts was determined by monitoring emissions throughout the test, and by examining the physical condition of the catalyst core at the conclusion of the test. Tests were performed periodically to determine changes in catalytic activity of the catalyst core. Detailed parametric studies were also run at the beginning and end of the durability test, using propane as a fuel. The test catalysts proved to be capable of low emissions operation after 1000 hours diesel aging, with no apparent physical degradation of the catalyst support. Typical emissions during the 1000 hours of testing were: Unburned hydrocarbons (C_3 vppm), 4; Carbon monoxide (vppm), 50; Nitrogen Oxides (vppm), 4. Further durability testing is required to determine the actual life of the test catalyst cores.

*CATCOM is a tradename of Engelhard Minerals & Chemicals Corporation.
CATATHERMAL is a tradename of Engelhard Minerals & Chemicals Corporation.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Catalyst Combustion Low emissions gas turbine combustion Durability testing	Unclassified - unlimited STAR Category 85 ERDA Category UC-96

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No of Pages	22. Price*
Unclassified	Unclassified	223	

* For sale by the National Technical Information Service, Springfield, Virginia 22161

PART I -

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by R. M. Heck, M. Chang, H. Hess and R. Carrubba

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PREPARED FOR

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AND

ENERGY RESEARCH AND

DEVELOPMENT ADMINISTRATION

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I. SUMMARY

The objective of NASA contract NAS3-19416 was to experimentally demonstrate the durability of two CATCOM* catalysts in a combustion environment. Life tests** of 1,000 hours duration were successfully completed with two catalyst cores, identified as DXB-222 and DXC-532, using #2 diesel fuel and operating at catalytically supported thermal combustion conditions. This contract was funded by ERDA and managed by NASA/Lewis.

These atmospheric life tests were conducted at steady state conditions using an air preheat temperature of 640°K and a reference velocity of 14 meters/second. The adiabatic flame temperature of the fuel/air mixture was 1527°K.

The performance of the catalyst cores was determined by monitoring emissions of UHC, CO and NO_x throughout the life test, and by examining the physical condition of the catalyst core at the conclusion of the life test. Scheduled activity tests were performed periodically during the life test to determine changes in catalytic activity of the catalyst core. Detailed parametric studies were performed at the beginning and end of each life test, using propane as a fuel. Parametric testing was performed at pressures of 1×10^5 N/M^2 to 5×10^5 N/M^2, air preheat temperatures of 633°K to 810°K and reference velocities of 14 M/S to 30 M/S.

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*CATCOM is a trade name of Engelhard Minerals and Chemicals Corp.
**Life test implies a 1,000 hour durability test throughout this report.

These studies were carried out in a test rig which was designed and constructed under the contract. The key component of this rig was a nominal one-inch diameter tubular reactor, in which the catalyst was mounted. Operation of this reactor was essentially adiabatic.

Although some catalyst degradation did occur, both catalyst cores DXB-222 and DXC-532 proved to be capable of low emissions operation after 1,000 hours of operation with #2 diesel. Apparently there was no physical degradation of the catalyst support. For both cores, typical emissions during the 1,000 hours of life testing were:

Unburned Hydrocarbons (C_3 vppm)	4
Carbon Monoxide (vppm)	50
Nitrogen Oxides (vppm)	4

These test results proved the feasibility of using CATCOM catalysts DXB-222 and DXC-532 in CATATHERMAL* combustion, catalytically supported thermal combustion, for at least 1000 hours of low emission steady state operation with #2 diesel fuel.

The preferred catalyst core selected from these studies for further testing was DXB-222. This catalyst proved to have a wider range of low emissions operation with #2 diesel fuel after 1,000 hours of aging.

*CATATHERMAL is a trade name of Engelhard Minerals & Chemicals Corporation.

It is recommended that additional life testing of DXB-222 be carried out at higher pressures, in order to more closely simulate gas turbine engine operating conditions, and determine durability at increased operating pressure. It is further recommended that a parallel effort be carried out to test DXB-222 in realistic combustion hardware to evaluate transient and response characteristics.

II. INTRODUCTION

The concept of using catalysts for low emission combustion processes has been intensively explored by Engelhard Industries Division of Engelhard Minerals and Chemicals Corporation over the past five years. Laboratory tests have shown the feasibility of low emissions operation, particularly NO_x emissions, with a wide variety of gaseous and liquid fuels[1,2]. Rig tests at NASA Lewis, Westinghouse and Wright Patterson Air Force Base have confirmed these laboratory results, and also showed the ease of scale-up and improved temperature pattern factor for CATCOM catalysts[3,4,5].

NASA Lewis Research Center realized that information on the durability of the catalyst and catalyst support in the extreme conditions of a combustion environment was required to further demonstrate the practicality of candidate CATCOM catalysts. In addressing this question, the NASA contract NAS3-19416, entitled "Catalyst and Catalytic Substrate Material for Gas Turbine Engine Combustion" was awarded to Engelhard Industries on March 21, 1975. The period of performance of this contract was 18 months. Under this contract relevant information was to be obtained on the long term operation capabilities of CATCOM catalysts. This contract was funded by ERDA and managed by NASA/Lewis.

The program under this contract was divided into four tasks as follows:

Task I - Survey and Selection of Contractors Catalysts and Catalytic Substrates for Parametric and Endurance Testing

Task II - Test Facilities

Task III - Sub-scale Catalytic Substrate Parametric and Endurance Testing

Task IV - Reporting Requirements.

For reference, the detailed Work Statement is given in Appendix A.

Task I of the contract required selection of catalyst cores for endurance testing, based on catalyst screening results at Engelhard Industries. Under Task II, a test rig and adiabatic tubular reactor were constructed. Task III involved life testing of two selected catalyst cores. These life tests were conducted at conditions which simulated steady state operation of an automotive gas turbine. Testing was satisfactorily completed on two catalyst cores designated DXB-222 and DXC-532.

The details of this contract, the construction of the test rig, the performance test results and conclusions regarding the durability of the catalyst cores are discussed in this report.

III. TASK I - SELECTION OF TEST CATALYST CORES

A. CRITERIA AND JUSTIFICATION FOR CATALYST CORE SELECTION

During the first month of the contract, a thorough review of in-house catalyst screening data was conducted in order to select the most promising catalyst cores for life testing. The guidelines upon which this selection was based are shown in Table III-1.

As the contract period progressed, on-going catalyst development programs provided supplemental information on new catalyst cores. With the approval of the NASA Program Manager, one of these catalyst cores was substituted into Task III, replacing one of the originally chosen cores. This substitution was made based on in-house test results, which showed that the new catalyst core had better potential for higher temperature stability.

For purposes of clarity, only the data pertinent to the two Engelhard catalyst cores actually tested in Task III plus a standard reference catalyst, will be reviewed.

B. PROPOSED CATALYTIC CORES

During the past five years, Engelhard Industries has been actively engaged in a catalyst core development program, aimed at

TABLE III-1

Guidelines In Catalytic Core Selections

1. Durability and life of the catalytic core at the specified operating conditions.

2. Low emissions (NO_x, CO and HC) characteristics and operation at the specified operating conditions.

3. Ignition characteristics.

4. Cost of catalyst materials.

5. Availability of catalyst.

6. Compounds or elements which act as poisons to the catalysts.

7. Catalytic core degradation.

8. Catalytic core maximum operational temperature.

9. Developmental status.

10. Contractor's in-house screening test parameters (inlet and outlet temperature, inlet pressures, reference velocity, heat release rates, test fuels, test duration and fuel-air ratios).

11. In-house screening test results (NO_x, CO and HC emissions, combustion efficiency, ignition characteristics, pressure drop and degradation, if any).

12. Identification of catalyst support materials.

13. Identification of catalytic core.

14. Differences between the screened and recommended catalytic cores.

selection of prime candidates for combustion applications. These catalyst cores were screened using the following test sequence:

1. Ignition Properties
2. Support Performance
3. Accelerated Thermal Aging
4. Emissions at Simulated Commercial Gas Turbine Engine Operating Conditions
5. Life Testing

As this sequence progresses, candidates that fail are eliminated from the next step.

The "control" (or reference) catalyst core throughout this sequence was designated DXA-111. This "first generation" catalyst core has been tested successfully in many large scale test rigs including those at NASA-Lewis, Westinghouse and Wright Patterson AFB[3,4,5]. The catalyst cores proposed in Task I showed significantly improved performance over DXA-111.

In this catalyst development program, over 150 catalyst compositions were tested at one stage or another of the screening procedure. Catalytic components ranging from base metals to rare earths to precious metals, as well as combinations of these, were tested. For the NASA Program, candidates were selected on the basis of their known properties and the NASA Program requirements.

The two proprietary Engelhard catalyst cores, which were life tested in Task III are designated as DXB-222 and DXC-532 and are described in Table III-2. Both catalyst cores have the same catalytic components with the major differences being: 1) In the ratio of Pd to Pt, and; 2) the specific high temperature stabilizers used. In relation to the control catalyst core DXA-111, both DXB-222 and DXC-532 are prepared on an improved ceramic support material. Catalyst cores DXB-222 and DXC-532 showed the most improved ignition characteristics of all catalysts tested in-house. Both DXB-222 and DXC-532 have a broader range of low emissions operation in comparison to DXA-111. In addition, DXB-222 and DXC-532 showed excellent thermal stability throughout the screening test series. From short term testing, the combination of support, stabilizers and catalytic components on DXB-222 and DXC-532 appeared to be the most promising for long term durability in life testing. The 1000 hour life tests under this contract were necessary to determine life potential.

The following data in support of selection of catalyst core DXB-222 and DXC-532 show that the main criteria for selection was the improvement in the thermal stability and emission characteristics over the control catalyst core DXA-111.

TABLE III-2

Properties of Test Catalyst Cores

Catalyst Identification	Catalyst Components	Support
DXB-222	Palladium and Platinum (Combined level up to 5%)	256 Channels/in^2 Zircon Composite
DXC-532	Palladium and Platinum (Combined level up to 5%)	256 Channels/in^2 Zircon Composite

NOTE: In all cases, the above catalyst cores contain proprietary stabilizers. These stabilizers represent major differences in the two test catalysts.

C. BACKGROUND INFORMATION ON TEST CATALYST CORES

1. Standard Laboratory Screening Procedures

Frequently, the last step in the demonstration of a new catalyst core is the actual life testing of the catalyst under a commercial operating environment. This is primarily because a realistic life test is extremely time consuming and expensive. For purposes of efficiency and economy, catalysts which are not promising from an application standpoint must be eliminated prior to the life testing stage.

In developing the CATCOM catalysts, it was necessary to develop rapid but reliable screening tests for selection of catalyst core candidates for life testing. The screening test sequence was designed to select candidates having a good probability of subsequent success in life testing. Catalyst performance was first evaluated using a coarse screening procedure, which narrows down the number of candidates, followed by more detailed evaluations simulating commercial operations.

The tests used for screening catalyst cores for "catalytically supported thermal combustion" were as follows:

Ignition temperature: Will the catalyst core ignite at a useful operating temperature and sustain this ignition

characteristic? (Some catalysts exhibited low ignition temperatures, but on subsequent ignitions, this temperature increased.)

Thermal degradation: Will the catalyst support withstand the temperature involved in combustion operations?

Accelerated thermal aging: Will the catalyst core perform adequately with sustained ignition characteristics and low emissions after exposure to combustion temperatures?

Emissions: Will the catalyst core give acceptable emissions under simulated commercial combustion conditions, with a variety of combustion fuels?

Life test: Will the catalyst core maintain acceptable performance for required operating times of the combustor application?

As these screening procedures progressed, catalyst cores that showed the most significant improvement over the control catalyst DXA-111 were selected for the next testing sequence.

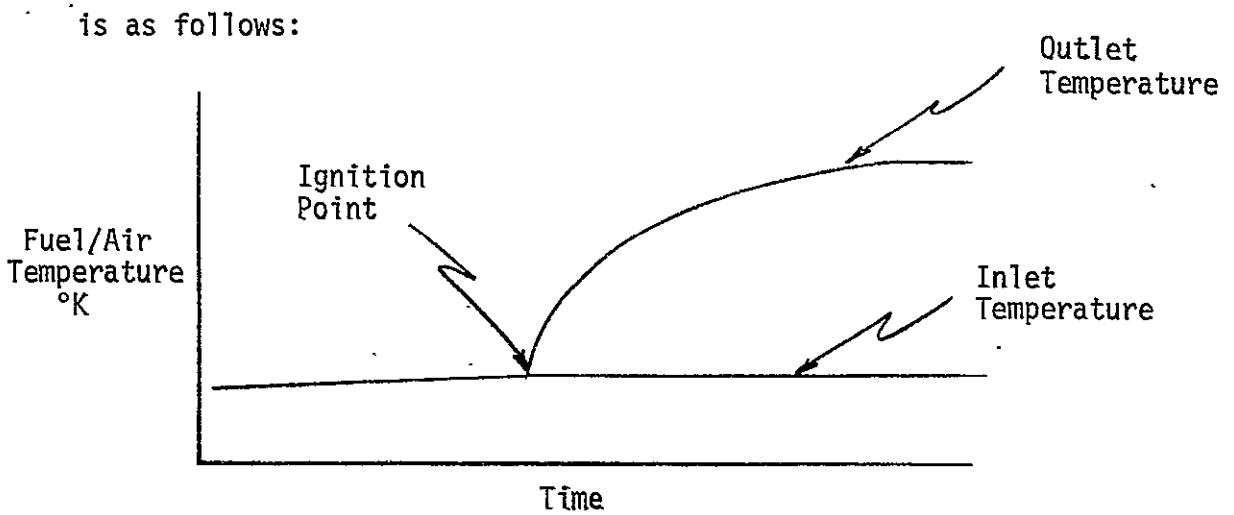
A brief description of each test follows:

Ignition Temperature: The inlet temperature of the fuel/air mixture is raised in 10°K increments until catalytic

reaction begins within the catalyst core. Typically, this experiment is performed under the following conditions:

Space Velocity$_{NTP}$:	~28 $M^3/S\text{-}M^3$ (100,000 $Ft.^3/Hr.\text{-}Ft.^3$
Fuel Type:	Variable
Air/Fuel Wgt.:	38/1 (g/g)
Pressure:	1×10^5 N/m^2 (1 atm.)

The typical temperature response on a strip chart recorder is as follows:



Thermal Degradation: Three separate experiments are performed on the catalyst support:

Thermal Shock: The support is placed in a furnace preheated to either 1170°K or 1270°K. After 10 minutes in the furnace, the support is removed and allowed to cool in ambient air. The support is physically examined for damage after cooling is complete. This process is repeated 10 times at each temperature level. These

test results depend on the test specimen size. As a minimum, a support block of .127M (5"Φ)* is used.

Sag and Melt Point: The support is initially placed in a preheated furnace for 24 hours at 1589°K. At the end of this 24 hour period the support is removed and examined for structural defects due to sagging of channels or melting. These observations are recorded and the support placed back in the furnace for another 24 hour period. For each thermal cycle, the furnace temperature is raised in increments of 56°K. The temperature at which the channels first begin to sag or support melting occurs is recorded and the test is terminated. This test is terminated at 1820°K.

Differential Thermal Analysis: The support is placed in a DTA apparatus and the temperature for phase transition is determined.

Accelerated Thermal Aging: As a baseline, a fresh catalyst sample is tested in the laboratory reactor to determine its "virgin" activity. The tests consist of a standard ignition test, followed by a hydrocarbon conversion test, as described below.

An identical sample is then thermally aged at 1590°K for 24 hours in a preheated furnace with air as the environment.

*Φ is used as a symbol for diameter.

Following this aging step, the catalyst is removed from the furnace and the ignition temperature measurement and hydrocarbon conversion test are carried out.

The conditions for the hydrocarbon conversion test are:

Space Velocity:	~28, 56, 69 M^3/sec-M^3 (100,000, 200,000 and 250,000 ft.^{3}/hr.-ft.^{3})
Air/Fuel Ratio:	80/1 (g/g)
Fuel:	Commercial propane
Inlet Temperature:	670°K
Pressure:	1×10^5 N/m^2 (1 atm.)

Hydrocarbon conversion is measured at each space velocity, once steady state has been attained.

Comparison between catalysts can be done by comparing their relative activity. Relative activity is defined as the space velocity required to maintain 50% hydrocarbon conversion level for the tested catalyst divided by the corresponding space velocity for DXA-111.

The above conditions have been deliberately chosen so that complete combustion is not achieved, even for the best catalysts. Differences between catalysts cannot be determined if the conditions are such that complete combustion is usually achieved.

Emissions Testing: The catalyst core is tested in a laboratory test rig using commercial combustor fuels under conditions which partially simulate commercial gas turbine operation. Specifically, the following parameters are set to duplicate proposed design conditions for stationary gas turbine engines:

Space velocity

Air preheat temperature

Air/fuel weight ratio

Combustion efficiency and emissions exiting the catalyst core are determined for performance comparisons.

Life Testing: The catalyst core is run in the laboratory test rigs using the fuel specific to the proposed commercial application, under partially simulated, full-load, commercial operating conditions. These conditions naturally vary with each commercial operation. Due to rig limitations, it is usually not possible to operate at proposed commercial operating pressures.

2. Ignition Characteristics

The ignition characteristics of the catalyst core are highly dependent upon the nature of the fuel. Table III-3 shows the ignition characteristics of DXA-111 for a variety of fuels used in commercial combustion applications. Notice that the most refractory fuel is methane. Determination of improvements in the methane ignition temperature represents the first coarse screen of catalyst testing sequence.

Catalytic cores with initially good ignition characteristics may deteriorate in repeated ignitions due to thermal degradation, resulting in substantial increases in subsequent ignition temperatures. Many virgin catalysts ignited below 530°K but subsequent ignitions ranged as high as 810°K. These catalysts were eliminated from further consideration.

Table III-4 shows the methane ignition results for the two proposed catalyst cores. DXB-222 and DXC-532 showed the best methane ignition characteristics, and had a total of only 5-10°K increase after repeated ignition experiments. This lowering of ignition temperature relative to DXA-111 is attributed to the increased intrinsic activity of the catalyst components in these catalytic cores. DXB-222 and DXC-532 also showed good thermal stability, in that repeated ignitions showed no significant degradation.

TABLE III-3

Ignition Performance of Engelhard DXA-111

Fuel	Catalytic Ignition Temperature (°K)
Hydrogen	290
Coal Gas	430
Methane	740
Propane	605
JP-4	510
#2 Diesel	540
Methanol	455
Benzene	515

Range of Test Conditions:

Fuel/Air (wgt.) = .0263 g/g
(.313 g/g for Coal Gas)

Space Velocity $_{NTP}$ = 28 to 83 $M^3/S\text{-}M^3$

TABLE III-4

Ignition Performance of
Engelhard Catalytic Core Candidates

Catalytic Core Designation	Methane Ignition Temperature (°K)
DXA-111	740
DXB-222	550
DXC-532	570

Test Conditions:

Fuel/Air (wgt.) = .0263 g/g

Space Velocity $_{NTP}$ = ~28 $M^3/S\text{-}M^3$

3. Catalyst Support Stability

The chemical and physical stability of the catalyst support is important in the selection of the catalyst core. The catalyst support must be compatible, such that the catalyst can be prepared on the catalyst support, and the catalyst support must not adversely affect the performance of the catalyst core under combustion conditions.

During this development program, over 20 support candidates were screened. Some of the common support materials available for high temperature operation are α-Al_2O_3, cordierite, mullite, SiN and SiC. A number of manufacturers such as DuPont, American Lava, Corning, Pure Carbon, NGK, Kyocera and W. R. Grace are engaged in marketing high temperature honeycomb supports.

Engelhard has found that alumina and zircon composites are acceptable substrate materials.

The three prescreening tests used to select support candidates are:

Thermal shock

Sag and melt point

Phase transition (DTA)

The results of the thermal shock tests on the improved support proposed for use in this program are shown in Table III-5. As a contrast, many other supports actually shattered during the first cycle of this test procedure.

The sag and melt point test explored the maximum operating excursions possible during the combustion conditions. The test results show (see Table III-6) that, even at 1820°K, no problems in channels collapsing nor support melting were noticed. To support this conclusion, the DTA scan was run (see Table III-6) and results showed no phase change occurred up to 1820°K. This temperature represents the upper limit for this particular DTA apparatus.

4. Accelerated Thermal Aging

Catalyst cores that showed significant improvements over DXA-111 in ignition and support evaluations were further tested in the accelerated thermal aging test. Experience from automotive catalyst development has shown that a catalyst must be resistant to accelerated thermal aging to sustain acceptable performance under actual operating conditions. This accelerated test procedure was designed to simulate exposure of the catalyst core to actual combustion temperatures.

TABLE III-5

Thermal Shock Test Results
For Catalyst Core Support

Test Temperature	Appearance of 1st Crack	Final Disposition
1170°K	None after 10 cycles	Complete retention of integrity
1270°K	None after 10 cycles	Complete retention of integrity

TABLE III-6

Thermal Stability For
Catalyst Core Support

Test	Results
Sag and melt point	No change up to 1820°K *
Differential Thermal Analysis	No phase change up to 1820°K

* Equipment limited to 1820°K maximum temperature.

The results of these tests for the proposed catalyst cores are shown in Figure III-1. Note that both cores exhibit better performance than DXA-111. In contrast many of the catalyst cores tested and rejected had conversion levels from 0 to 20%.

5. Emissions and Combustion Efficiencies

Emissions and combustion efficiency tests represent the first test in the screening sequence where the catalyst core is tested under operating conditions approaching full-load, commercial combustion conditions. Since DXA-111 was selected as the first generation catalyst for outside testing, its characteristics were studied extensively, looking at the following responses:

Air preheat temperature (Fig. III-2)
Catalyst core outlet temperature (Fig. III-3)
Effect of combustor fuel properties (Table III-7)
Fuel/air weight ratio in combustor feed (Fig. III-4)
Space velocity of catalyst core (Fig. III-5)

Figure III-3 shows that, for catalyst core operating temperatures above 1360°K, the emissions for propane fuel are well below anticipated Federal Standards for automotive turbine and stationary turbine applications[6,7]. In addition, Table III-7 shows that these same low emissions can be obtained for a range of combustion fuels.

Figure III-1

Accelerated Thermal Aging Results
On Selected Catalyst Cores

Fuel: Commercial Propane
Air/Fuel (wgt.): 80/1 (g/g)
Air Preheat: 670°K
Aging Temperature: 1590°K
Pressure: 1×10^5 N/M^2
Aging Time: 24 hours in air

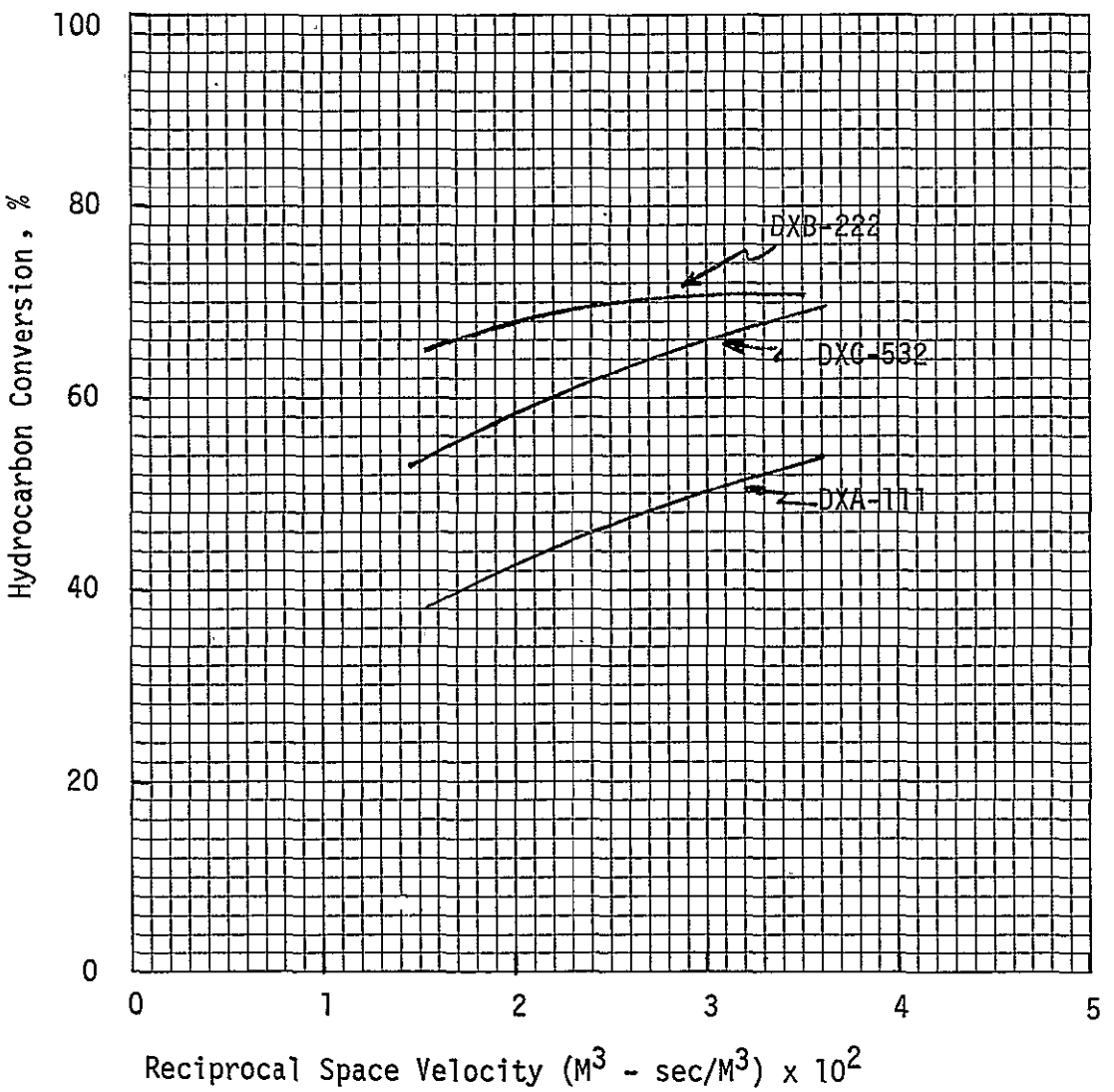


Figure III-2

Effect of Air Preheat Temperature on Combustion Efficiency For DXA-111

Fuel: Commercial Propane
Air/Fuel (wgt.): 38/1 (g/g)
Space Velocity$_{NTP}$: ~ 28M^3/sec-M^3
Pressure: 1 x 10^5 N/M^2

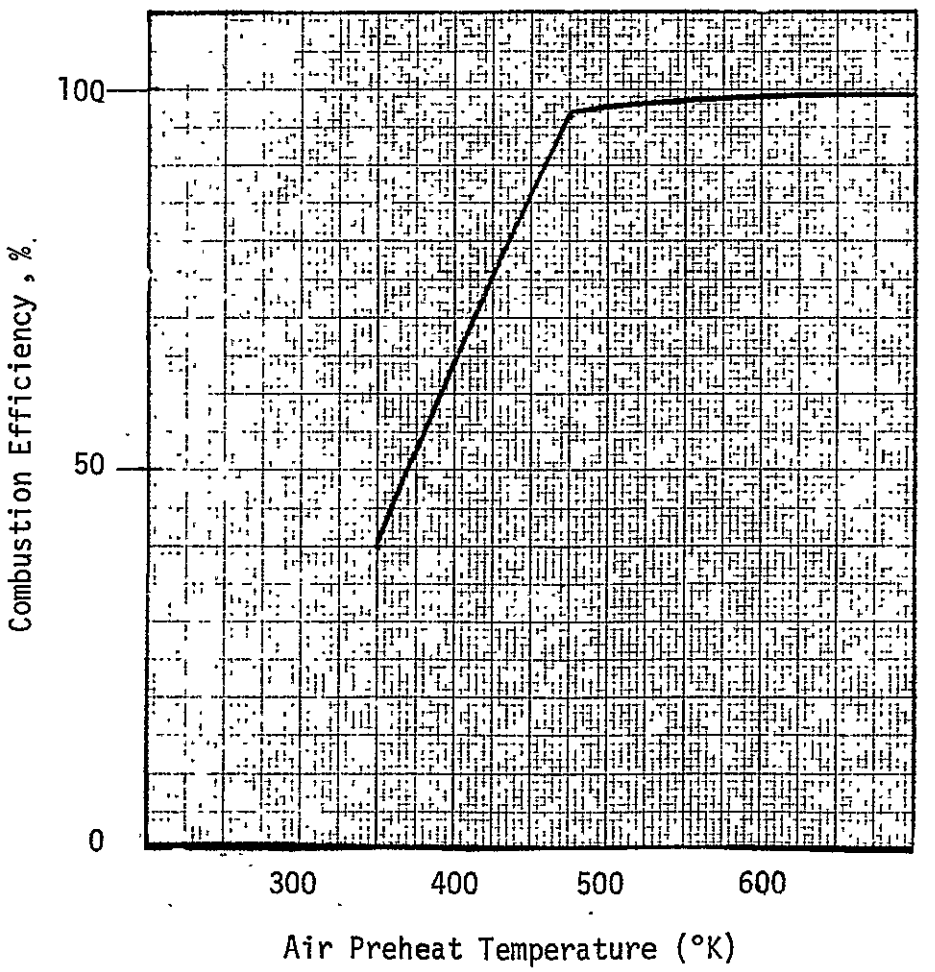


Figure III-3

Effect of Catalyst Core Outlet Temperature on Emissions For DXA-111

Fuel: Commercial Propane
Fuel/Air: 0.0263 (g/g)
Pressure: Atmospheric
Inlet Temperature: Varied
Space Velocity NTP: ~ 28 $M^3/s\text{-}M^3$

Legend:

▲ Carbon Monoxide
■ Hydrocarbons
● NO_x
---Instrument Background Noise Level

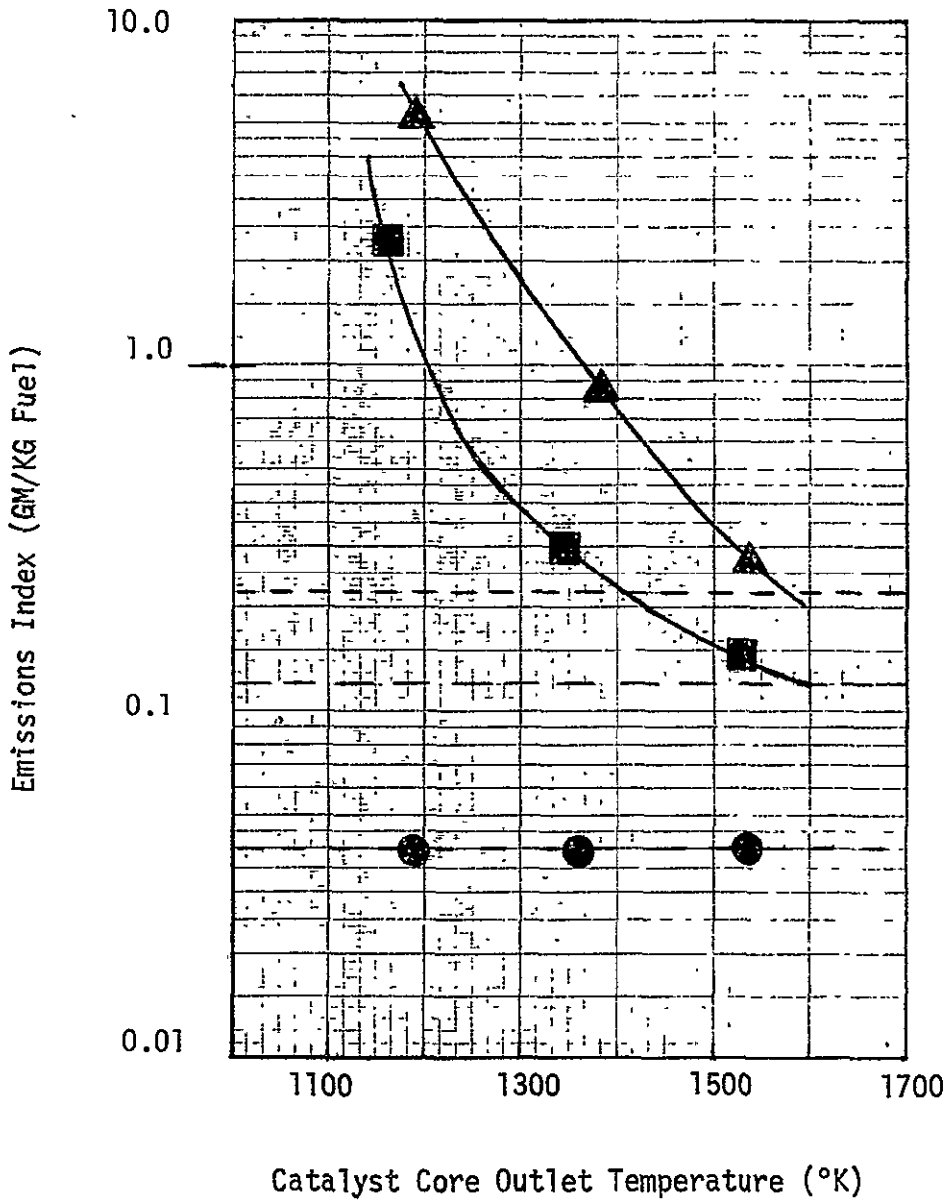


TABLE III-7

Emission Data For
DXA-111 Using Various Fuels*

Fuel	HC(asC_3) vppm	CO vppm	NO_x vppm
Methane	0	10	1
Propane	2	11	1
#2 Diesel	2	10	7
JP-4	0	15	1

* Typical Conditions:

A/F Wgt.: 40/1 (g/g)
Air Preheat: 740°K
Space Velocity $_{NTP}$: $\sim 28 M^3/s\text{-}M^3$
Pressure: 1×10^5 N/M^2

Figure III-4

Response of Combustion Efficiency for DXA-111 To Changes in Fuel/Air Ratio

Air Preheat Temperature: 670°K
Space Velocity$_{NTP}$: ~ 28 M^3/s-M^3
Pressure: 1×10^5 N/M^2
Fuel: Commercial Propane

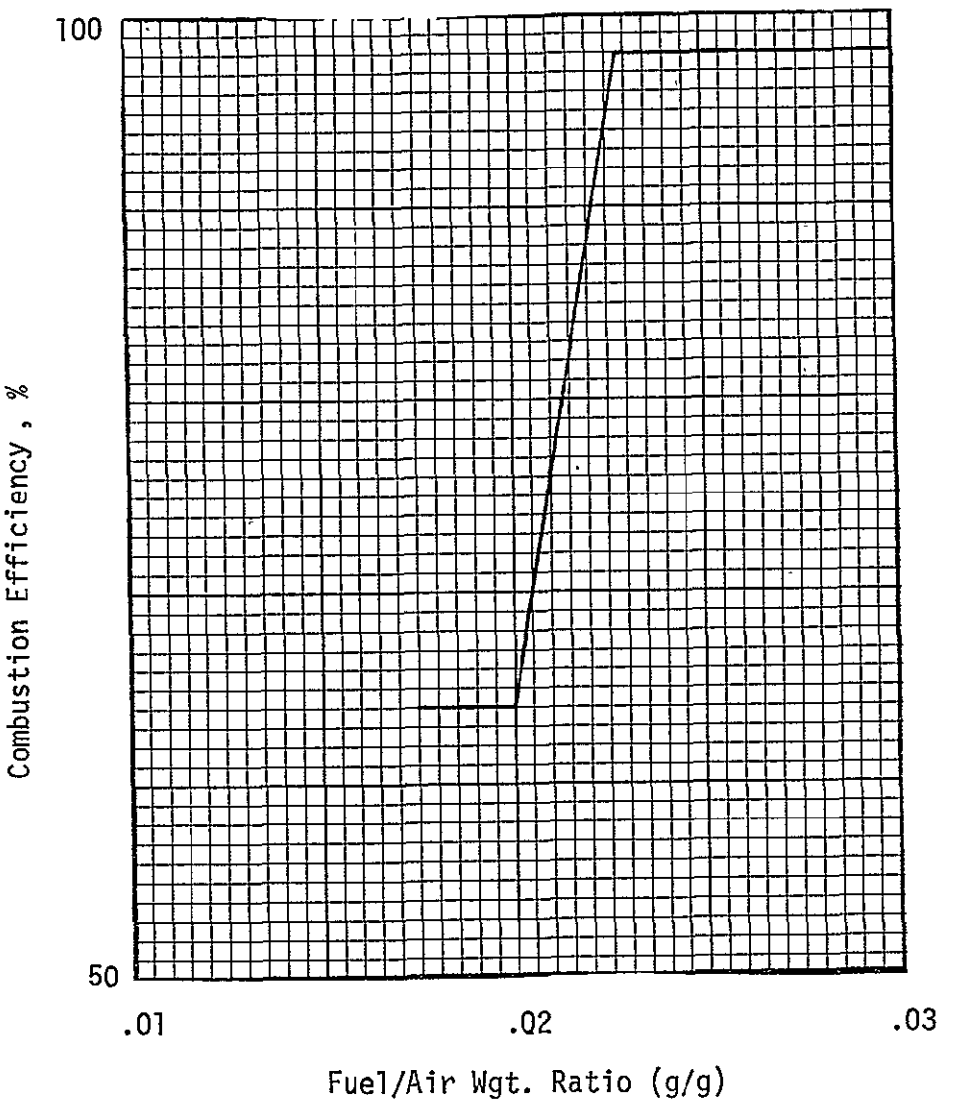
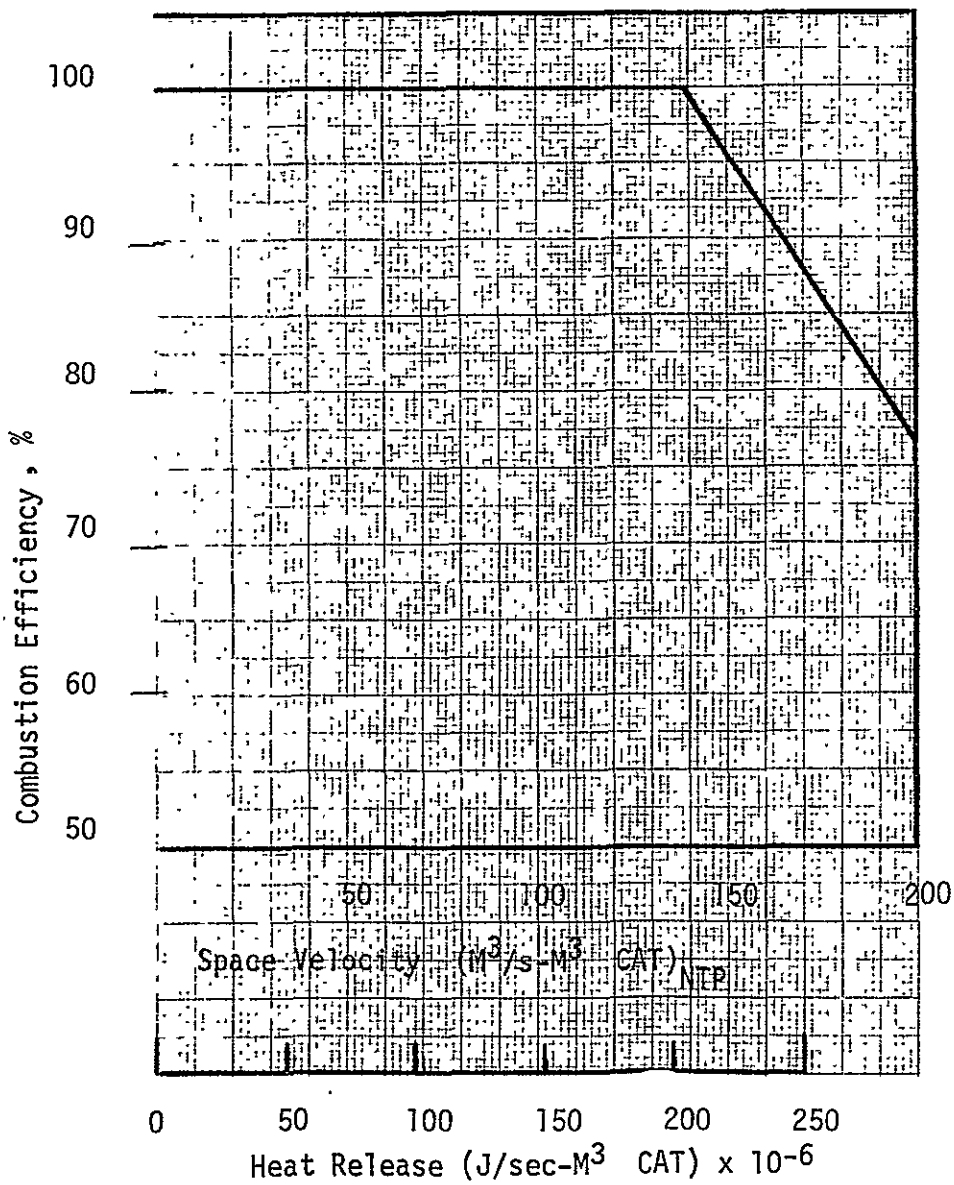


Figure III-5

Effect of Space Velocity on
Combustion Efficiency For DXA-111

Fuel: Commercial Propane
Fuel/Air: .026 (g/g)
Pressure: 1×10^5 N/M^2
Inlet Temperature: 670°K



Since the emissions performance on DXA-111 was acceptable under typical commercial operating conditions (see Table III-7), improvements in the operating range were considered an important criteria in screening for catalyst core improvements. One test used was to determine the response of combustion efficiency as a function of air preheat temperatures. Improvements in catalyst core performance would be indicated by achieving high combustion efficiencies at lower preheat temperature compared to DXA-111.

Figure III-6 demonstrates that both DXB-222 and DXC-532 yielded essentially 100% fuel conversion at temperatures as low as 500°K, for the stated conditions. This is about 150°K lower than for the control catalyst, DXA-111. These improvements may result in a wider turndown range for these catalyst cores and, thus, better performance characteristics.

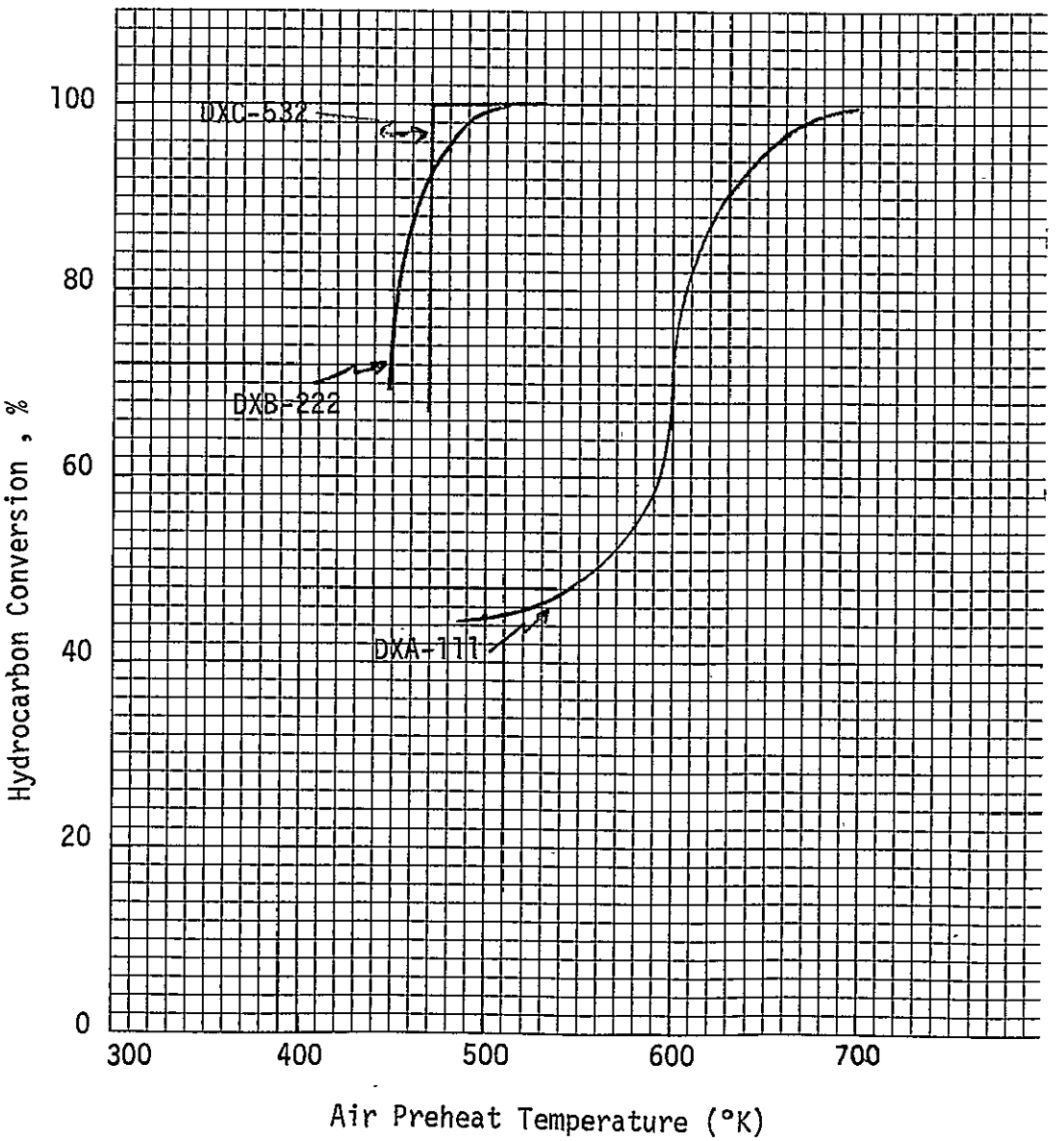
Many of the guidelines presented in Table III-1 for selection of test catalyst cores in Task III of this contract are satisfied as shown by the performance data for control catalyst core DXA-111. However, comparative screening tests indicate that catalyst cores DXB-222 and DXC-532 may have significant improvements over DXA-111 in

- ignition characteristics
- broader operating range for low emissions
- thermal stability

Figure III-6

Response of Hydrocarbon Conversion
To Increasing Air Preheat Temperature

Fuel: Commercial Propane
Space Velocity: ~ $28M^3/s\text{-}M^3$
Air/Fuel (wgt.): 38/1 (g/g)
Pressure: 1×10^5 N/M^2



and yet maintain all the excellent performance qualities shown for DXA-111.

The questions relating to poisons and catalyst core degradation must, by necessity, be answered with long term life testing, which represents the final rationale for testing of catalyst cores DXB-222 and DXC-532 as part of this contract.

IV. TASK II - TEST FACILITIES

A. DESIGN AND CONSTRUCTION OF TEST RIG

In order to accomplish the experimental program to be described in Task III, a test rig was designed, constructed and installed in the CATCOM laboratory at Engelhard's Menlo Park Research Laboratories. This test rig had to be capable of the following modes of operation:

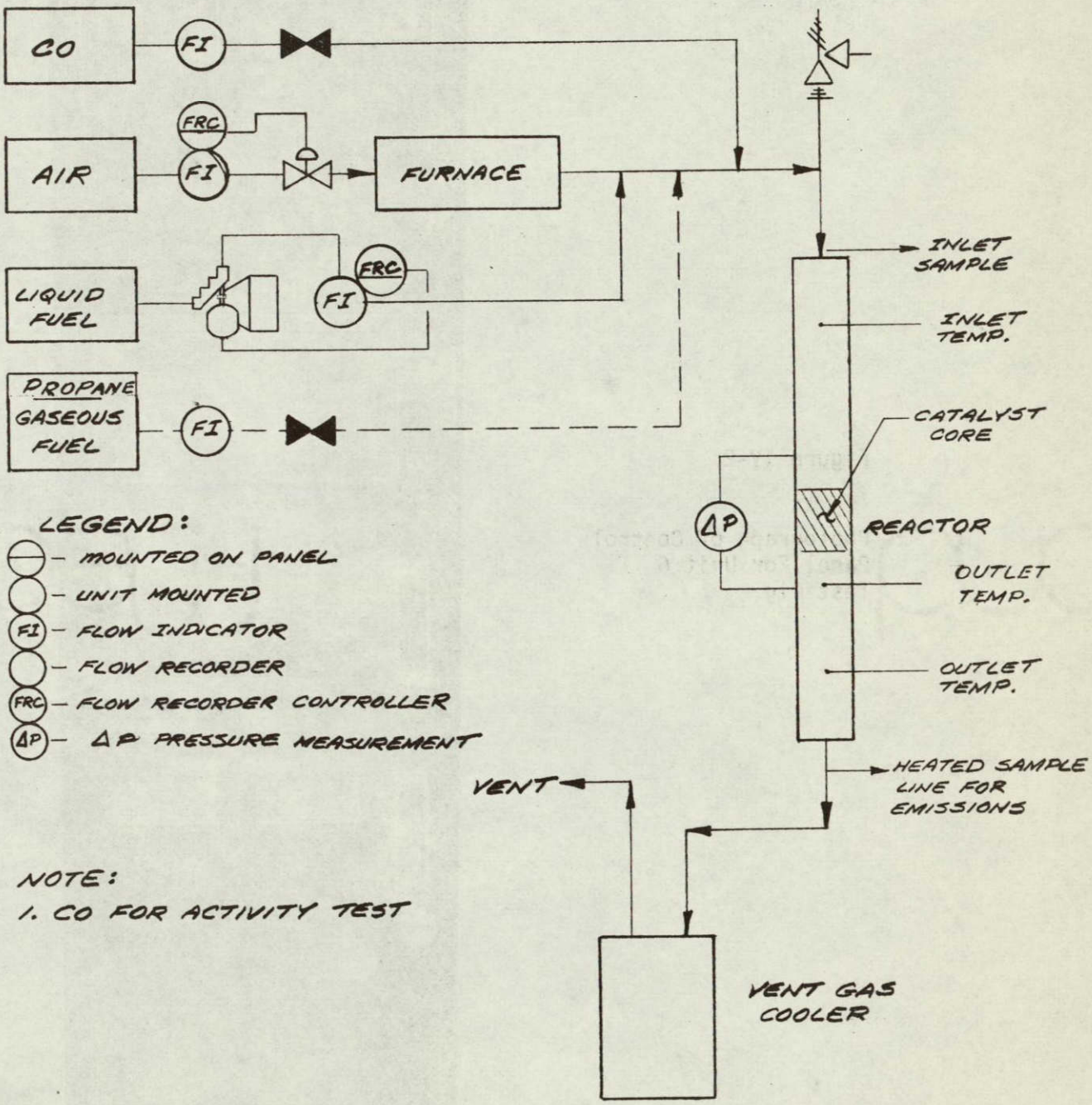
1. Steady-state life testing using liquid fuels - automated, unattended.
2. Parametric testing with either gaseous or liquid fuel - manual.
3. Activity testing with gaseous fuel - manual.

Based on past experience in evaluating CATCOM catalysts, a .0254 M diameter (1"Ø) adiabatic reactor was constructed. The reactor was designed to operate downflow with an adiabaticity ranging from 90 to 100%.

The schematic for the test rig is shown in Figure IV-1. Photographs showing the completed test rig and panelboard are shown as Figures IV-2 and IV-3. Detailed drawings are contained in Appendix F. The main elements of the test rig (designated unit #6) are as follows:

Figure IV-1

Schematic of Unit 6 Test Rig



BLOCK DIAGRAM OF TEST UNIT

NASA CONTRACT #NAS3-19416

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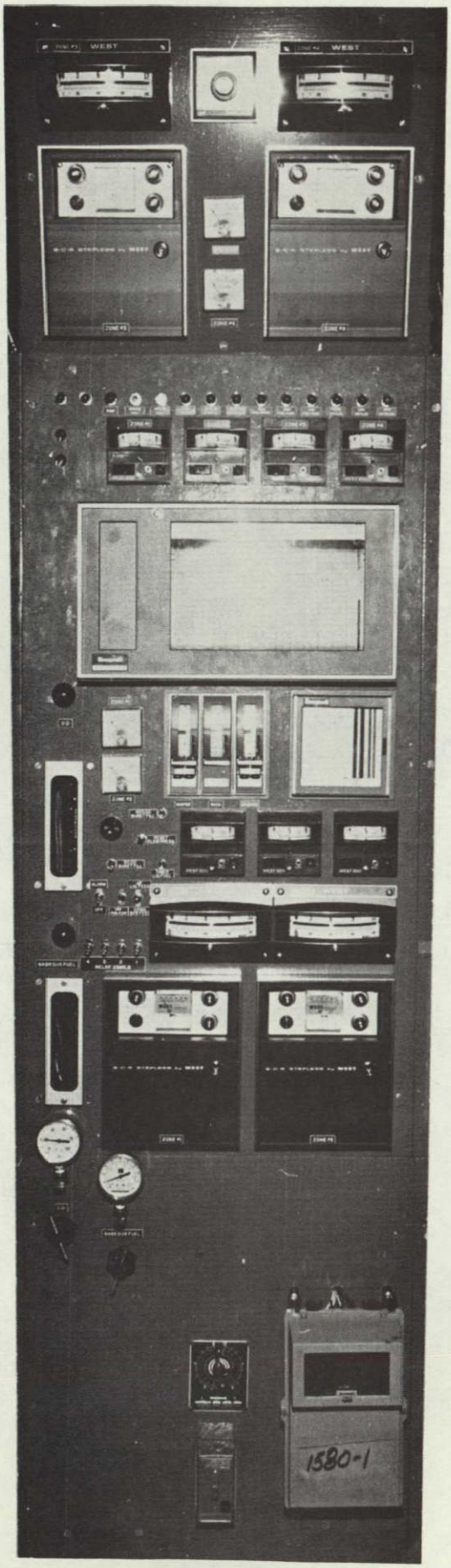

Figure IV-2

Photograph of Control Panel For Unit 6 Test Rig.

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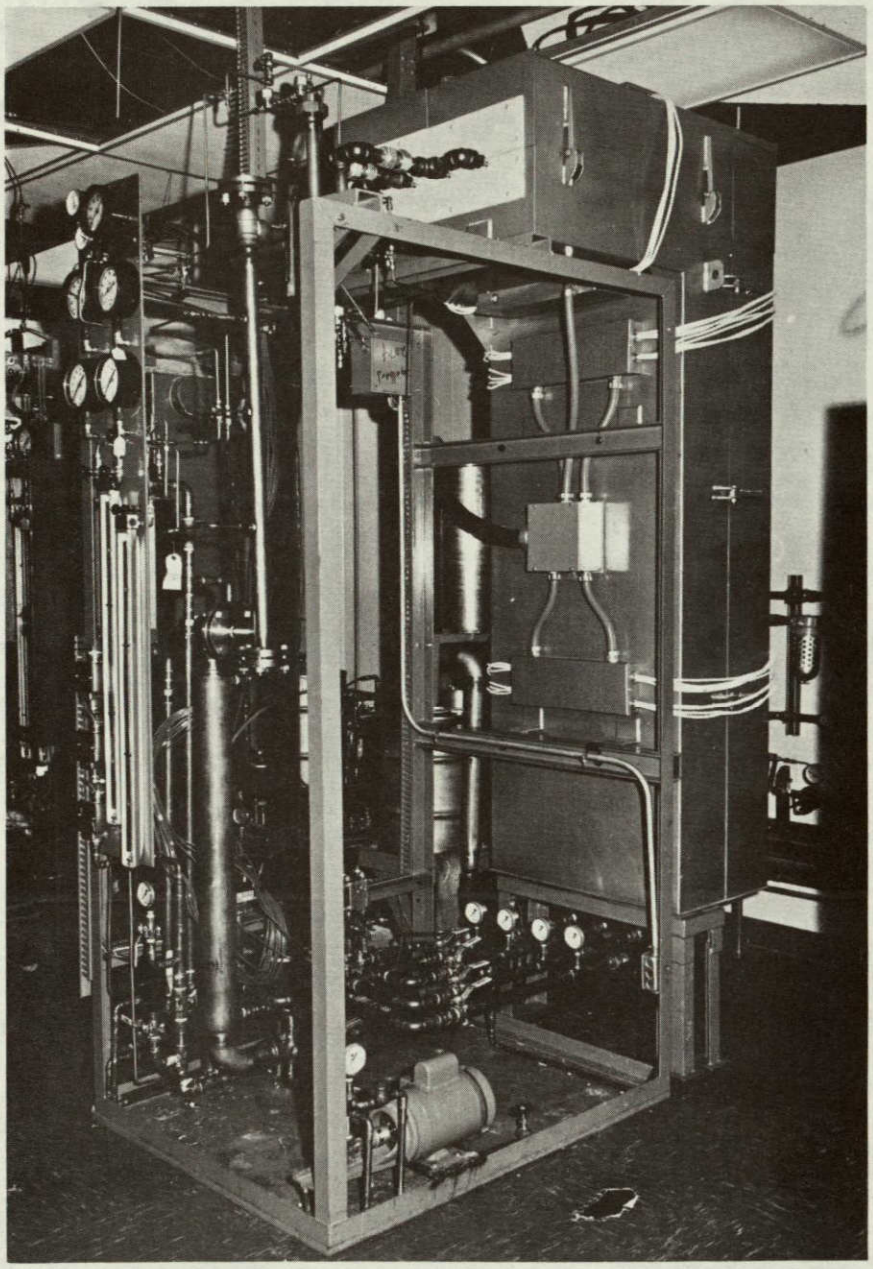


Figure IV-3 Photograph Showing Physical Layout of Equipment For Unit 6 Test Rig

1. Air feed control loop for automatic or manual operation.
2. Fuel (liquid) control for automatic or manual operation.
3. Air preheat section.
4. Fuel injection and mixing section.
5. Reactor section.
6. Exhaust gas cooling and venting.
7. Carbon monoxide feed for activity testing.
8. Propane feed section for parametric testing.

Table IV-1 lists the operating ranges for the test facility.

The experimental reactor used in testing the catalyst cores at combustion conditions is detailed in Appendix F. This reactor was constructed of Inconel 601 pipe and could be operated for endurance testing at 1533°K and 1×10^5 N/M^2 (1 atm.) and short term testing at 1533°K and 5×10^5 N/M^2 (5 atm). The reactor was instrumented for measurement of

- catalyst core inlet and outlet temperature
- catalyst core pressure drop
- catalyst core inlet pressure
- catalyst core emissions

The pressure drop apparatus consisted of a manometer with pipe tap locations upstream and downstream of the catalyst core in accordance with ASME recommended practice.[8]

TABLE IV-1

Operating Ranges for Unit 6

Automatic Control Operation:

Air Flow	1.85×10^{-3} to 5.9×10^{-3} Kg/S
Air Preheat Temperature	up to 810°K
Fuel Flow (Liquid)	6.7×10^{-5} to 67×10^{-5} kg/S
Reactor Pressure	1.0×10^{5} N/M^2 to 5×10^{5} N/M^2
Adiabatic Flame Temperature*	Up to 1533°K
Fuel Type	#2 Diesel

Manual Operation:

Air Flow	1.85×10^{-3} to 66.7×10^{-3}/Kg/S
Air Preheat Temperature	up to 810°K
Fuel Flow (Gaseous)	1.7×10^{-4} to 17×10^{-4} Kg/S
Reactor Pressure	1.0×10^{5} to 5.0×10^{5} N/M^2
Adiabatic Flame Temperature *	up to 1533°K
Fuel Type	Chemically Pure (C.P.) Propane

* For conditions of 90% reactor adiabaticity, adiabatic flame temperature may be increased to 1570°K without damage to reactor walls.

The emission samples were taken with a .00635M diameter (1/4"Ø) water-cooled sampling probe. The sampling train adhered to SAE Standard ARP-1256. The description of each individual analytical instrument is listed in Table IV-2. The standard calibration procedure of each instrument is detailed in Appendix E.

The product collection and vent system were designed to cool the combustion gases sufficiently so they could be vented into existing house vent facilities.

The operation of Unit #6 is best described by considering the start-up and line-out of the unit for life testing. The following sequence was followed:

1. Turn on electrical power to unit.
2. Set air flow on control loop to specifications in operating instructions.
3. Begin heat up of air using furnace automatic control.
4. Line-out operation of exhaust gas cooler and vent system.
5. Check out shutdown sequence for operability.
6. Check out operation of instrumentation on the reactor (thermocouples, catalyst core pressure drop, water cooled sampling probe, etc.).

TABLE IV-2

Description of Analytical Systems for Emissions

Emissions	Analytical Equipment	Range	Calibration Gas
UHC (as C_3)	Beckman Model 402 Flame Ionization Detector	50,000 Vppm 100 Vppm 10 Vppm	19,000 Vppm C_3H_8 47 Vppm C_3H_8 10 Vppm CH_4
CO	Beckman Model 315B Non-Dispersive Infrared	5,000 Vppm 500 Vppm 50 Vppm	4,000 Vppm CO 400 Vppm CO 10 Vppm CO
CO_2	Beckman Model 315B Non-Dispersive Infrared	15% 3%	10% CO_2 1.5% CO_2 0.5% CO_2
O_2	Beckman Model 742 Polarographic Analyzer	25% 25%	12% O_2 Zero Air
NO/NO_x	Beckman Model 951 Chemiluminescence Analyzer	1,000 Vppm 10 Vppm	600/900 NO/NO_x Vppm 1.8/2.2 NO/NO_x Vppm

7. When the air preheat temperature to the reactor has reached specified conditions, line-out on automatic control.
8. At this point in the start-up sequence, the air flow is on automatic control and the reactor instrumentation is functioning. All safety shutdowns must be in the "off" position before fuel can be brought on.
9. The fuel flow is now ready to be brought into the unit. Using liquid fuel as an example, the flow setting on the pump is established on bypass and slowly turned into the unit.
10. As the fuel is brought on, the technician notes the temperature responses in the reactor to determine lined-out operation for life testing.

This same start-up and line-out sequence is followed for parametric testing and the carbon monoxide activity testing.

The detailed operating instructions for all tests performed as part of this contract are given in Appendix E.

B. TEST RIG PERFORMANCE CHECK OUT

After the operational check out, the performance of the test rig was evaluated under "catalytically supported thermal combustion" conditions. The purposes of this evaluation were:

1. Determine the effect of cooling by the water-cooled sampling probe on reactor adiabaticity and emissions.
2. Compare emissions, pressure drop and outlet temperature of Unit 6 to those of an existing laboratory test rig.

1. Water-Cooled Probe Performance

The test rig reactor was designed to operate from 90 to 100% adiabaticity during life testing and over much of the design operating range. In this heat loss range, the performance measurements should be typical of large scale combustors. However, with the added cooling effect of the water cooled sample probe downstream of the .0254M Ø catalyst core, the performance measurements could have been in error because the probe can significantly cool the back section of the catalyst core.

The effect of the water-cooled probe was measured to determine:

a. The best location for emission measurements without quenching the combustion reactions in the catalyst core.

b. The effect on reactor adiabaticity at the location selected.

A series of experiments were run measuring the probe quenching effect, defined as percentage decrease in measured outlet temperature (PD) from the catalyst core using the following equation:

$$PD = \frac{\text{(Temperature Measured Without Probe)-(Temperature Measured With Probe)}}{\text{(Temperature Measured Without Probe)}} \times 100$$

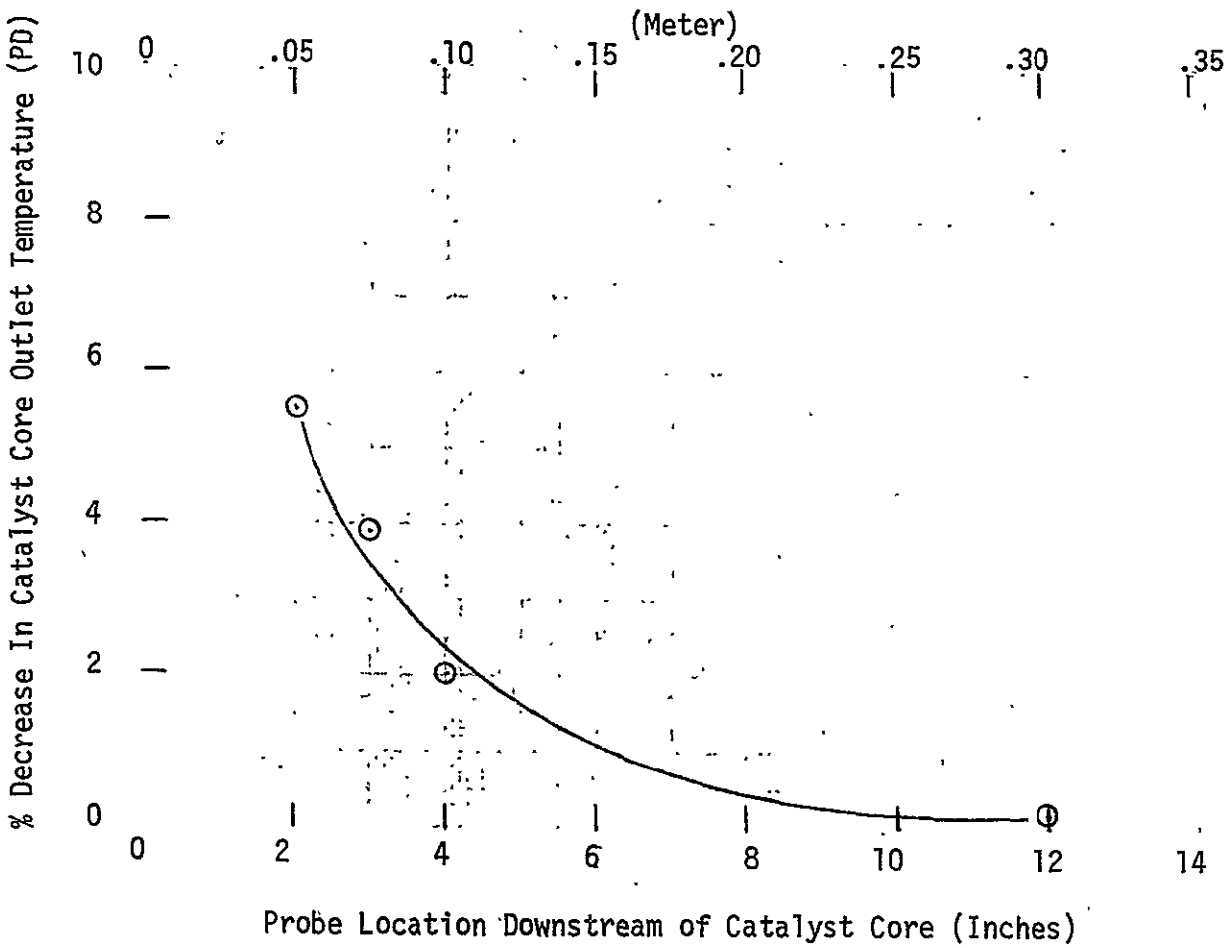
These measurements were conducted under combustion conditions.

The results for the experiments are shown in Figure IV-4. For a probe location .1016M (4") downstream of the catalyst core, a 2-3% decrease occurred in the measured outlet temperature. These tests were run at very conservative conditions with a mass flow approximately 60% of proposed life test conditions. Tests conducted at actual life test conditions showed that the probe (located at .1016M downstream) reduced the adiabaticity of the reactor from 89% to 87%. This was judged to be a reasonable trade off between satisfactory emission measurements and undesirable quenching effects during the life tests. The .1016M downstream location was selected for emissions measurements.

Figure IV-4

Cooling Effect of Water-Cooled Sampling Probe
Under Combustion Conditions

Run Conditions: Reference Velocity = 9 M/S
Fuel/Air Ratio (Wgt.) = .0268
Air Preheat Temperature = 653°K
Measured Outlet Temperature = 1513°K
Pressure: 1×10^5 N/M^2



Further test results with the water-cooled sample probe defined the reactor adiabaticity over the range of design operating conditions. The percent adiabaticity (PA) of the reactor is defined as

$$PA = 100 \frac{\left(\begin{array}{c}\text{Maximum}\\ \text{Measured Outlet}\\ \text{Temperature}\end{array}\right) - \left(\begin{array}{c}\text{Measured Inlet}\\ \text{Temperature}\end{array}\right)}{\left(\begin{array}{c}\text{Adiabatic Flame}\\ \text{Temperature}\end{array}\right) - \left(\begin{array}{c}\text{Measured Inlet}\\ \text{Temperature}\end{array}\right)}$$

Initial operation at test conditions over the test rig design range resulted in the response of PA, as shown in Figure IV-5.

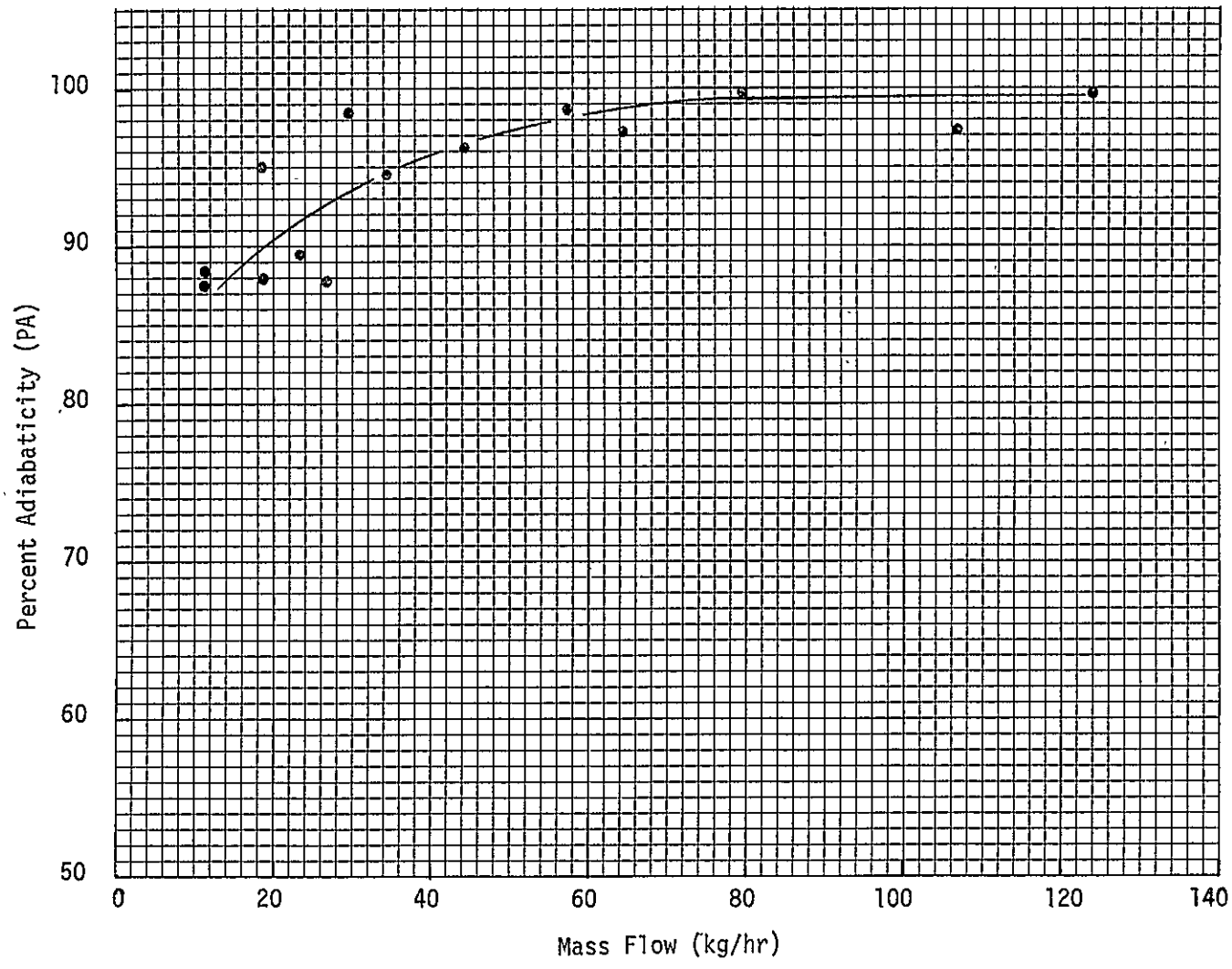
The results show that increasing the mass flow decreases the percent of heat loss and increases the percent adiabaticity. This is expected, since increasing the mass flow, at a constant air/fuel ratio, in a fixed geometry increases the heat released while the heat loss remains fairly constant. Hence, the system approaches 100% adiabaticity. The mass flow rates plotted cover the range of the parametric studies.

2. Performance Comparison with Existing Test Rig

The final series of check outs of Unit 6 involved side-by-side comparisons of identical experiments performed in Unit 6 and an existing Engelhard test rig (Unit 5). These comparisons were made for both #2 diesel and C.P. propane. The results are tabulated in Tables IV-3 and IV-4. These data indicate that the differences between the responses are well within experimental error.

Figure IV-5

Adiabaticity Of Test Rig Reactor *



* Water cooled sampling probe located .102M downstream.

TABLE IV-3

Comparison Study of Unit #6
With Unit #5 (#2 Diesel Fuel)

	Unit #6	Unit #5
Run Number	6-13E	5-103B
Catalyst Core	DXB-412	DXB-412
Catalyst Core Dimensions	.0254 M φ X .152 M L	.0254 M φ X .152 M L
Air Flow (Kg/S x 10^3)	4.26	4.26
A/F Wgt. (g/g)	38.4	38.4
Reference Velocity (M/S)	17.2	16.9
Pressure (N/M^2)	1×10^5	1×10^5
Air Preheat Temperature (°K)	673	673
Catalyst Core Outlet Temperature (°K)	1376	1353
Pressure Drop (%)	10.2	11.2
Emissions (Vppm @ Nominally 12.5% O_2)*		
CO	130	192
UHC (As C_3)	1	1
NO/NO_x	1	1
Percent Adiabaticity	85	87

* Emissions at .102M downstream of outlet catalyst face with water cooled sampling probe.

TABLE IV-4

Comparison Study of Unit #6
With Unit #5 (C.P. Propane Fuel)

	Unit #6	Unit #5
Run Number	6-13A	5-102B
Catalyst Core	DXB-412	DXB-412
Catalyst Core Dimensions	.0254 M φ X .152 M L	.0254 M φ X .152 M L
Air Flow (Kg/5 x 10^3)	4.26	4.26
A/F Wgt. (g/g)	39.5	39.5
Reference Velocity (M/S)	17.2	16.8
Pressure (N/M^2)	1 x 10^5	1 x 10^5
Air Preheat Temperature (°K)	678	683
Catalyst Core Outlet Temperature (°K)	1503	1533
Pressure Drop (%)	11.3	14.5
Emissions (Vppm @ Nominally 12.5% O_2)*		
CO	9.0	22
UHC (As C_3)**	--	--
NO_x	--	--
Percent Adiabaticity	92	94

* Emissions at .305M downstream of outlet catalyst face with water cooled sampling probe.

** UHC and NO_x analyzers not functioning at time of experiments.

Another response that is typical for combustion operation in the laboratory test rigs and noted in Unit 6 is the fact that when fuel is brought on to the catalyst core, an increase in measured inlet temperature occurs. For instance, the inlet temperature response for Unit 6 and Unit 5 for the runs listed in Table IV-3 were:

	Temperature Reading on Air Preheat Thermocouple °K	
	Fuel Off	Fuel On
Unit 6	673	825
Unit 5	673	793

This is observed because of the close proximity of the inlet thermocouple, i.e., .0254 M (1") away from the catalyst core inlet face. Radiation from the catalyst inlet face and thermal conduction up the reactor wall causes the inlet thermocouple to read an artifically higher inlet temperature.

C. OPERATING PROCEDURES

Operation of Unit 6 included routine equipment operating procedures and special test procedures designed for evaluation of the selected catalyst cores. Data reduction procedures were also handled as part of the operation of the test units. The routine operating procedures are detailed in Appendix E for reference.

V. TASK III - PARAMETRIC AND ENDURANCE TESTING

A. EXPERIMENTAL TEST PROGRAM

The testing program selected in this study was designed to serve the following purposes:

1. Test the long-term durability of catalysts under combustion conditions.
2. Determine an acceptable low emissions operating range for the catalysts.
3. Provide adequate information for selection of a preferred catalyst core.

In addressing these requirements, a test sequence was set up, which focused mainly on low emissions operation during a 1,000 hour life test with #2 diesel. This life test provided a means of measuring either abrupt or long-range changes in a catalyst core's overall performance. To measure more subtle changes in the activity of the catalyst core, periodic activity tests were conducted at 250 hour intervals using carbon monoxide as a fuel.

The acceptable low emissions operating range for a CATCOM catalyst was determined using C. P. Propane as fuel over a wide range of select variables. Two catalyst cores, designated as DXB-222 and DXC-532 were tested in this experimental program.

The specifics of the overall testing sequence can be represented schematically as follows:

Virgin Catalyst

↓

24 hour break-in period

↓

initial CO activity test

↓

initial set of propane parametrics to map performance range

↓

CO Activity Test

↓ 1000 hour life test with #2 diesel fuel

↓ CO activity test every 250 hours

↓

Final propane parametrics to map performance range changes

The initial 24 hour break-in period of each catalyst core was required because of the nature of each catalyst preparation. On many commercial catalyst preparations, it is very deceiving to test

a catalyst without removing the so-called "flush" activity. It is better to have a break-in period to remove this initially high activity and stabilize the catalyst's activity level. This prevents potential problems with interpretation of experimental results due to compounding with an artifically high initial activity. The break-in period consisted of operating each catalyst core for 24 hours at the actual life test conditions (see Table V-2 for conditions).

1. Life Test with #2 Diesel

Since the main purpose of this study was to measure the durability of catalyst cores at combustion conditions for extended periods of steady-state operation, the life test conditions were selected to simulate a steady-state operating point for an automotive gas turbine. The test fuel chosen was #2 diesel, since it is the most probable fuel for this application. In addition, this fuel contains additives and impurities that provide a sound test for determining the effects of potential poisons on the catalyst core. Table V-1 contains the analyses of the fuels used in the life tests.

The steady-state conditions for the 1,000 hour life test are shown in Table V-2. These life tests were conducted on a continuous basis when possible. During shutdown, a house air purge was maintained over the test catalyst cores.

TABLE V-1

Analyses of #2 Diesel Fuels Used For Catalyst Life Tests[1]

Test	ASTM D-975	Batch #1[2]	Batch #2[3]
Gravity, API @ 60°F (289°K)	-	34.4	-
Flash Point, °K	>324.9 or legal	338.2	-
Pour Point, °K	-	255.5	-
Water and Sediment, V%	<0.05	<.05	-
Carbon Residue	<0.35	-	-
Ash, Wt.%	<0.01	<0.004	-
Distillation Temperature, °K			
Initial		446.2	-
10%		477.2	-
50%		523.2	-
90%	555.4 to 611.2	575.2	-
End Point	-	605.2	-
Viscosity, SU at 311°K	32.6 to 40.1	34.2	-
Joule/Kg., gross	-	4.55×10^7	-
Sulfur, Wt.%	<0.50	0.15	0.17
Nitrogen, wppm	-	59.9	71.5
Phosphorous, Wppm	-	<1.0	<1.0
Lead, wppm	-	<1.0	1.6

[1] Majority of analyses performed by Saybolt and Co.

[2] Batch #1 used for DXB-222 life test.

[3] Batch #2 used for DXC-532 life test.

TABLE V-2

Life Test Conditions

Air Flow:	3.29×10^{-3} Kg/S
Fuel Flow:	8.66×10^{-5} Kg/S
Air/Fuel Wgt:	38/1 (g/g)
Inlet Temperature:	633°K
Inlet Pressure:	1×10^{5} N/M^{2}
Reference Velocity:	14 M/S
Fuel Type:	#2 Diesel
Space Velocity $_{NTP}$:	51 M^{3}/S - M^{3} Cat.
Catalyst Test Piece:	.0254M ϕ x .1524M L
Adiabatic Flame Temperature:	1527°K

The maintenance of low emissions performance during the life test is considered the prime criteria for determining changes in a specific catalyst core's performance. This life test also provides a measure of the physical durability of the catalyst core support material. The results of this test would provide information on long term durability of CATCOM catalyst cores.

2. Carbon Monoxide Activity Test

In conducting the CO activity test, the life test conditions are discontinued and the CO activity test conditions are then established. The catalyst core is not disturbed and remains inside the test rig reactor.

This test consists of measuring the response of CO conversion to increases in the air preheat temperature. The carbon monoxide test gas was purchased from Scientific Gas Products and is rated chemically pure (C.P.) with a 99.7% minimum purity specification. The remaining test parameters are held constant and are shown in Table V-3. Typical responses for this test are shown in Figure V-1.

The response curve in Figure V-1 provides two important facts about the catalyst cores' activity. The CO ignition temperature, defined as the lowest air preheat temperature required to obtain a measurable temperature rise across the catalyst core, is a measure of intrinsic catalytic activity. Increases in the ignition temperature

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Figure V-1

Typical Response Obtained From Carbon Monoxide Activity Test

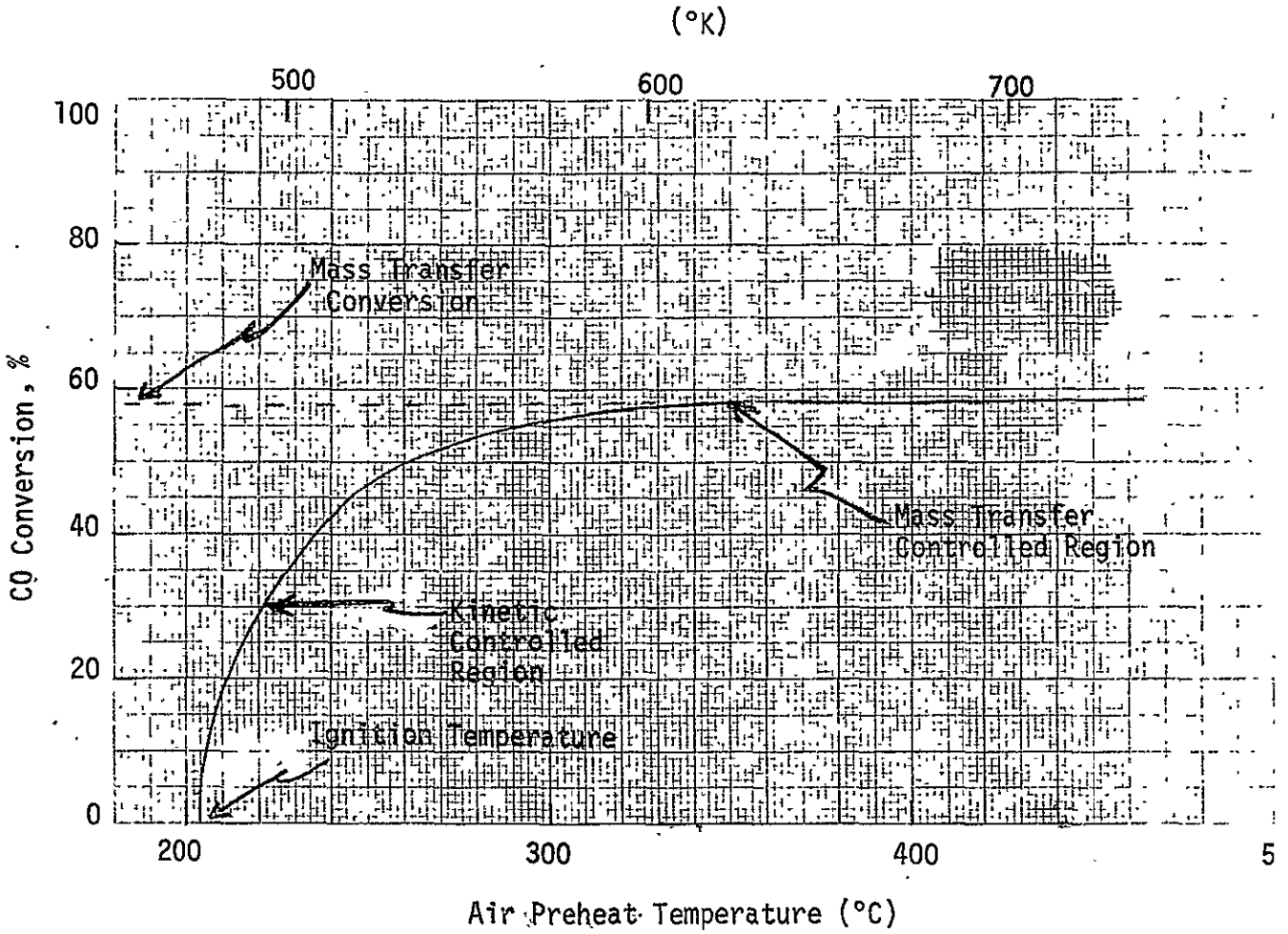

TABLE V-3

Carbon Monoxide Activity Test Conditions

Air Flow:	10.55×10^{-3} Kg/S
Fuel Flow:	4.09×10^{-5} Kg/S
Air/Fuel Wgt.:	258/1 (g/g)
Inlet Temperature:	Varied up to 773°K
Inlet Pressure:	1×10^{5} N/M^{2}
Reference Velocity:	36 M/S
Fuel Type:	C.P. Carbon Monoxide
Space Velocity $_{NTP}$:	125 M^{3}/S-M^{3} CAT.

Variable	Range
Pressure	$1 \times 10^5 - 5 \times 10^5$ N/M^2
Air Preheat Temperature	630 - 810°K
Adiabatic Flame Temperature	1306 - 1533°K
Reference Velocity	14 - 30 M/S

C. P. Propane was selected as the test fuel because:

a. The high level of purity of the fuel and combustion properties of propane would represent a conservative test for the catalyst capabilities. Lower molecular weight paraffinic fuels of high purity are very difficult to oxidize. The propane used was purchased from Scientific Gas Products and is rated chemically pure (C.P.) with a minimum 99.0% purity specification.

b. The fuel presentation system for #2 diesel would not function over such a broad operating range.

The propane parametrics was conducted initially at the start-of-life testing to determine the range of operation of a virgin catalyst, and at the end of life testing to determine if changes in catalyst activity had occurred for propane after 1,000 hours.

reflect possible changes in the energy of activation or pre-exponential factor using the Arrhenius rate of expression as the typical reaction rate model. The sloping portion of the response curve in Figure V-1 indicates that in this temperature range the rate of reaction is kinetically controlled. The region showing a constant conversion level as a function of temperature is considered to be mass transfer controlled. A mass transfer controlled reaction is independent of the catalyst and temperature, and is only a function of the apparent geometric surface area of the catalyst. If the mass transfer conversion declines with catalyst age, then the apparent mass transfer area is decreasing.

The utility of this CO activity test is that it provides a means to monitor subtle changes in catalyst core activity without disturbing the catalyst test piece in the reactor.

The catalyst core that retains the highest apparent mass transfer area and lowest ignition temperature is judged the better performer, at least with regards to CO activity.

3. Propane Parametric Testing

In order to define the low emissions operating range for test catalysts, a series of parametric studies was carried out over the following operating range:

The specific variables were studied by constructing a statistical experimental design covering 4 variables at 3 levels each. The design chosen was a 1/3 replicate factorial design, which reduced the number of experimental runs from 81 to 27. Repeat runs were also conducted as a measure of experimental error. The actual block design used is shown in Table V-4.

The initial program parametrics provided the range of acceptable low emissions operation for propane as fuel with a specific catalyst. The final propane parametric, after 1,000 hours aging, provided information on the changes in propane activity due to life testing. These criteria would also be weighed in selecting a preferred catalyst core.

B. EXPERIMENTAL RESULTS

The experimental results for life testing, activity testing and parametric studies of the two catalyst cores, DXB-222 and DXB-532, are reviewed separately in the following sections.

Direct comparisons of results from testing of DXB-222 and DXC-532 and selection of the preferred catalyst core are contained in Section VI of this report.

TABLE V-4 - 1/3 Replicated Factorial Design For 4 Variables At 3 Levels

Pressure $N/M^2 \times 10^{-5}$	1									3									5								
Air Preheat Temperature °K	633			722			810			633			722			811			633			722			810		
Reference Velocity M/S / Adiabatic Flame Temperature °K	14	22	30	14	22	30	14	22	30	14	22	30	14	22	30	14	22	30	14	22	30	14	22	30	14	22	30
1366	X					X		X				X		X		X				X		X					X
1450			X		* X		X				X		X					X	X					X		X	
1533		X		X					X	X					X		X				X		X		X		

* Replicate Run to Determine Experimental Error

1. Performance of Catalyst Core DXB-222

a. Life Testing with #2 Diesel Oil

The most useful technique for monitoring performance of a catalyst during life testing is to monitor daily the input variables and output responses from the test. A control plot of the most critical observations then provides a method for detecting trends which may indicate a degradation in the performance of the catalyst or problems in test rig operation.

Control charts were maintained on a daily basis for the following:

- exhaust gas composition (CO, UHC, NO_x, CO_2, O_2)
- pressure drop
- air preheat temperature
- catalyst core outlet temperature

The resulting plots over the entire 1,000 hour life test of catalyst core DXB-222 are shown in Figures V - 2,3,4,5,6, and 7.

Perhaps the most significant control plot in the present life test is the exhaust gas analysis, and in particular, the emissions of CO, UHC and NO_x. The gas compositions are reported as measured in the exhaust, which was nominally 12.5% oxygen. These plots provide a measurement of stable operation during life testing.

Figure V-2 Hydrocarbon Emission Control Chart During Life Testing of Catalyst Core DXB-222

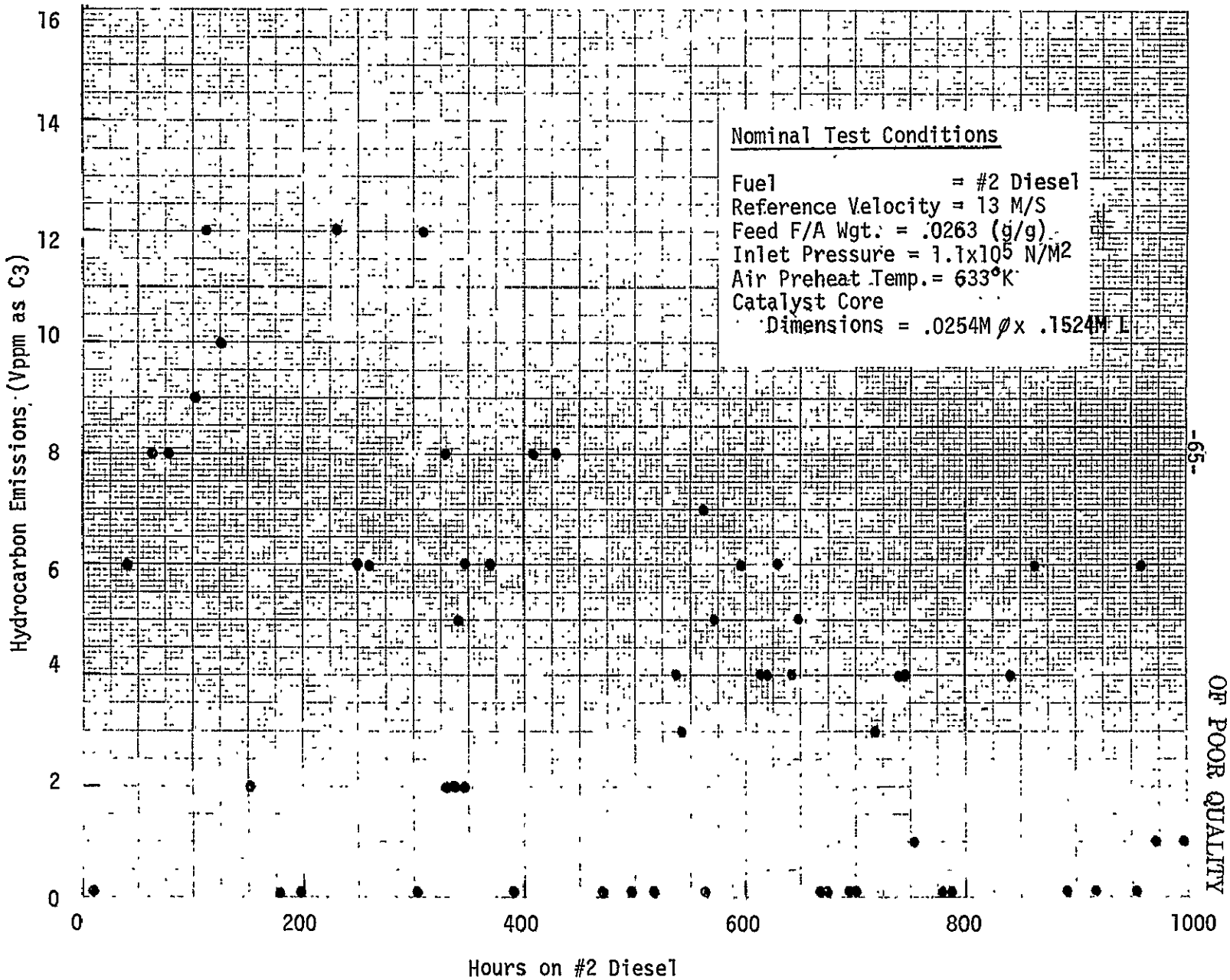

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Figure V-3 Carbon Monoxide Emission Control Chart During Life Testing of Catalyst Core DXB-222

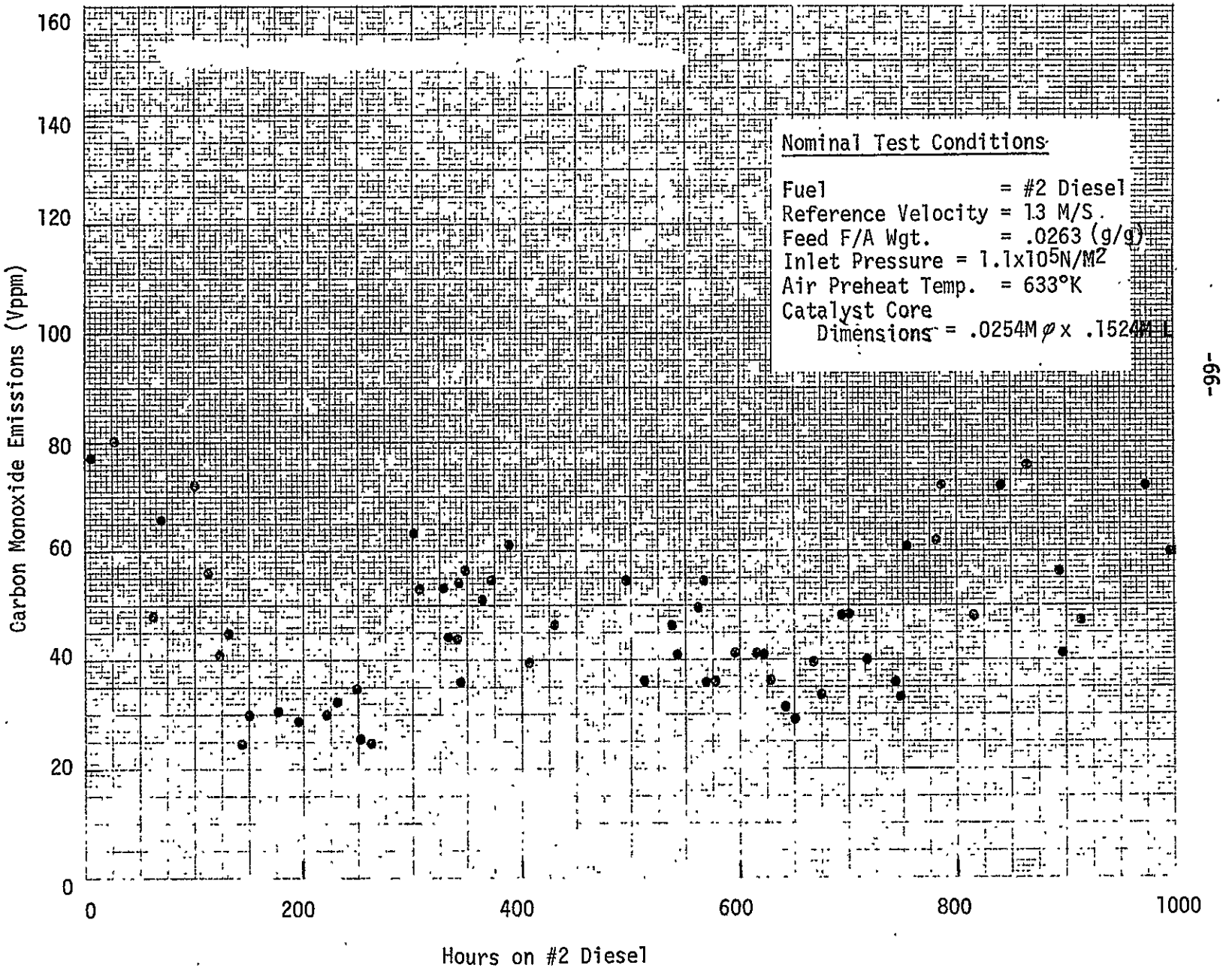

Figure V-4 NO_x Emission Control Chart During Life Testing of Catalyst Core DXB-222

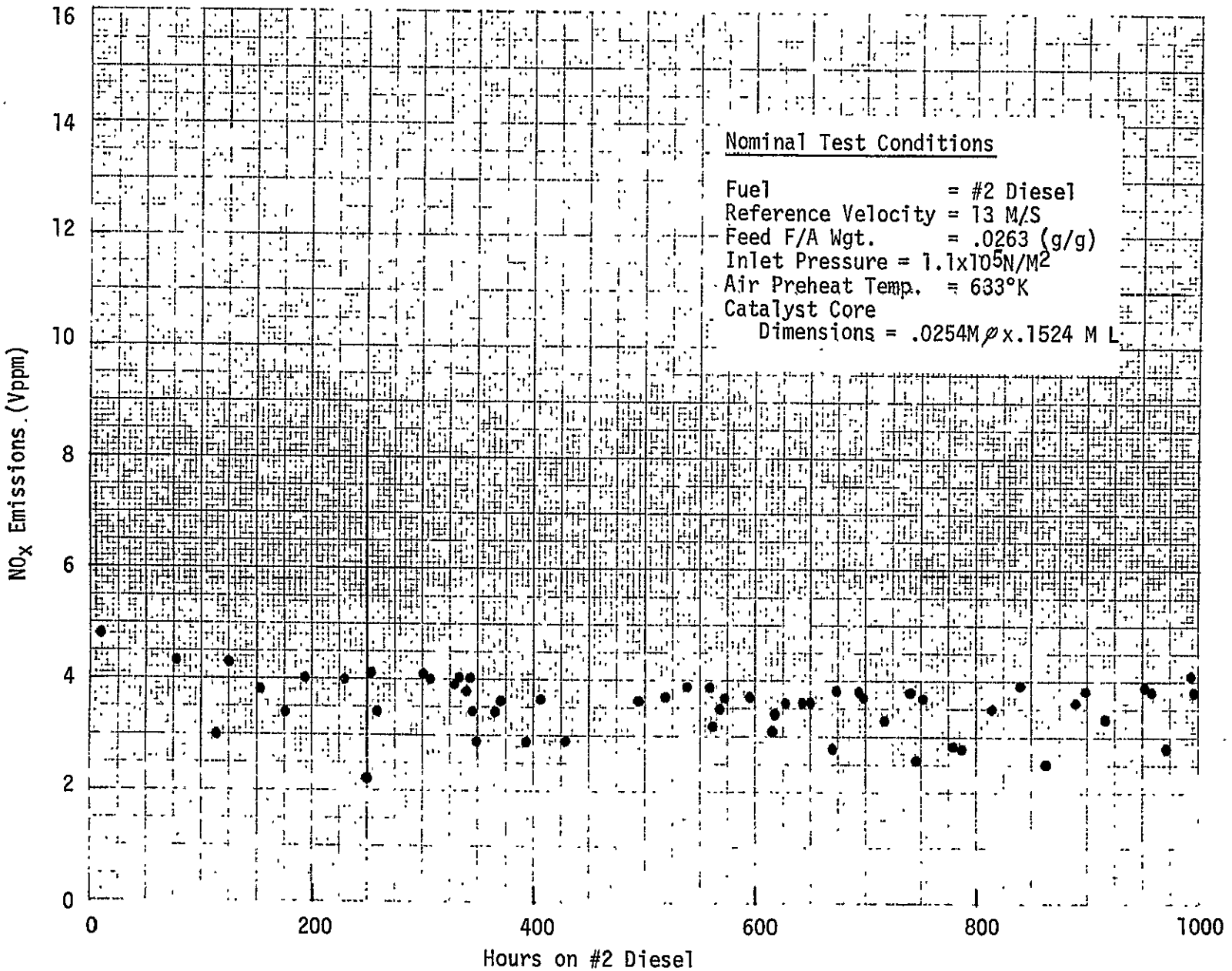

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Figure V-5 CO_2 and O_2 Control Chart During Life Testing of Catalyst Core DXB-222

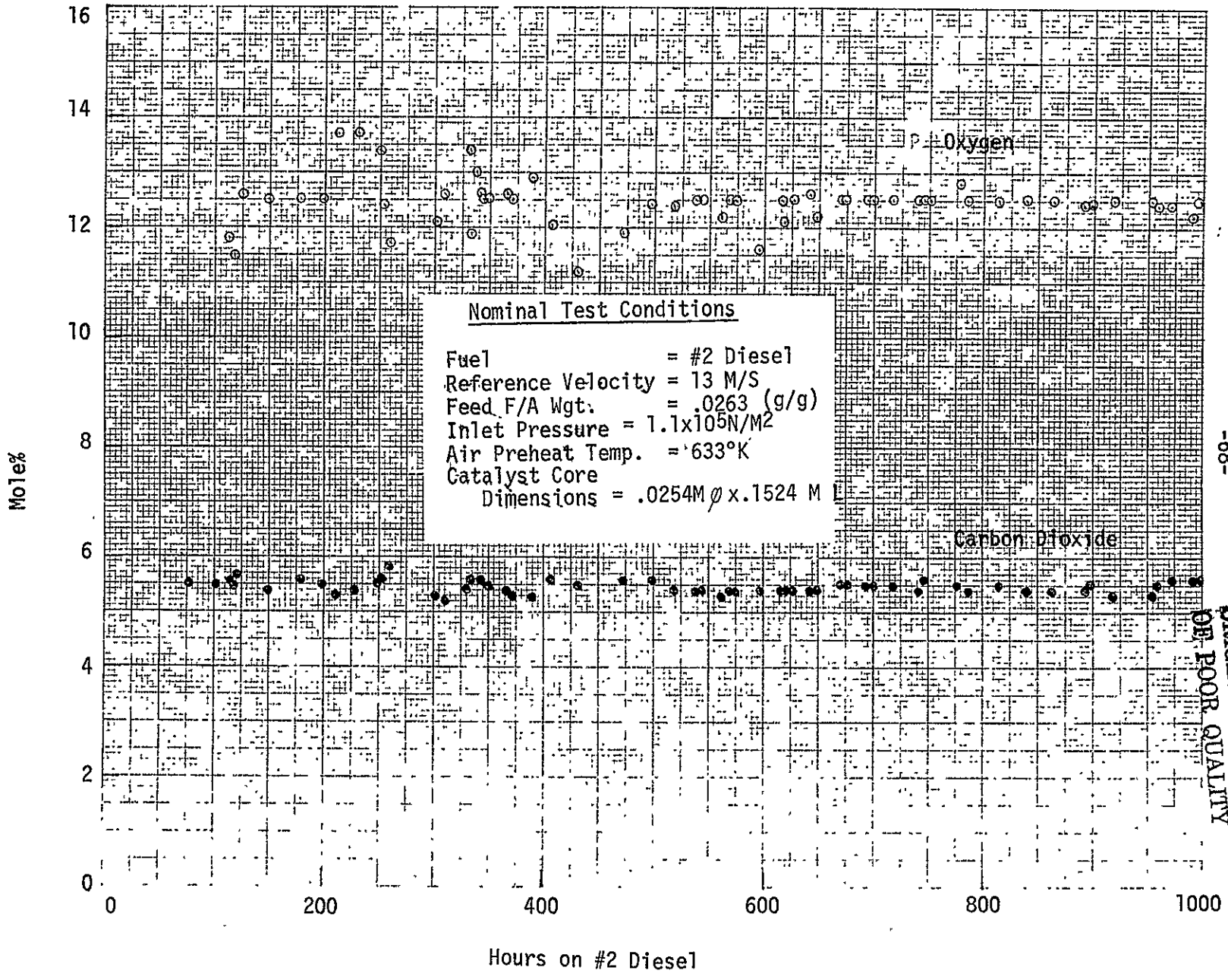

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Figure V-6 Temperature Control Chart During Life Testing of Catalyst Core DXB-222

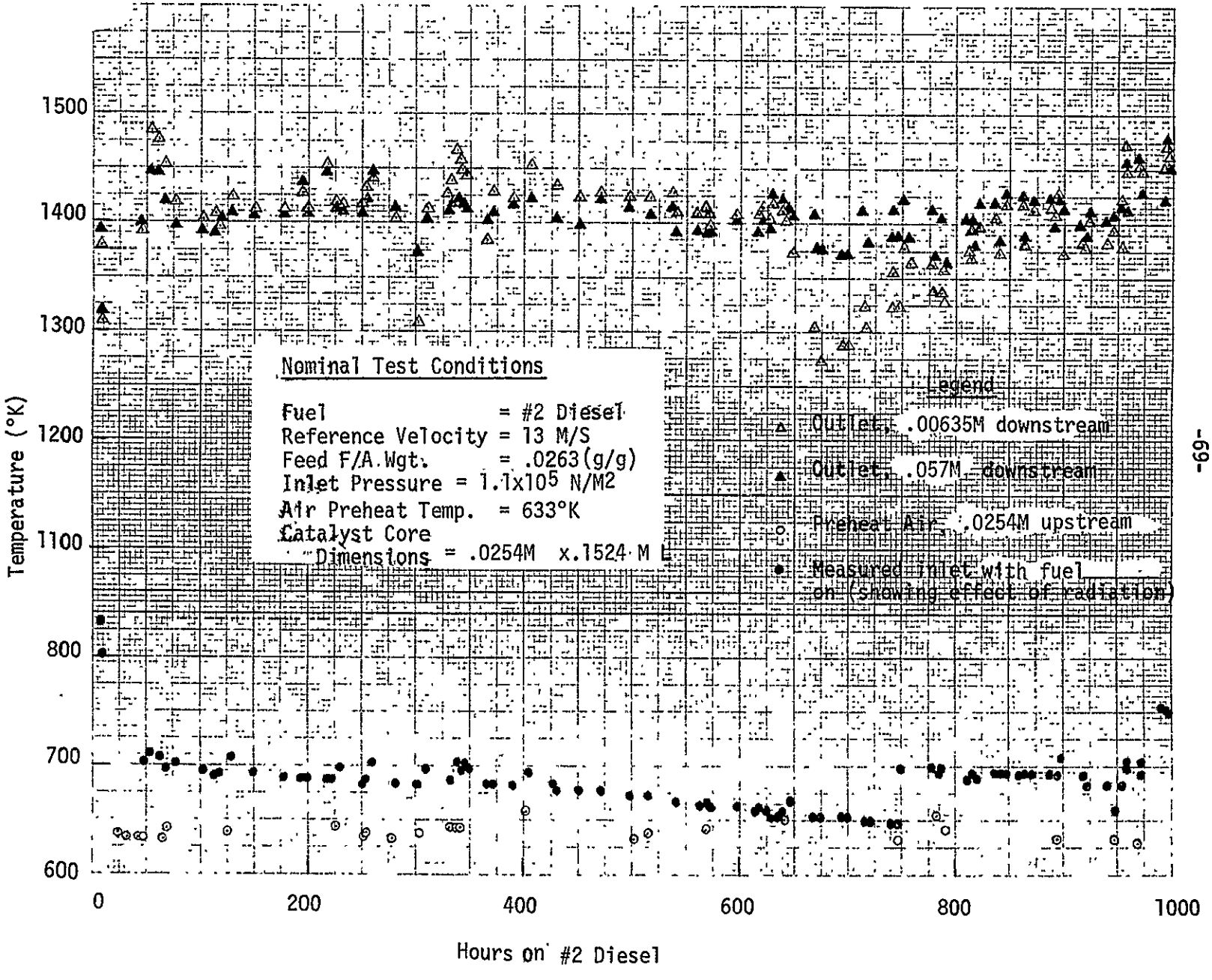
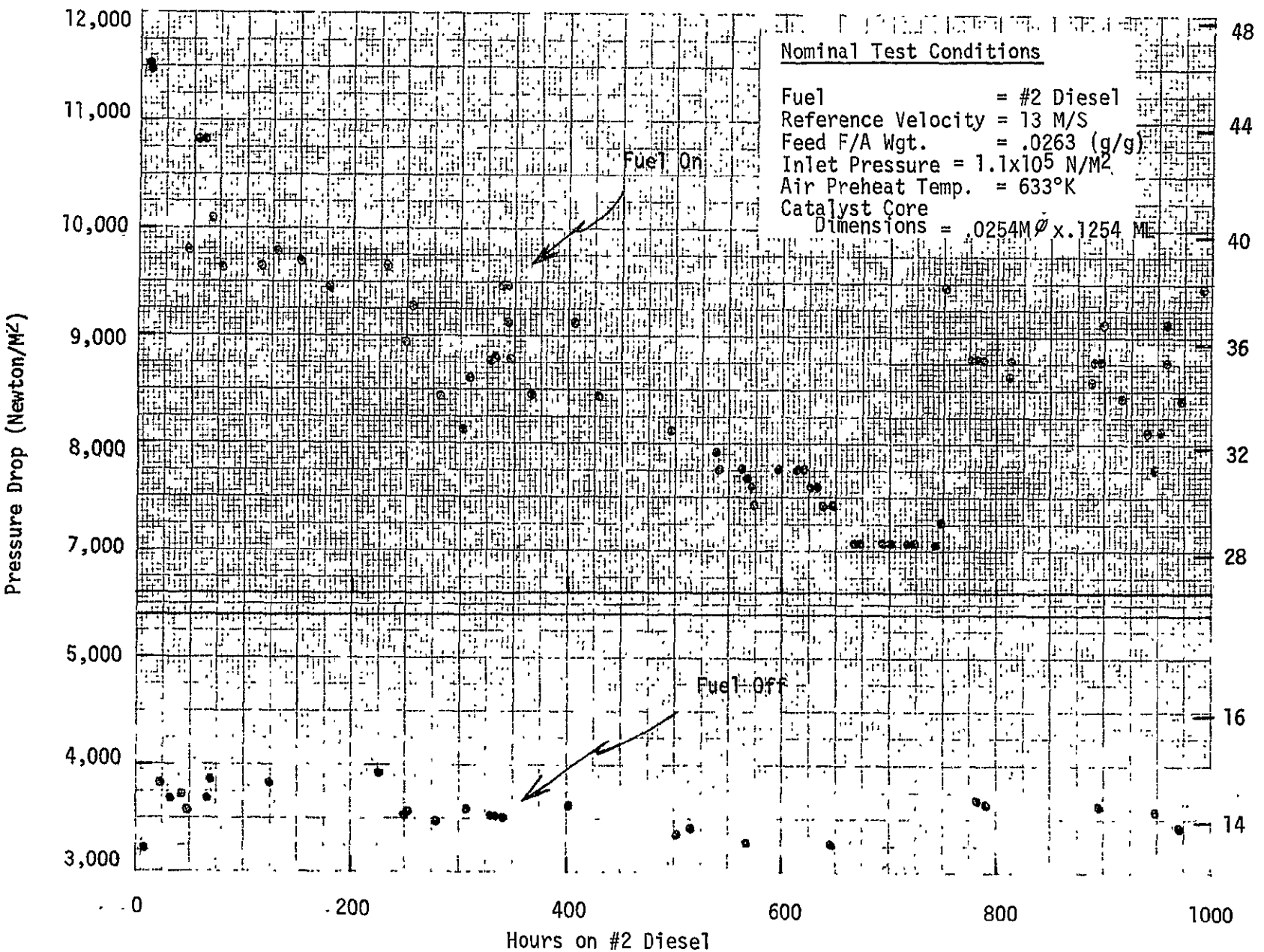


Figure V-7 Pressure Drop Control Chart During Life Testing of Catalyst Core DXB-222



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Figures V-2,3 and 4 indicate that the emissions of DXB-222 are essentially constant throughout the life test, showing no change in the catalyst cores overall performance.

During the 1,000 hour life test of DXB-222, the average emissions were as follows:

Emission	Mean	Standard Deviation
UHC (vppm as C_3)	3.8	3.6
CO (vppm)	47	14
NO_x (vppm)	3.5	0.5

The CO and UHC emission results correspond to a mean combustion efficiency of 99.89%. All three emission levels are well within anticipated federal standards for stationary gas turbines(7). These emissions can also be translated into steady-state automotive gas turbine operation at 10 miles per gallon for comparison with automotive standards.

Emission	Mean Measured Emission Corrected to Automotive Operation g/mile	Automotive Standard (g/mile) Year 1977	1978
UHC	0.07	1.5	.41
CO	0.58	15.	3.4
NO_x	0.062	2.0	.4

Note that this comparison is strictly based on steady-state operation and does not account for transients nor cold start.

It should be noted that the NO_x emissions during the life testing of DXB-222 probably results from the essentially quantitative oxidation of the fuel bound nitrogen in #2 diesel fuel[2]. At the adiabatic operating temperature of the life test, no NO_x formation is expected due to nitrogen fixation.

Examining the temperature control chart (Figure V-6) indicates that the outlet temperatures remained constant (within experimental error) throughout the life test. Since the temperature measured .00635M downstream of the catalyst core indicated the highest value throughout the 1,000 hours, no burning was occurring downstream of catalyst core DXB-222 during life testing.

The control plots for pressure drop (Figure V-7) indicate that initially the pressure drop was higher but during the remainder of the life test no further changes were noted. This plot also proved useful in detecting an operating problem during this life test. At approximately 500 hours aging, the pressure drop declined dramatically as shown on the control chart. Removal of the catalyst holder revealed that the packing between the holder and the reactor wall had loosened and could cause bypassing. The holder was repacked in the reactor and the pressure drop resulting during the last 200 hours of life testing corresponded to the pressure drop observed at 400 hours testing.

The control charts depicting CO_2 vent gas analysis (Figure V-5) show the variation in #2 diesel fuel feed during the 1,000 hour life test. This variation in fuel feed corresponds to

a variation in adiabatic flame temperature from 1499 to 1565°K during the 1,000 hour life test of DXB-222.

A summary table comparing all the control variables and test responses at the beginning and end of the life test on DXB-222 is shown in Table V-5. This data is indicative of the control capabilities of the experimental equipment. The table shows that no significant alterations were made to the operating conditions of DXB-222 during life testing.

Another question that arises in regards to practicality of using catalysts in combustion processes is the durability of the catalyst core support material. Figure V-8 shows the photographs taken of DXB-222 after 1,000 hours life testing. The color changes shown when viewing the catalyst core from inlet to outlet are normal, and reflect the temperature gradients within the catalyst core during combustion operation at an adiabatic temperature of 1527°K. Physical examination of the catalyst showed that no observable physical damage to the catalyst core structure had occurred during testing. The catalyst support appears to be quite durable after 1,000 hours diesel life testing.

Analytical tests were performed on catalyst core DXB-222 at the conclusion of the life test in order to determine the effect of operation at combustion conditions on the retention of the precious metal catalytic component and on the thermal stability of the catalyst core. Assay results indicated that DXB-222 retained 56% of its precious metal after 1,000 hours aging. Results from BET surface

TABLE V-5

Comparison of Typical Operating Conditions and Performance Data At Start and End of Life Test for Catalyst Core DXB-222

	Start	End
Date:	11/19/75	2/27/76
Hours on #2 Diesel Fuel:	40	993
Air Flow (Kg/Sec.):	3.22×10^{-3}	3.22×10^{-3}
Fuel/Air Ratio (g/g):	0.0263	0.0268
Preheat Air Temperature (°K):	633	628
Outlet Temperature (°K)	1398	1453
Adiabatic Flame Temperature (°K):	1527	1540
Inlet Pressure (N/M^2)	1.1×10^5	1.1×10^5
Pressure Drop (N/M^2):	9779	9431
Percent Pressure Drop:	8.8	8.6
Reference Velocity (M/S):	13.0	12.9
Combustion Efficiency (%):	99.85	99.89
Space Velocity $_{NTP}$ Nominal (Sec^{-1})	34.7	34.7
Heat Release Rate ($Joules/S \cdot M^3 \cdot N/M^3$):	4.3×10^2	4.4×10^2
Emissions[1] (Vppm @ Nominally 12.5% O_2)		
CO	80	60
UHC (As C_3)	6	1
NO_x	-	4.2
Catalyst Core Dimensions, Nominal:	0.0254M in dia. by 0.152M Long	

[1] All emissions measured with water cooled sampling probe located at 0.102M downstream of catalyst core.

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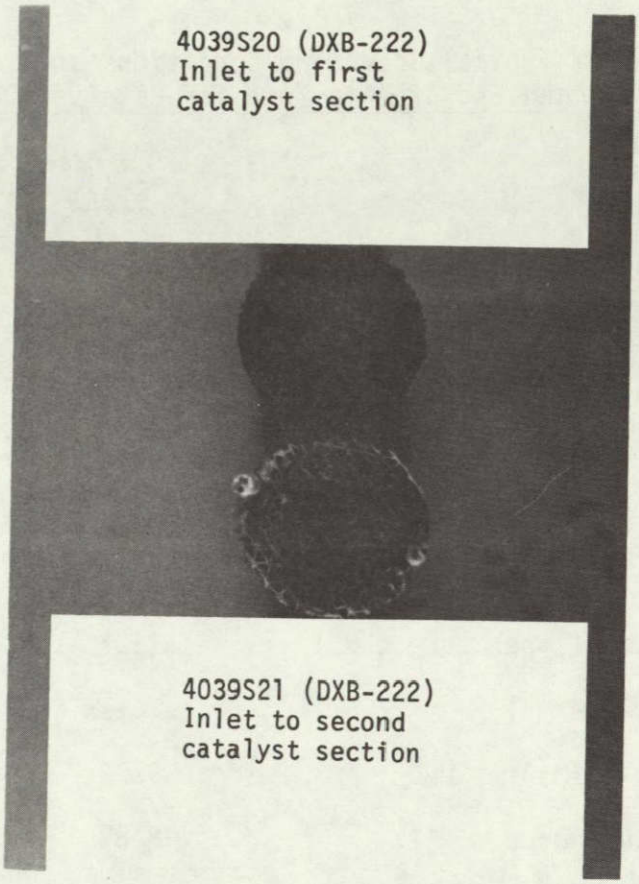

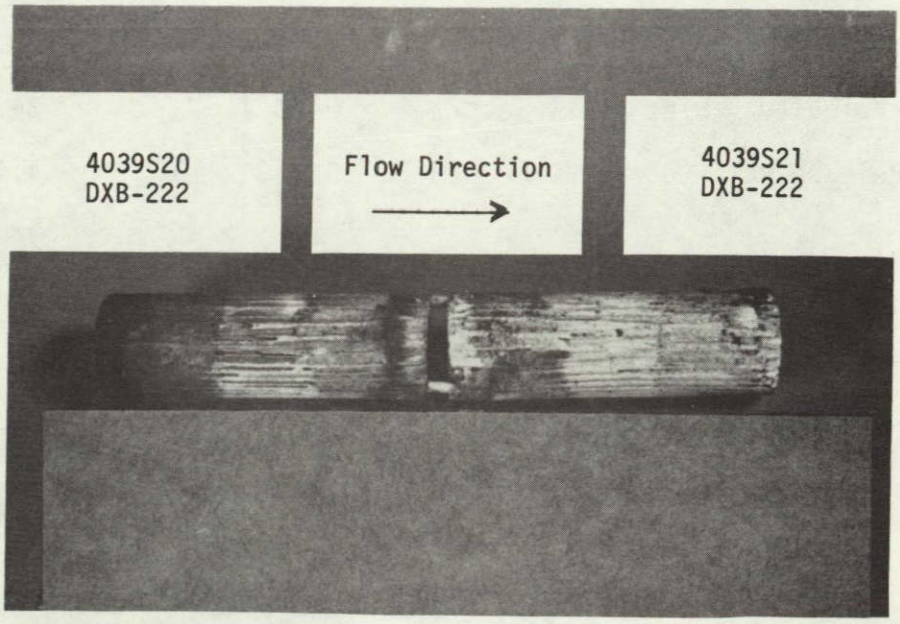

Figure V-8 Photographs of Catalyst Core DXB-222 After 1000 Hours Life Testing

area measurements showed that catalyst core DXB-222 retained 16% of its initial surface area. These results are all relative to a lined-in catalyst core (i.e., aged 24 hours at life test conditions). At present, it is felt that the most probable mechanism for the precious metal loss is detachment of the washcoat from the support. Techniques, gained from experience in auto exhaust catalyst preparation, are available for increasing the adhesion of the washcoat to the monolith. These improved techniques should reduce the precious metal loss without decreasing the performance durability of DXB-222.

Additional analyses were obtained with a scanning electron microscope and an x-ray diffractometer. These results were negative in that no contaminants were found on DXB-222 after life testing.

Overall, the life test results indicate that CATCOM catalyst core DXB-222 can operate under combustion conditions for at lease 1000 hours without loss of low emissions performance due to physical or catalytic degradation. Although analytical measurements showed a loss of both surface area and precious metal over the course of the life test, these changes apparently do not have a significant effect on the overall catalyst performance.

b. Carbon Monoxide Activity Test

The response of carbon monoxide conversion to increasing air preheat temperature was measured on a scheduled basis during life testing of catalyst core DXB-222. These results are plotted in Figure V-9.

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Figure V-9 Carbon Monoxide Activity Test Response During Life Testing of Catalyst Core DXB-222

Legend

1 24 Hours Aging

2 250 Hours Aging

3 500 Hours Aging

4 750 Hours Aging

5 1000 Hours Aging

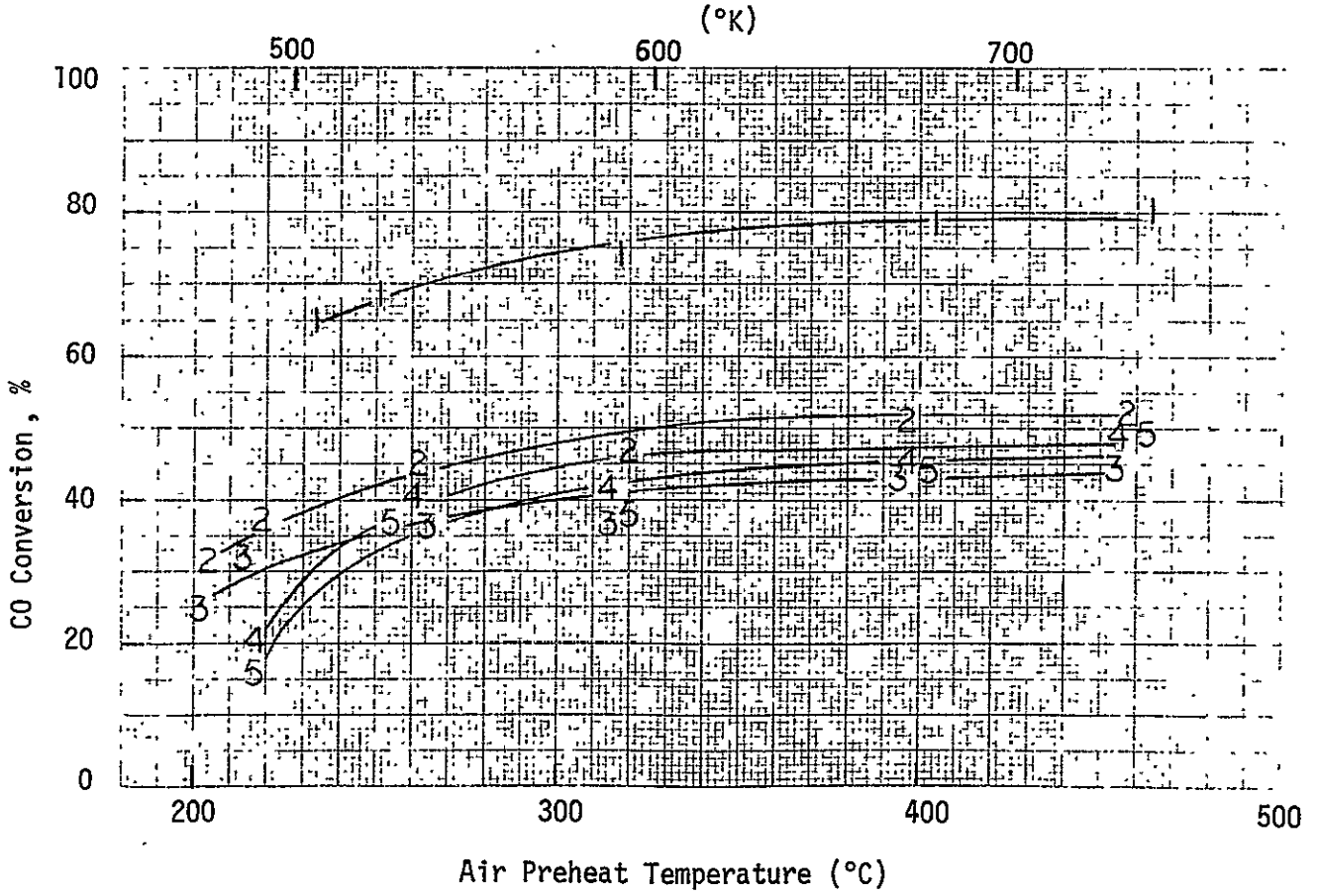
Run Conditions

Reference Velocity = 36.5 M/S

Feed CO = 4000 Vppm

Pressure = 1×10^5 N/M^2

Catalyst Core Dimensions = .0254M ø x .1524 M L



Examining each response curve indicates that between 24 hours and 250 hours of aging with #2 diesel fuel, a significant change in the catalyst cores' activity has occurred for carbon monoxide as fuel. After 250 hours, very minor changes are occurring as determined by this test procedure. These curves can further be interpreted by considering the CO ignition temperature and the mass transfer limited CO conversion for each test period.

Figure V-10 shows a plot of CO ignition temperature versus time period. Below 500 hours, the catalyst core DXB-222 ignites at the initial test temperature of 463°K so that an accurate measurement of the ignition temperature is not available for this time period. After 500 hours, the ignition temperature begins to increase and at 1,000 hours has reached 483°K. Apparently, the intrinsic catalytic activity of DXB-222 for CO is still changing after 1,000 hours life testing.

Figure V-11 shows the plot of mass transfer limited conversion versus time period. This response indicates that the conversion level declines rapidly from 80% for the fresh catalyst to approximately 50% during the first 250 hours aging. For this to occur, the apparent mass transfer geometric area has declined 40% from that originally available. Further decline in mass transfer limited conversion is negligible from 250 hours up to 1,000 hours aging.

Figure V-10

Response of Ignition Temperature of Carbon Monoxide During Activity Tests on Catalyst Core DXB-222

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Run Conditions

Reference Velocity = 36.5 M/S

Feed CO = 4000 ppm

Pressure = 1×10^5 N/M^2

Catalyst Core Dimensions = .0254M ø x .1524M L

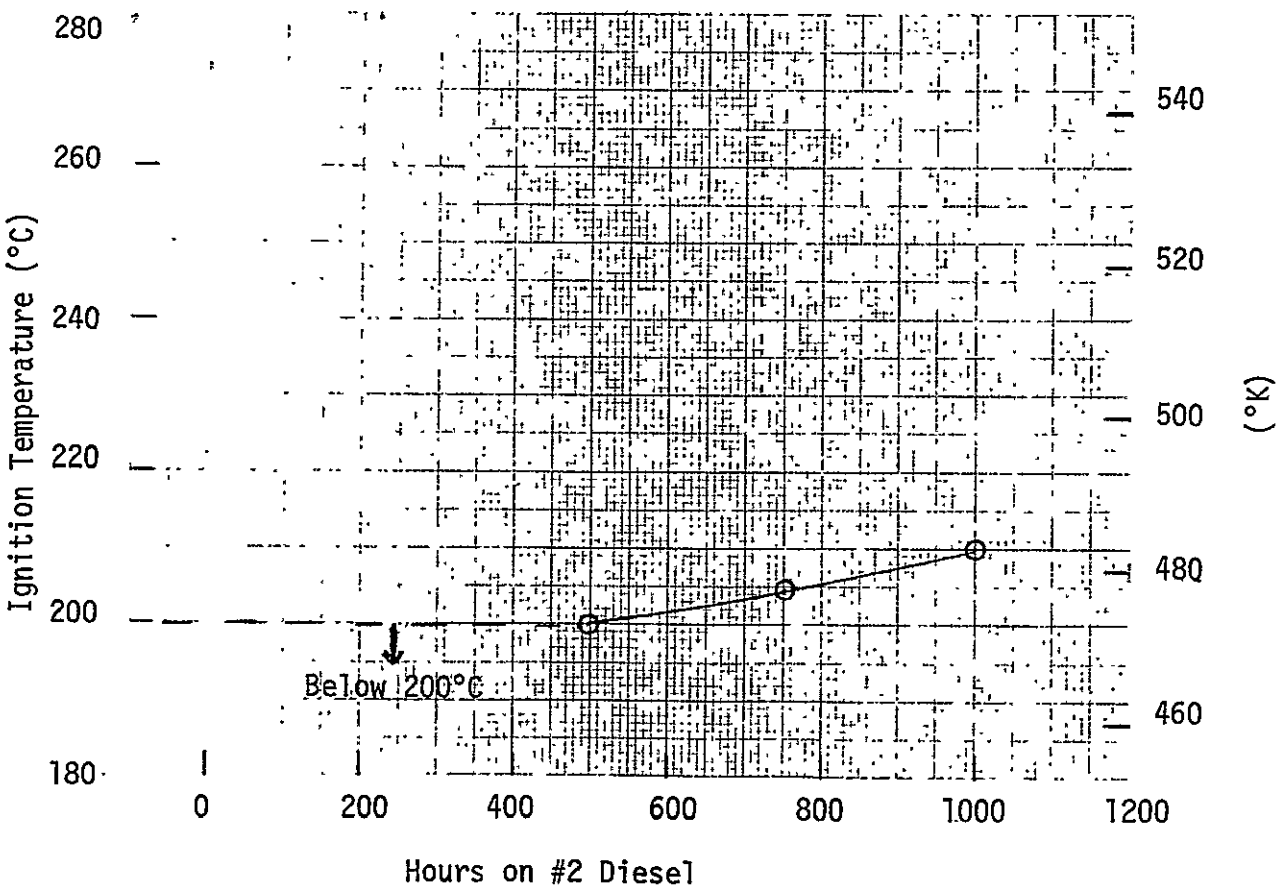


Figure V-11

Response of Mass Transfer Limited Conversion of Carbon Monoxide From Activity Tests on Catalyst Core DXB-22

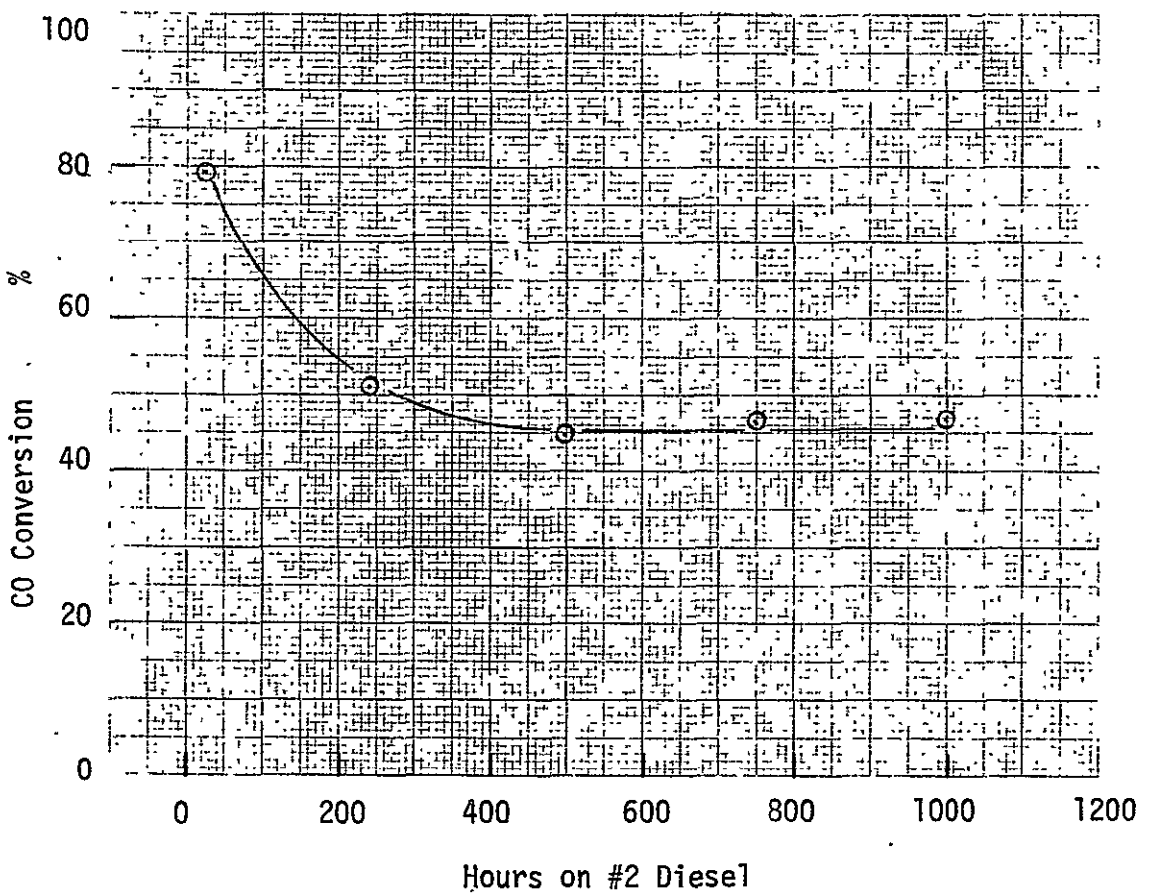
Run Conditions

Reference Velocity = 36.5 M/S

Feed CO = 4000 Vppm

Pressure = 1 x 10^5 N/M^2

Catalyst Core Dimensions = .0254M x .1524 M L



These results indicate that changes in catalyst core DXB-222's intrinsic activity for carbon monoxide are still occurring at 1,000 hours as depicted by increasing ignition temperature. However, the apparent mass transfer area of the catalyst core, as measured by the mass transfer limited CO conversion, appears to have stabilized after 250 hours aging.

c. Propane Parametric Studies

The propane parametric studies conducted at the beginning of the 1,000 hour life test on catalyst core DXB-222 provided information on the region of low emissions operation of a fresh CATCOM catalyst with C. P. Propane fuel. The final parametrics provided information on the effect of aging on the retention of catalytic activity for low emissions operation with C. P. Propane.

Table V-6 contains a tabulation of the response of combustion efficiency from the 1/3 replicate factorial statistical design for four variables at these levels. Analyzing the combustion efficiency response for the initial propane parametrics indicated the following region of operation of the main control variables for low emissions:

TABLE V-6

Combustion Efficiency Response of Propane Parametrics
Before and After 1000 Hour Life Test on Catalyst Core DXB-222

Run #	Inlet Pressure (x 10^{-5}) N/M^2	Preheat Air Temperature °K	Reference Velocity M/S	Adiabatic Flame Temperature °K	Combustion Efficiency (%) Initial	Final
6-26A	3.1	734	13.3	1471	99.96	
6-41A	3.0	733	14.8	1523		98.67
6-26B3	5.1	653	13.5	1477	0	
6-41B	5.0	653	15.2	1482		0
6-26C	5.1	718	13.2	1375	98.36	
6-41C	5.1	722	14.5	1408		18.65
6-26D	5.1	808	20.73	1478	99.93	
6-41D	5.1	808	22.6	1475		84.31
6-26E	3.1	803	28.1	1473	99.86	
6-41E	3.1	808	30.9	1475		91.51
5-109F	1.2	718	13.16	1538	99.89	
6-41F	1.2	708	14.2	1530		99.7
6-27A	3.1	638	21.1	1462	99.88	
6-42A	3.1	653	23.5	1482		24.54
6-27B	3.1	711	28.03	1500	99.81	
6-42B	3.1	723	31.1	1545		24.47
4-92E2	3.1	643	14.5	1497	99.94	
6-42C	3.1	633	14.6	1534		99.58
5-109B	1.3	721	19.57	1477	99.89	
6-42D	1.2	723	22.7	1474		37.58
5-109D	1.4	638	20.55	1526	99.94	
6-42E	1.2	653	25.8	1554		31.12
6-27F	5.1	718	27.42	1469	47.03	
6-42F	5.1	723	31.1	1474		16.87
6-28A	3.1	723	20.8	1394	99.61	
6-43A	3.1	650	22.82	1394		16.91
5-110A	1.2	828	13.46	1486	99.91	
6-43B	1.2	808	14.4	1475		99.6
5-112B	3.1	803	13.1	1389	99.93	
6-43C	3.1	808	14.4	1394		88.65

(Continued)

TABLE V-6 (continued)

Combustion Efficiency Response of Propane Parametrics
Before and After 1000 Hour Life Test on Catalyst Core DXB-222

Run #	Inlet Pressure (x 10^{-5}) N/M^2	Preheat Air Temperature °K	Reference Velocity M/S	Adiabatic Flame Temperature °K	Combustion Efficiency (%) Initial	Final
5-112D	5.1	813	13.1	1537	99.96	
6-43D	5.1	808	14.5	1583		99.95
6-31D	5.1	733	22.56	1523	99.96	
6-43E	5.1	728	23.0	1550		13.69
6-31F	5.1	655	31.96	1489	99.83	
6-43F	5.1	658	32.4	1559		21.77
5-110C	1.4	808	25.23	1542	99.86	
6-44A	1.2	808	31.0	1595		99.6
5-112A	1.2	708	21.24	1459	99.76	
6-44B	1.2	723	22.87	1474		35.96
5-109E	1.3	638	13.74	1397	99.67	
6-44C	1.2	653	16.4	1406		31.17
6-31C	3.1	633	30.5	1367	44.19	
6-44D	3.1	653	32.1	1406		12.4
5-109C	1.3	648	30.92	1474	49.65	
6-44E	1.2	653	35.0	1482		21.14
5-112C	3.1	803	20.29	1496	99.96	
6-44F	3.1	808	22.7	1547		99.81
5-109A	1.4	723	24.86	1394	97.57	
6-45A	1.2	723	31.0	1394		23.26
6-31A	1.2	728	22.09	1479	99.74	
6-45B	1.2	723	22.9	1474		35.58
6-31D	5.1	653	22.96	1399	28.29	
6-45C	5.1	678	24.45	1436		0
6-31E	5.1	808	30.01	1379	99.23	
6-45D	5.1	808	30.8	1314		17.74
5-110B	1.2	803	20.5	1391	94.96	
6-45E	1.2	808	22.6	1394		82.45

Air Preheat Temperature:	$\geq$653°K
Adiabatic Flame Temperature:	$\geq$1449°K
Reference Velocity:	$\leq$30 M/S
Pressure:	$\leq 5 \times 10^5$ N/M^2

The low emissions operating region for DXB-222 with C. P. Propane is very broad prior to life testing. The only marginal operating conditions are at low air preheat (<653°K) and low adiabatic flame temperature (<1449°K).

The results in Table V-6 also define the region for low emissions operation after 1,000 hours of aging as follows:

Air Preheat Temperature:	$\geq$808°K
Adiabatic Flame Temperature:	$\geq$1533°K
Reference Velocity:	$\leq$22 M/S
Pressure:	1×10^5 N/M^2

The performance of catalyst core DXB-222 after 1,000 hours diesel aging has declined significantly in regards to the range of low emissions operation for C. P. Propane.

The decline in activity for catalyst core DXB-222 relative to C. P. Propane fuel was not unexpected, considering the fact that low molecular weight paraffinic fuels (e.g., C. P. Propane) are more difficult to oxidize than fuels containing higher molecular weight paraffins (e.g., #2 diesel).

Since the results with C. P. Propane may be unduly conservative and not indicative of the catalyst's capabilities after 1,000 hours aging, a number of runs from the parametric matrix were repeated using #2 diesel to determine the performance of DXB-222 with a realistic fuel. These replicates covered a broad range of the region in which C. P. Propane had high emissions. Over this representative range of operating conditions from the propane parametrics, the performance of catalyst core DXB-222 with #2 diesel was acceptable, with high combustion efficiencies, as graphically shown in Figure V-12. Comparable results for C. P. Propane and #2 diesel fuel are also tabulated in Table V-7.

These parametrics conducted after 1,000 hours aging of DXB-222 indicate catalyst performance with a low molecular weight paraffinic fuel (propane) and a realistic high molecular weight fuel, #2 diesel. The final diesel parametrics gave information that was more representative in terms of commercial application.

Upon removal of catalyst core DXB-222 from the reactor test rig, after the variable study with #2 diesel, it was noticed that some internal damage to the catalyst core had occurred, blocking some support channel passages. Since no unusual increases in pressure drop occurred during life testing and the final propane parametrics, the damage had to be caused during the diesel parametrics. This damage was attributed to unvaporized fuel passing through the catalyst at

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Figure V-12 Plot of Comparison Runs for #2 Diesel and C. P. Propane After 1000 Hour Diesel Ageing of Catalyst Core DXB-222.

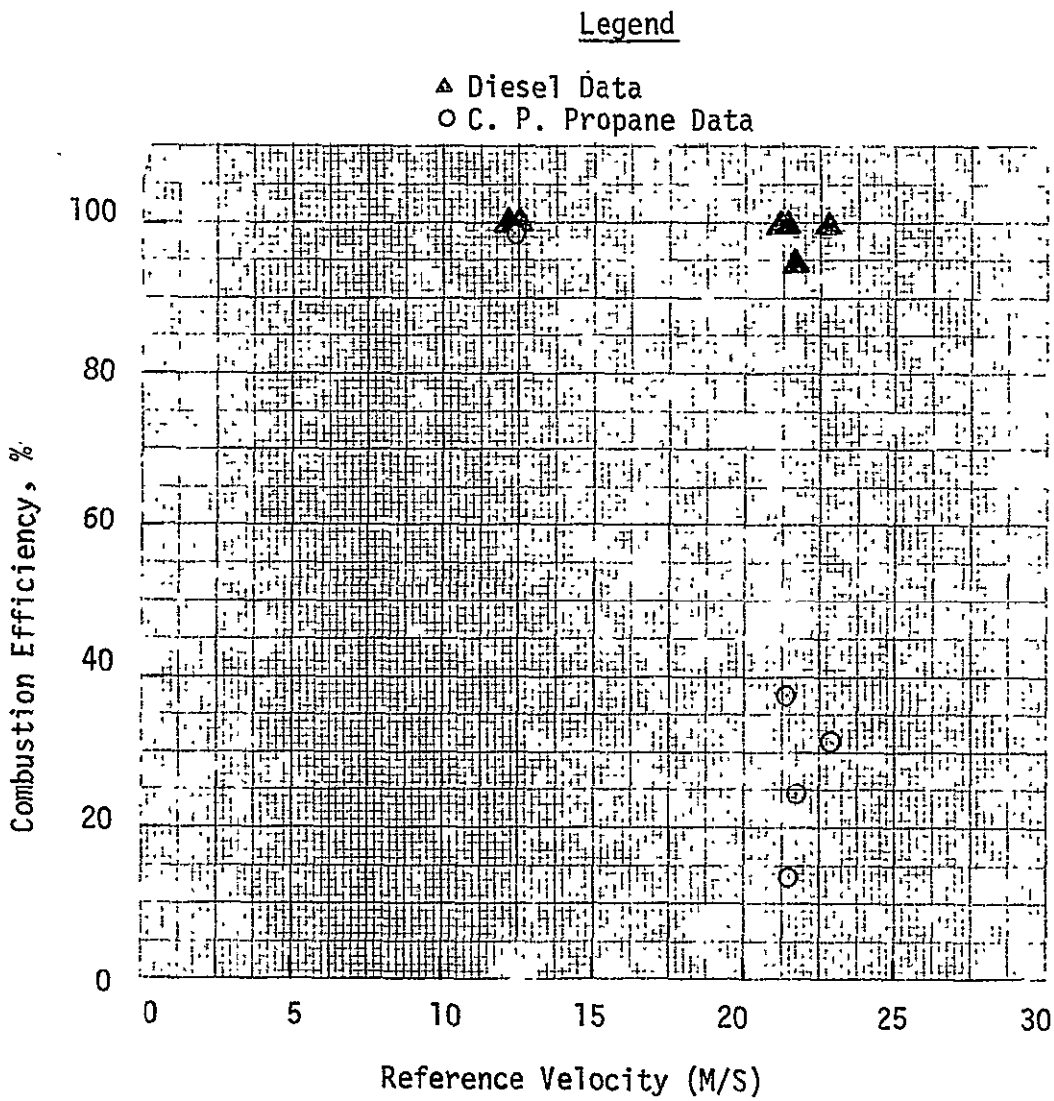

TABLE V-7

Comparison of Parametric Runs With C. P. Propane And #2 Diesel After 1000 Hours Ageing of DXB-222

Run #	Inlet Pressure (x 10^{-5}) N/M^2	Air Preheat Temperature °K	Reference Velocity M/S	Adiabatic Flame Temperature °K	Combustion Efficiency C.P. Propane	Combustion Efficiency #2 Diesel
6-41A	3.0	733	14.8	1523	98.67	
6-46A	3.1	723	14.3	1425		99.94
6-41B	5.0	653	15.2	1482	0	
6-46F	5.1	653	14.8	1445		99.96
6-42A	3.1	653	23.5	1482	24.54	
6-46D	3.1	653	23.3	1445		94.43
6-42D	1.2	723	22.7	1474	37.58	
6-46D	1.2	723	22.6	1440		99.76
6-42E	1.2	653	25.8	1554	31.12	
6-46C	1.2	653	25.5	1490		99.8
6-43E	5.1	728	23.0	1550	13.69	
6-46E	5.1	723	22.6	1490		99.92

the high fuel flow rate of this variable study. Catalyst core DXB-222 was still capable of low emissions operation, however the overall pressure drop naturally increased through the catalyst core.

The results of the propane and diesel parametrics indicate that a decline of activity has occurred with respect to low molecular weight paraffinic fuels. However, catalyst core DXB-222 still maintains high combustion efficiencies over a wide operating range with #2 diesel after the 1,000 hour life test.

d. Analysis of Propane Parametrics

Detailed analysis of the propane parametrics with DXB-222 was conducted in order to obtain: 1) a graphical representation, and; 2) a statistical model describing the responses of combustion efficiency, CO emissions and pressure drop. Since no control study was made to quantify modes or causes of deactivation from #2 diesel aging, this analysis was directed only at the initial propane parametrics on DXB-222.

The models that were tried in this study were limited to multiple linear regressions considering the first, second and third order combinations of interactions. Typical models such as Combustion Efficiency = A + B (Reference Velocity) + C (Adiabatic Flame Temperature) (Air Preheat Temperature) were considered.

1) Combustion Efficiency

A number of graphical techniques and statistical models were explored to represent the response of combustion efficiency to the control variables. This section contains a synopsis of these results; more detail can be found in Appendix D. The main conclusion was that no suitable description of this response was found.

Table V-8 summarizes typical results from the regression analysis models considered for describing combustion efficiency. The correlation coefficient set for selecting a satisfactory predictive model was .97, which corresponds to a standard error of ±5% (relative) in combustion efficiency. None of the models tried gave a correlation approaching this criteria.

2) Carbon Monoxide Emissions

Table V-9 lists the regression models investigated for the CO emissions response from the DXB-222 propane parametrics. This analysis showed no significant model was found for CO emissions.

No suitable graphical representation of the CO emissions data was determined from this study.

C-2

TABLE V-8

Typical Statistical Models For Combustion Efficiency

Variable In Regression Model	Correlation Coefficient
Vr	0.4337
T_I	0.4020
T_{OD}	0.2920
P_I	0.1870
$(T_I)(T_{OD})$	0.4616
$(T_I)(T_{OD})$, Vr	0.5873
(Vr),(T_I),(P_I),(T_{OD})	0.5889
Vr, T_I,(Vr) (T_{OD}), $(T_I)(T_{OD})$	0.6908

Note: All other 1st, 2nd, and 3rd order combinations of variations had correlation coefficients within range shown above.

TABLE V-9

Typical Statistical Models For Carbon Monoxide Emission

Variables In Regression Model	Correlation Coefficient
T_{OD}	0.5567
P_I	0.2736
T_I	0.1229
Vr	0.0731
Vr, T_I, P_I, T_{OD}	0.6190
T_{OD}, P_I T_{OD}, P_I	0.6744

Note: All other 1st, 2nd and 3rd order combinations of variables had correlation coefficients within range shown above.

3) Pressure Drop

Analysis of the pressure drop responses from the propane parametrics resulted in a very satisfactory graphical and statistical representation for both isothermal and combustion pressure drop. The models that proved to be the best predictors are shown below.

Isothermal

$$\frac{\%\Delta P}{P} = \frac{0.0564V^{1.6}}{p^{0.56}}$$

Standard Error = 0.582%

Maximum Error = 1.36%

Correlation Coefficient = 0.9945

Combustion

$$\frac{\%\Delta P}{P} = \frac{0.336V^{1.3}}{p^{0.77}}$$

Standard Error = 1.32%

Maximum Error = 3.38%

Correlation Coefficient = 0.9932

Where

P = Atm. (1×10^5 N/M^2)

V = M/S

The excellent agreement between the model prediction and test results is further depicted in Figure V-13 for combustion pressure drop. The isothermal pressure drop model yields comparable results between predicted and experimental values.

2. Performance of Catalyst Core DXC-532

a. Life Testing with #2 Diesel Oil

The daily performance during the life testing of catalyst core DXC-532 was monitored by recording the control input variables and output responses from the test rig. Observations were plotted daily on a control chart to monitor changes in DXC-532's performance in regards to:

- exhaust gas composition (UHC, CO, NO_x, CO_2, O_2)
- percent pressure drop
- air preheat temperature
- catalyst core outlet temperature

The performance of DXC-532 during life testing was quite satisfactory up to 600 hours on-stream. The control charts shown in Figures V-14,15,16,17,18 and 19 show very steady operation with regards to maintenance of low emissions. These gas compositions are plotted as measured in the exhaust, which has nominally 12.5% oxygen. However, a close examination of the control chart depicting outlet

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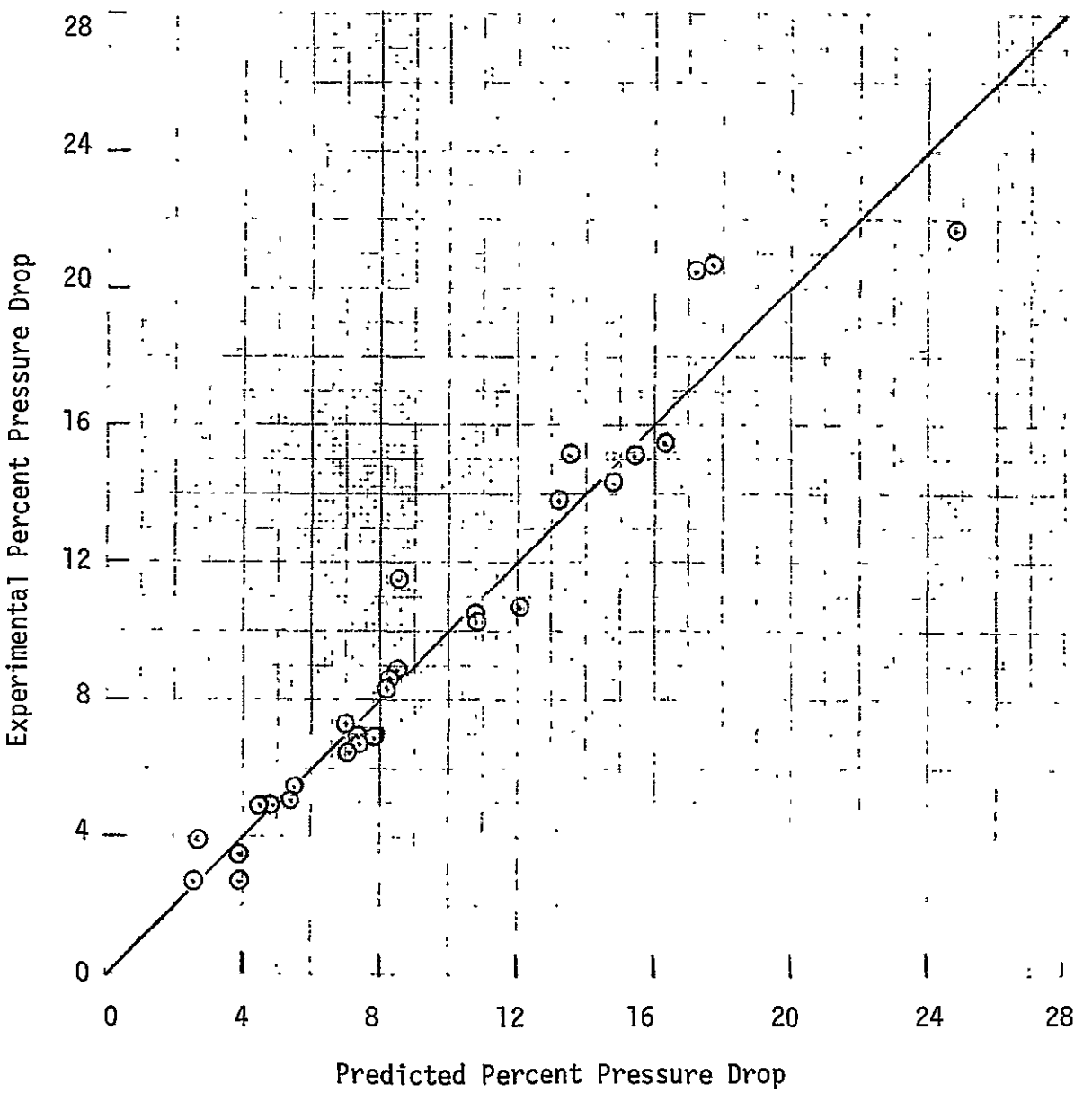
Figure V-13

Comparison of Experimental and Predicted Percent Pressure Drop of Catalyst Core DXB-222 (Combustion Condition).



temperatures downstream of catalyst core DXC-532 revealed that after 300 hours life testing, the maximum temperature location moved from .00635M downstream to .057M downstream. This indicates that some combustion was occurring downstream of the catalyst. Downstream burning was not present during the first few hundred hours of the life test.

Another phenomenon began to occur during the period of 400 to 600 hours life testing, which supported the observation that less conversion may be occurring in the catalyst core DXC-532.

The temperature start-up response of a typical catalyst core, when fuel is brought on at a specific air preheat condition, is shown in Figure V-20. Note that the outlet temperature quickly rises to achieve catalytically supported thermal combustion conditions. This type of response was representative of DXC-532's operation during the first 300 hours of life testing. Between 300 hours and up to 600 hours of life testing, the start-up response began to change, as indicated in Figure V-21. Figure V-21 indicated that there is a temporary, intermediate outlet temperature of approximately 1070°K, which appears before low emission operation is achieved. This intermediate is strictly part of the transient start-up response. Also when low emission combustion conditions are obtained, the maximum outlet temperature was located .057M downstream, however the emissions measured .1016M downstream showed no significant change.

The start-ups after 600 hours life testing with air preheat of 633°K resulted in the intermediate conversion level

Figure V-14 Hydrocarbon Emission Control Chart During Life Testing of Catalyst Core DXC-532

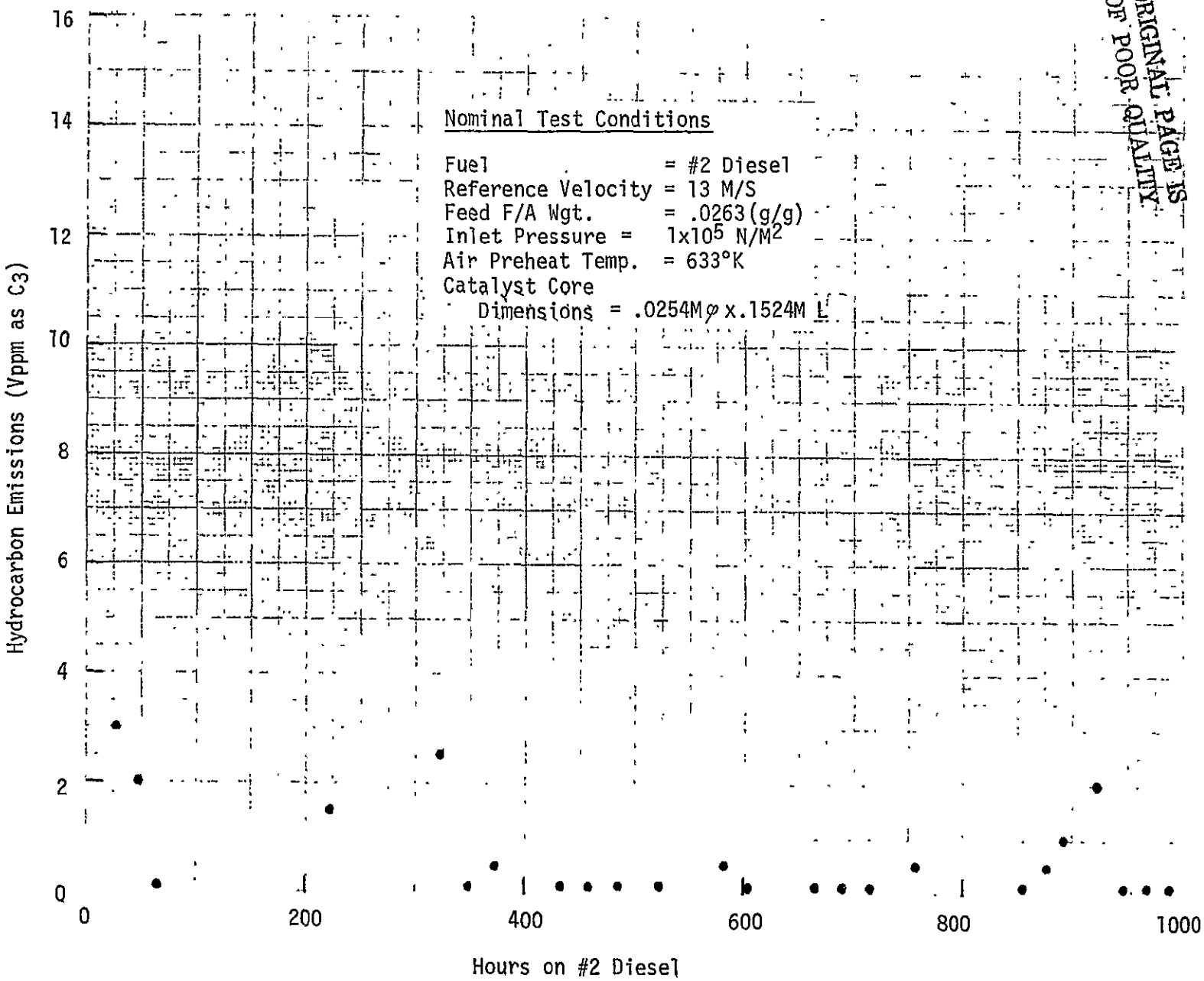


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Figure V-15 Carbon Monoxide Emission Control Chart During Life Testing of Catalyst Core DXC-532

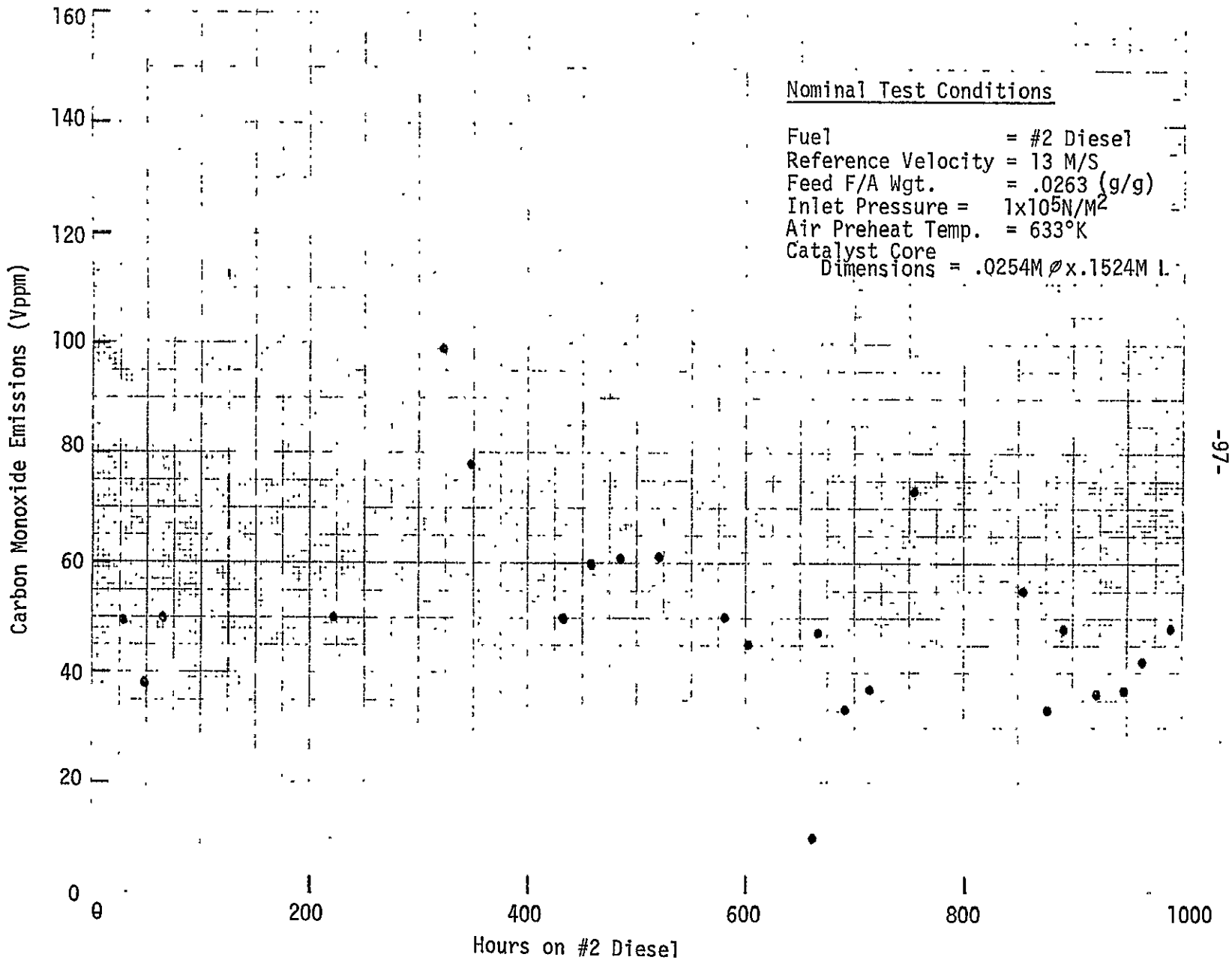

Figure V-16 NO_x Emission Control Chart During Life Testing of Catalyst Core DXC-532

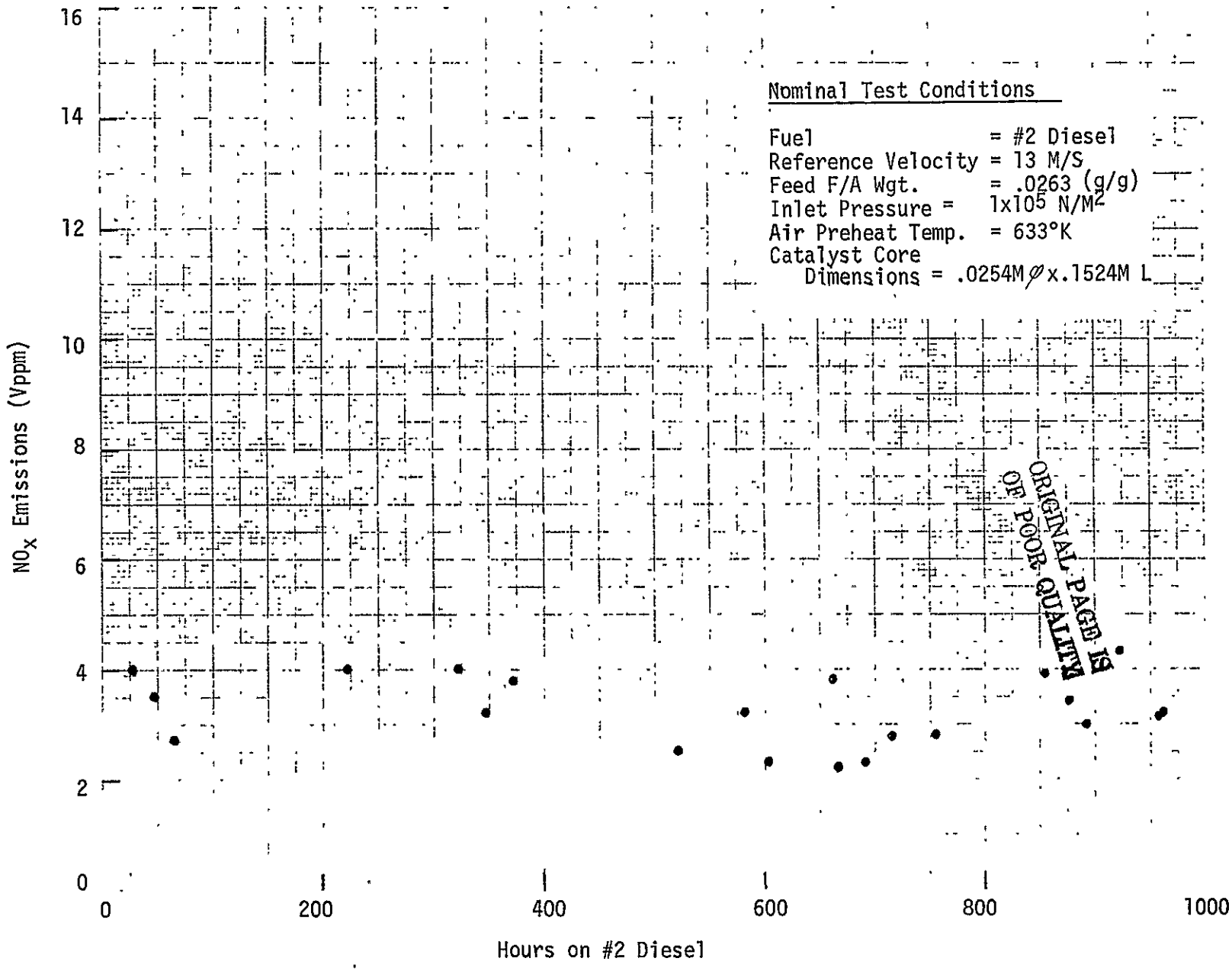

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Figure V-17 CO_2 and O_2 Control Chart During Life Testing of Catalyst Core DXC-532

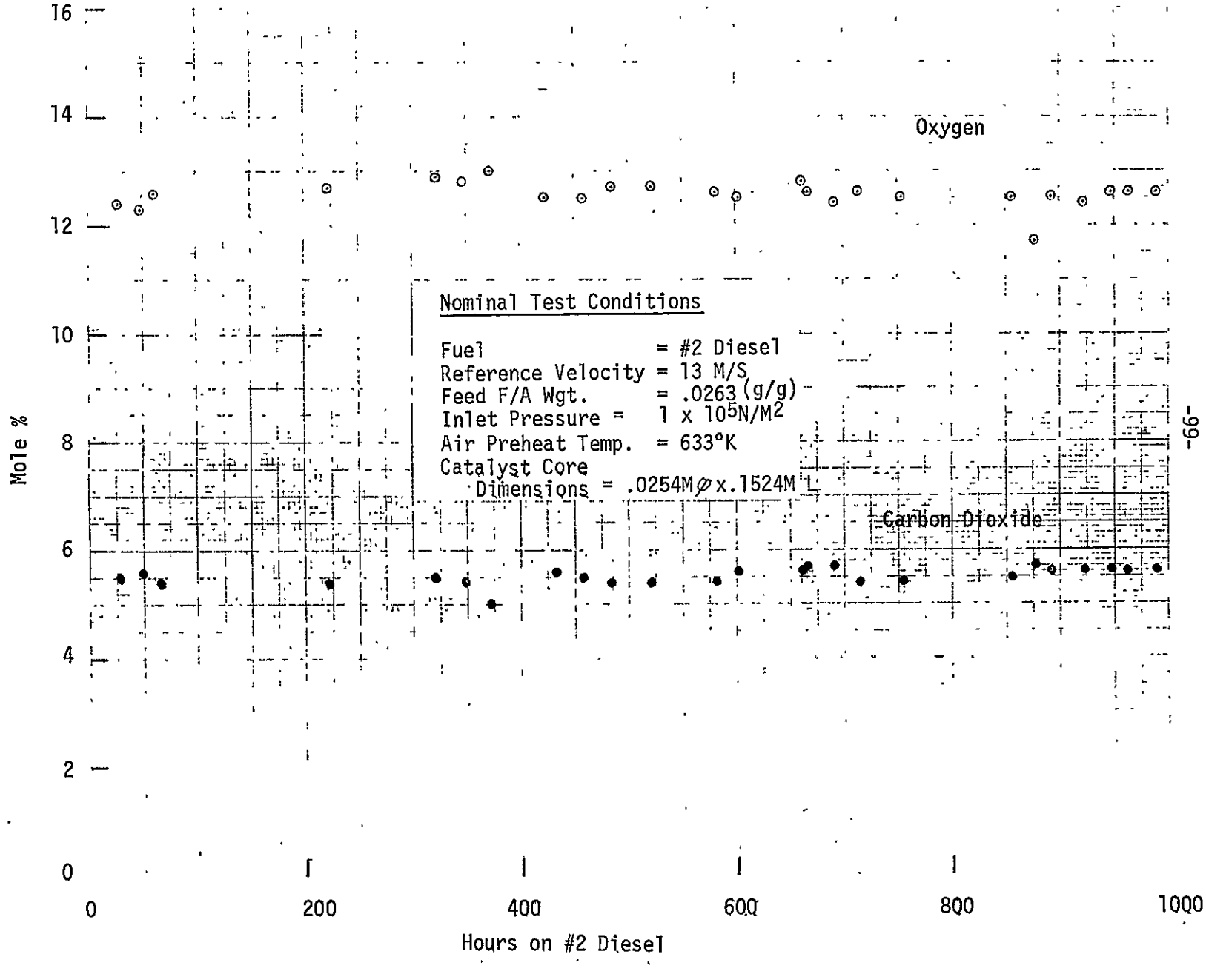

Figure V-18 Temperature Control Chart During Life Testing of Catalyst Core DXC-532

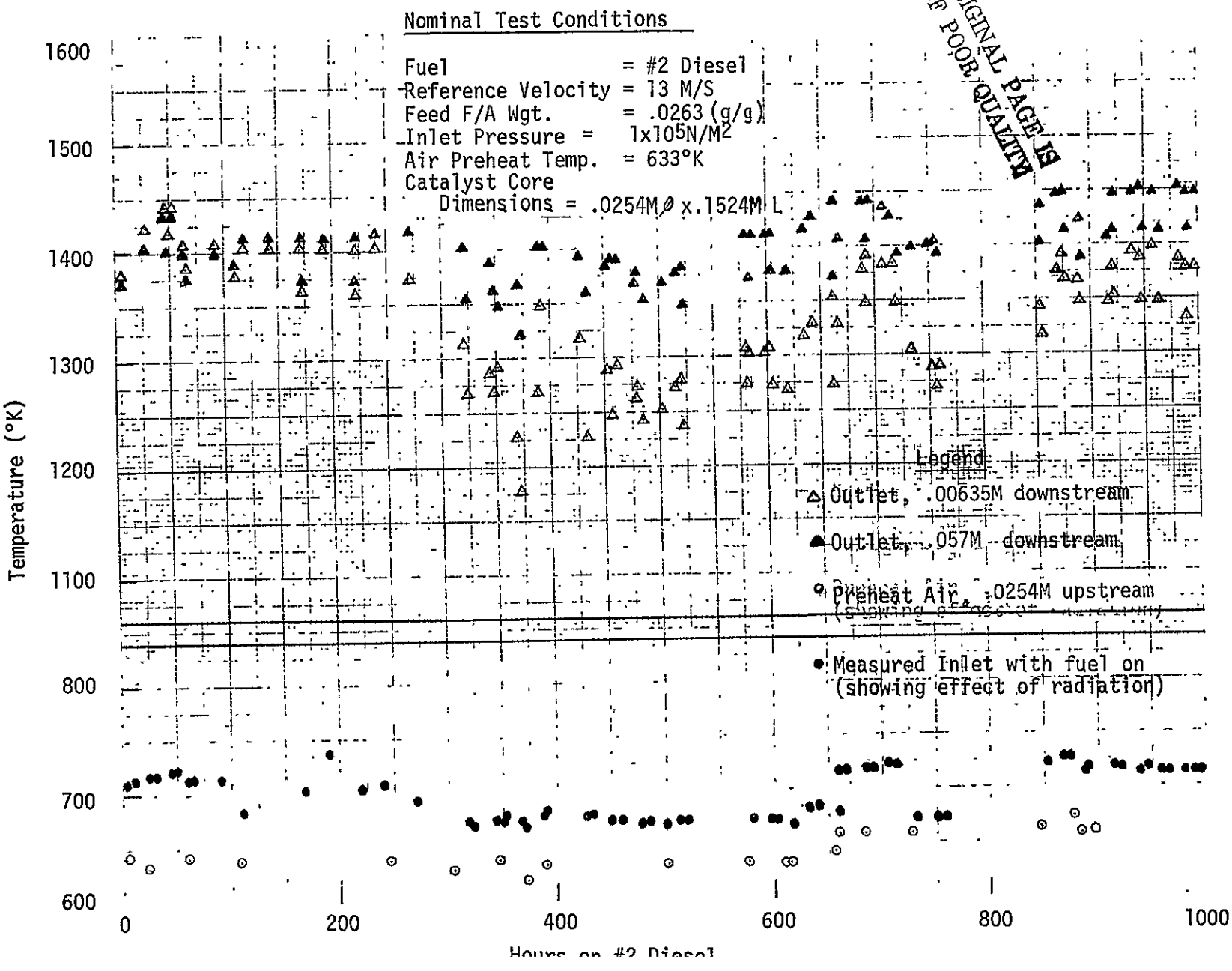

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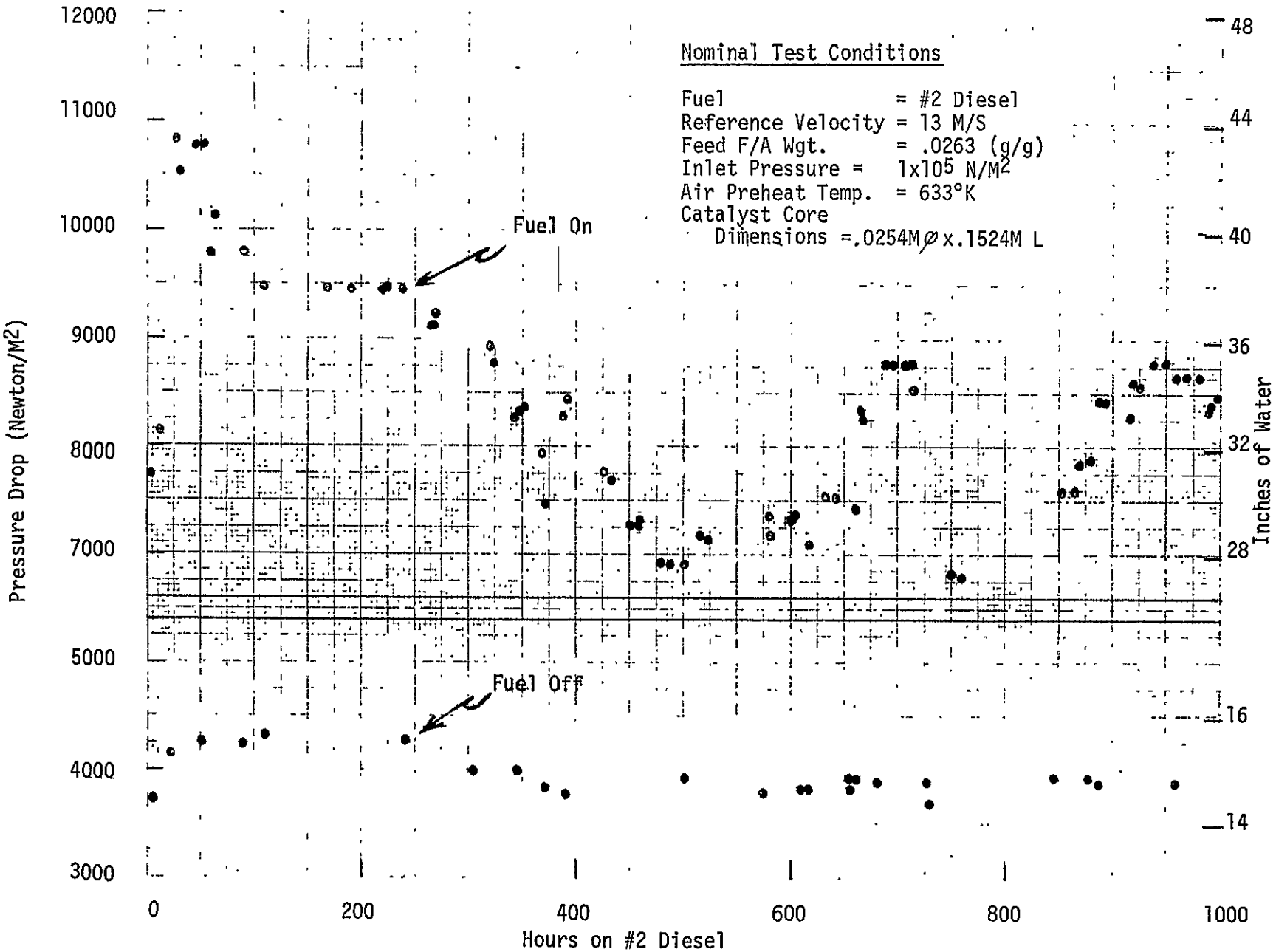
Figure V-19 Pressure Drop Control Chart During Life Testing of Catalyst Core DXC-532



stabilizing as shown in Figure V-22. Therefore, after 600 hours of life testing, the conversion across the catalyst core DXC-532 had decreased to the extent that low emissions was not obtained at the original life test operating conditions.

The low combustion efficiency operation with DXC-532 was easily corrected by raising the air preheat temperature from 633°K to 673°K gradually over the last 400 hours of life testing. The temperature response upon startup during the last 400 hours was as shown in Figure V-20 with this compensation in air preheat temperature. These increases in air preheat temperature are depicted on the temperature control chart (Figure V-18). Therefore, the emissions control charts during the last 400 hours life testing represents the emissions after the increase in air preheat temperature.

Considering the overall performance of DXC-532 during the 1,000 hour diesel life test, the following information on emissions are obtained:

Emission	Mean	Standard Deviatio
UHC (vppm as C_3)	0.6	0.9
CO (vppm)	49.6	17
NO_x (vppm)	3.3	0.6

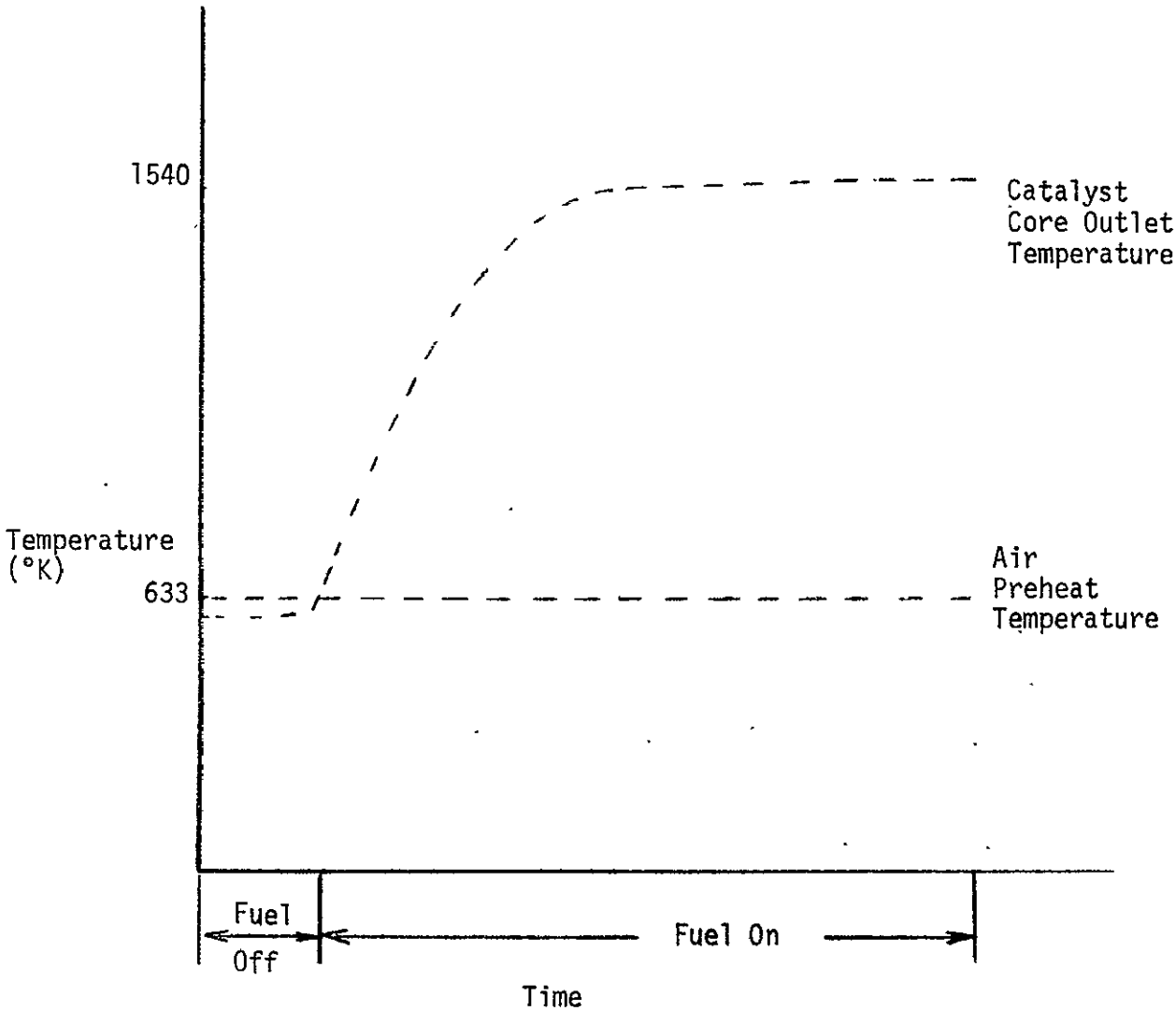


Figure VI-20 Typical Startup Response for Catalyst Core Resulting in Low Emissions Operation

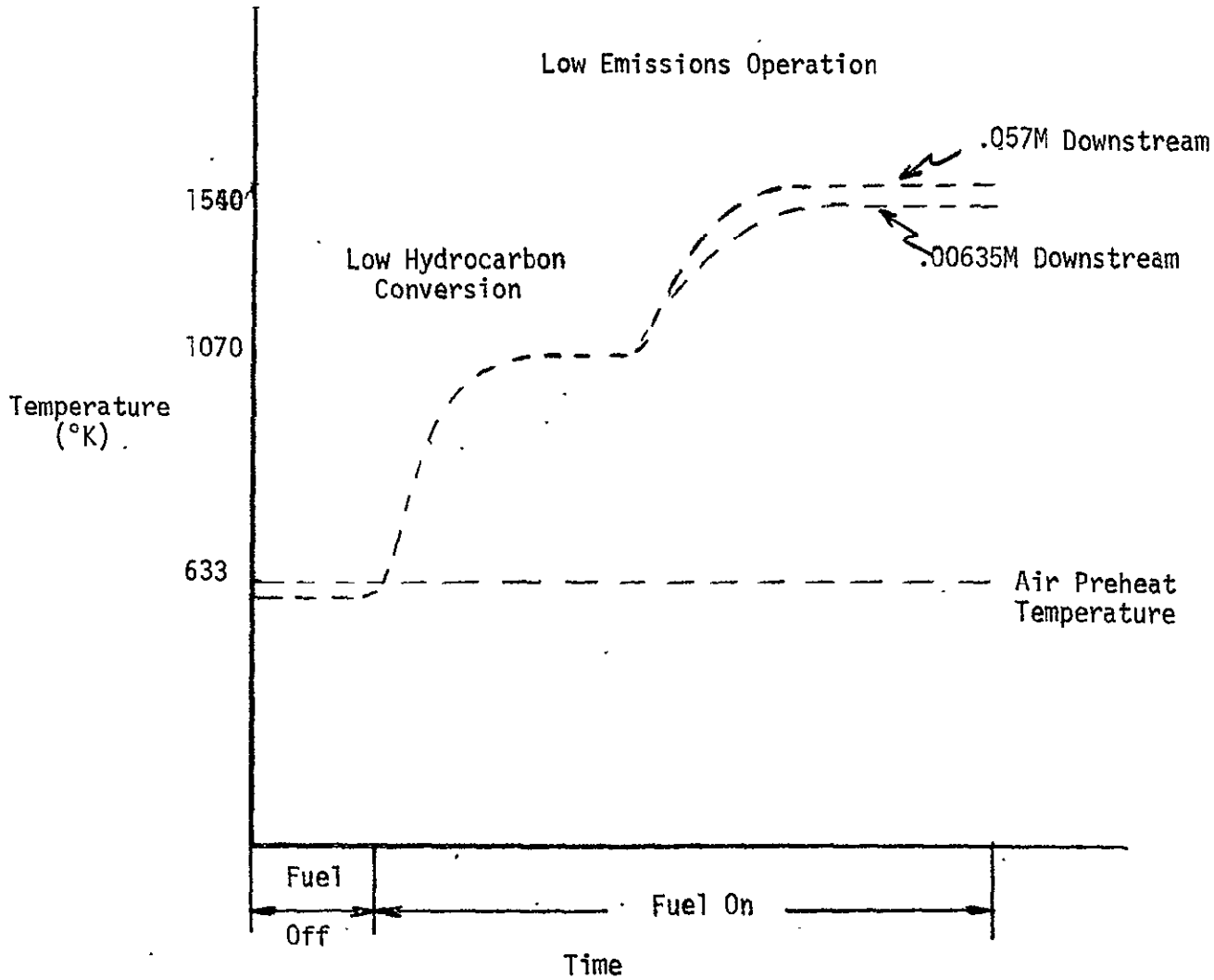


Figure V-21 Typical Startup Response of Catalyst Core DXC-532 After 400 Hours Life Testing

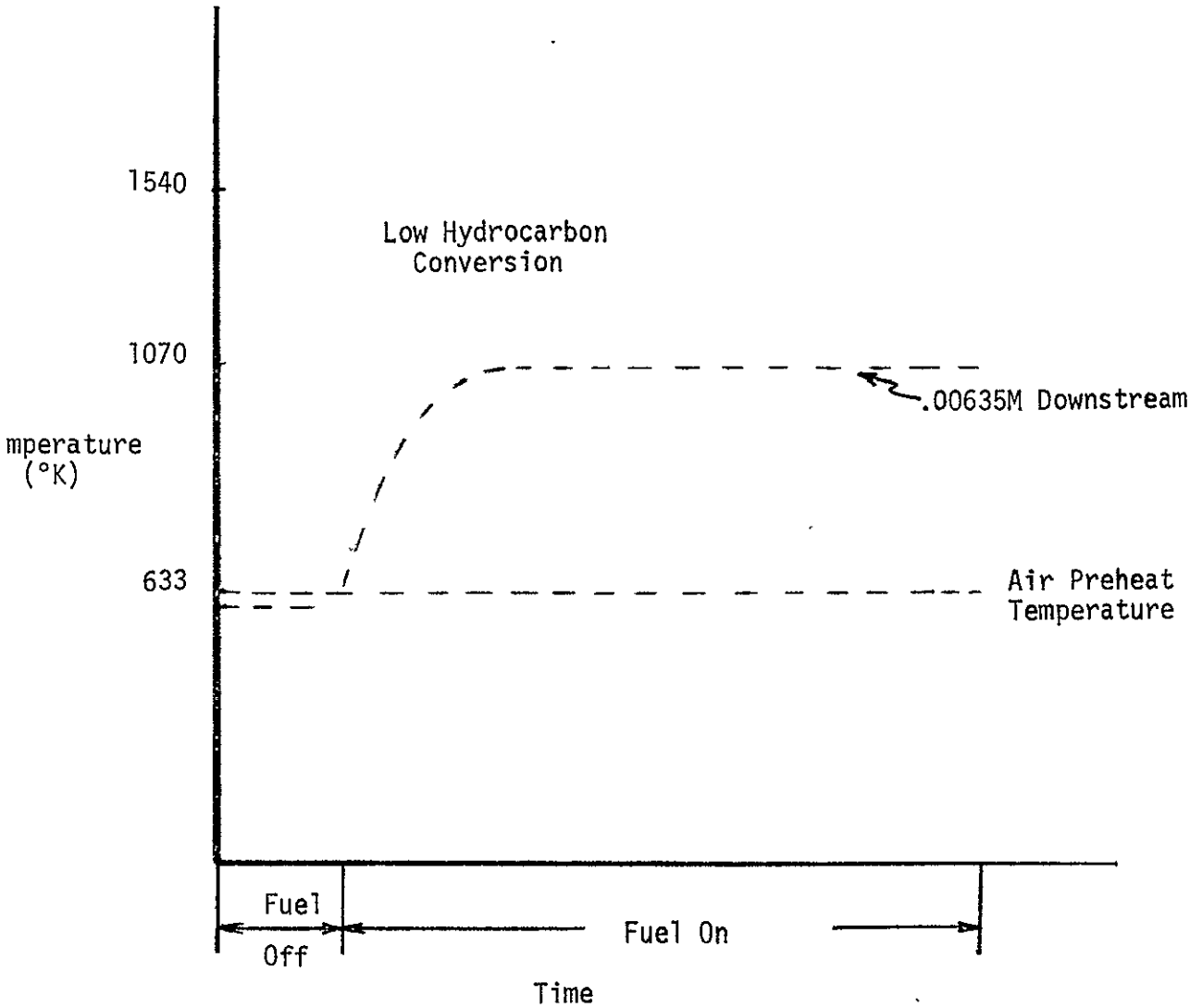


Figure V-22 Typical Startup Response of Catalyst Core DXC-532 After 600 Hours Life Testing

The NO_x emissions during this life test are probably the result of the essentially quantitative oxidation of the bound nitroger in the #2 diesel fuel. No NO_x formation is predicted due to nitrogen fixation at the life test operating conditions.

On the average, these emission results correspond to a steady state operation at a combustion efficiency of 99.9% over the 1,000 hour life test of DXC-532.

The emissions performance of DXC-532 during life testing was well below anticipated regulatory standards for stationary gas turbines(7), and can be translated for comparison to automotive standards by assuming steady state operation of an automotive gas turbine with an average fuel consumption of 10 mpg with the following results:

	Mean Measured Emissions Corrected to Automotive Operation	Automotive Standard Year	
Emissions	g/mile	1977	1978
CO	.6	1.5	.41
UHC	.009	15.	3.4
NO_x	.058	2.0	.4

This comparison is strictly based on steady state operation and does not account for transients nor cold starts.

The control chart maintained to indicate pressure drop through catalyst core DXC-532 (see Figure V-19) indicated an abrupt decrease in pressure drop around 300 hours aging. This proved to be an operational problem caused by loosening of the fiberfrax packing around the catalyst holder. The catalyst holder was repacked around 600 hours operation and the pressure drop returned to the normal value. Repacking was also required around 800 hours. The lowering in pressure drop indicates that some feed was bypassing the catalyst core resulting in erroneous experimental observations.

The control charts depicting CO_2 vent gas analysis (Figure V-17) shows the variation in #2 diesel fuel feed during the 1,000 hour life test. This variation in fuel feed corresponds to a variation in adiabatic flame temperature from 1511 to 1575°K during the 1,000 hour life test of DXC-532.

The changes in operating conditions and the responses for DXC-532 between the beginning and end of life test can be compared by referring to Table V-10. The only significant change that was made during the life test was the 40°K increase in air preheat temperature, which was needed to maintain low emissions operation.

The life test results, as reflected by the emissions performance of DXC-532, show that deactivation has occurred, but that the low emissions operation can be restored by increasing the air

TABLE V-10

Comparison of Operating Conditions and Performance Data At Start and End of Life Test for Catalyst Core DXC-532

Date	4/20/76	6/9/76
Hours on #2 Diesel Fuel	27	964
Air Flow (Kg/sec.)	3.22×10^{-3}	3.22×10^{-3}
Fuel/Air Ratio (g/g)	0.0264	0.0272
Preheat Air Temp. (°K)	633	663
Outlet Temp. (°K)	1421	1413
Adiabatic Flame Temp. (°K)	1530	1587
Inlet Pressure (N/M^2)	1.1×10^5	1.1×10^5
Pressure Drop (N/M^2)	10806	8678
Percent Pressure Drop	9.6	7.9
Reference Velocity (M/S)	12.8	13.8
Combustion Efficiency (%)	99.88	99.91
Space Velociyty, NTP Nominal (Sec^{-1})	34.7	34.7
Heat Release Rate (Joules/sec. M^2 ATM)	4.2×10^7	4.4×10^7
Emissions [1] (Nominally @ 12.5% O_2)		
CO (Vppm)	49	42
UHC, as C_3 (Vppm)	3	0
NO_x (Vppm)	4	3.2
Catalyst Core Dimension, Nominal	0.0254M in diameter by 0.152M l	

[1] All emissions measured with water cooled sampling probe located at 0.102M downstream of catalyst core.

preheat temperature from 533°K to 573°K. With this adjustment, the emissions performance of DXC-532 was extremely low during the remainder of the 1,000-hour life test.

Another aspect of the life test was to determine the physical durability of the catalyst core, particularly, the support material. Figure V-23 shows the photographs taken of catalyst core DXC-532 after the 1,000 hours testing. The color gradients along the direction of flow are normal, and reflect the temperature gradient through the catalyst at an adiabatic operating temperature of 1527°K. No collapse in channels nor physical damage to the support were visually apparent. The catalyst support appears to be adequate for extended operation at combustion conditions.

Analytical tests were conducted on catalyst core DXC-532 upon completion of the test series to determine the retention of the precious metal catalytic component and the thermal stability of the catalyst core. Assay results indicated that DXC-532 retained about 40% of the original precious metal after 1,000 hours operation. The BET surface area results showed that about 30% of the original area is retained after aging. These results are all relative to a lined-in sample of DXC-532 (i.e., aged for 24 hours at life test conditions). At present, it is felt that the most probable mechanism for the precious metal loss is detachment of the washcoat from the support. Techniques, gained from experience in auto exhaust catalyst preparation, are available for increasing the adhesion of the washcoat to the monolith. These improved techniques should reduce the precious metal loss without decreasing the performance durability of DXC-532.

Further analyses were conducted on the aged DXC-532 with a scanning electron microscope and an x-ray diffractometer. These analyses both indicated that deposits of lead were present on catalyst core DXC-532 after 1,000 hours life testing. (See Section VI for discussion of these results.)

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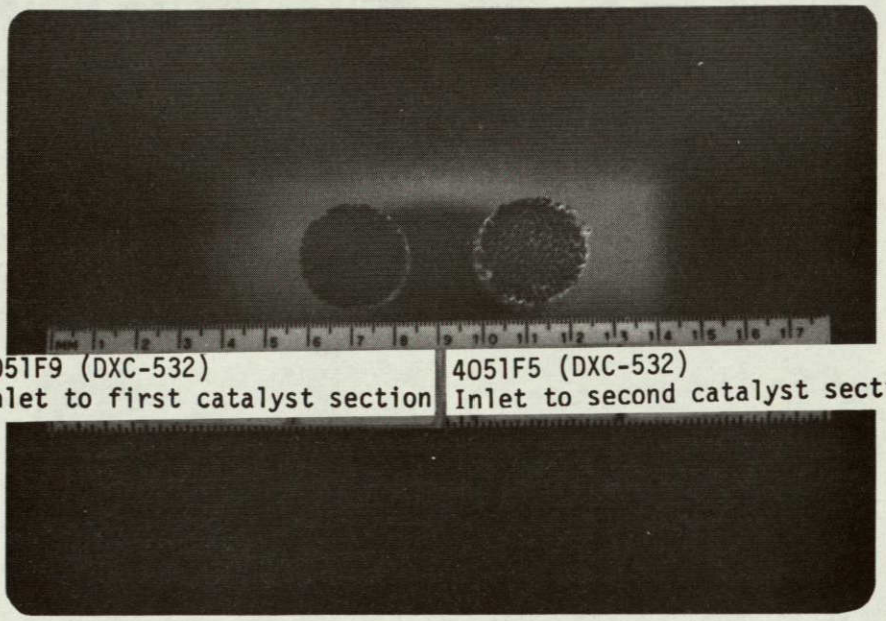

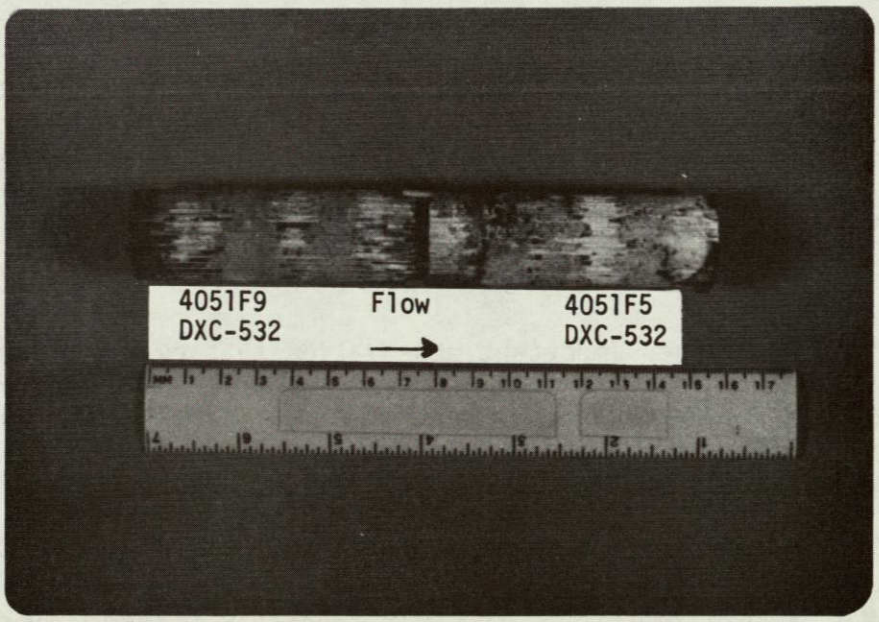

Figure V-23 Photographs of Catalyst Core DXC-532 After 1000 Hours Life Testing

The results of this 1,000-hour life test on catalyst core DXC-532 indicate that the deactivation that occurred can be compensated for by increasing the air preheat temperature by 40°K. With this compensation, DXC-532 can operate under CATATHERMAL conditions for at least 1000 hours without substantial loss of low emissions performance due to physical or chemical degradation.

b. Carbon Monoxide Activity Test

Carbon monoxide activity tests were conducted periodically during the life testing of catalyst core DXC-532. The results are detailed in Figure V-24. Analyzing the overall trends depicted in this figure indicate that between 24 hours aging and 250 hours aging a significant decline has occurred in the activity of the catalyst core DXC-532 for carbon monoxide fuel. After 250 hours, the changes are very minor as determined by this test procedure.

Another important observation that can be extracted from the data in Figure V-24 is the trend of CO ignition temperature versus aging time. These results are summarized in Figure V-25. The CO ignition temperature rose from 473°K to 503°K during the 1000 hours of life testing. Apparently, the intrinsic catalytic activity for CO has changed during the life test.

Figure V-24 Carbon Monoxide Activity Test Response During Life Testing of Catalyst Core DXC-532.

Legend	Run Conditions
1 24 Hours Aging	Reference Velocity = 36.5 M/S
2 240 Hours Aging	Feed CO = 4000 Vppm
3 500 Hours Aging	Pressure = 1×10^5 N/M^2
4 660 Hours Aging	Catalyst Core Dimensions = .0254M ϕ x .1524M L
5 1000 Hours Aging	

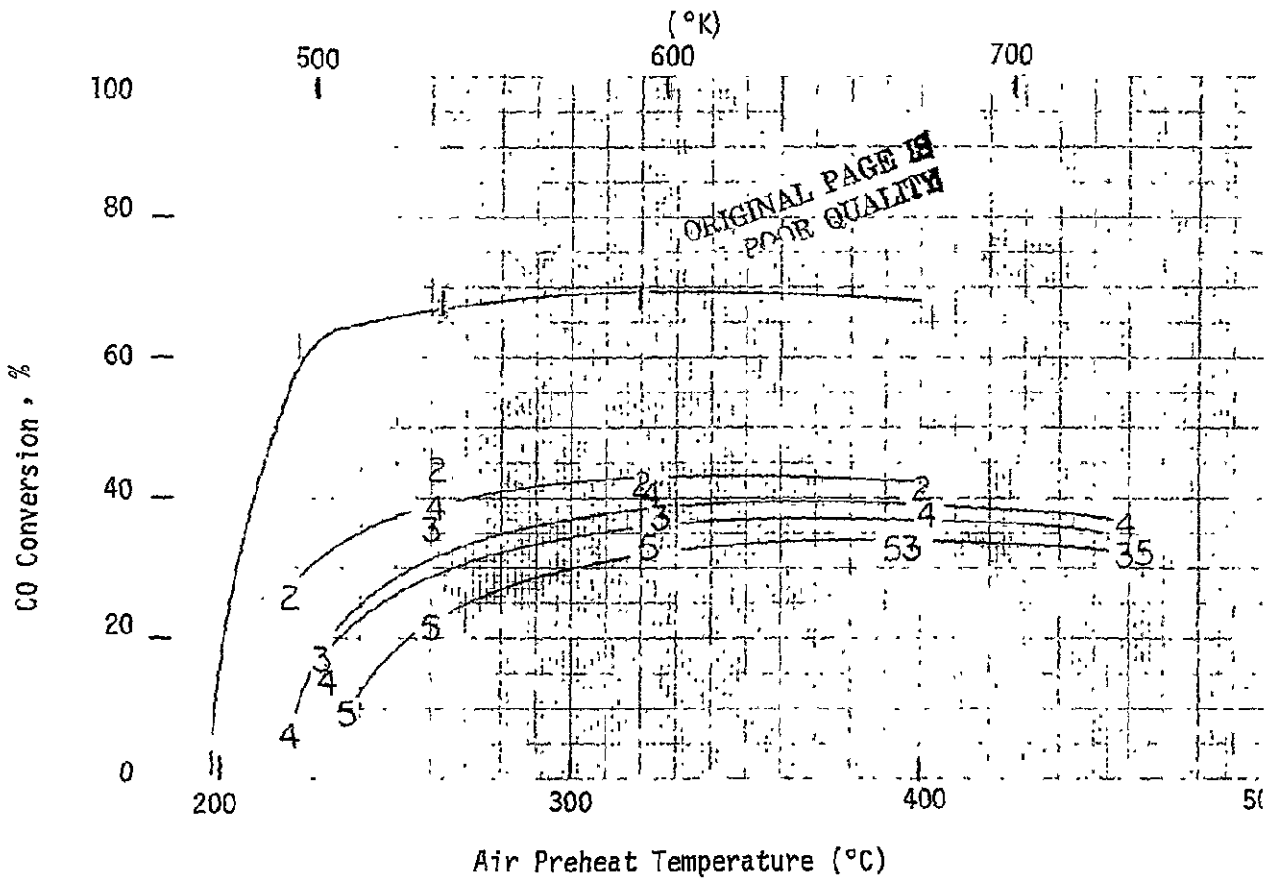

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Figure V-25 Response of Ignition Temperature of Carbon Monoxide During Activity Tests on Catalyst Core DXC-532.

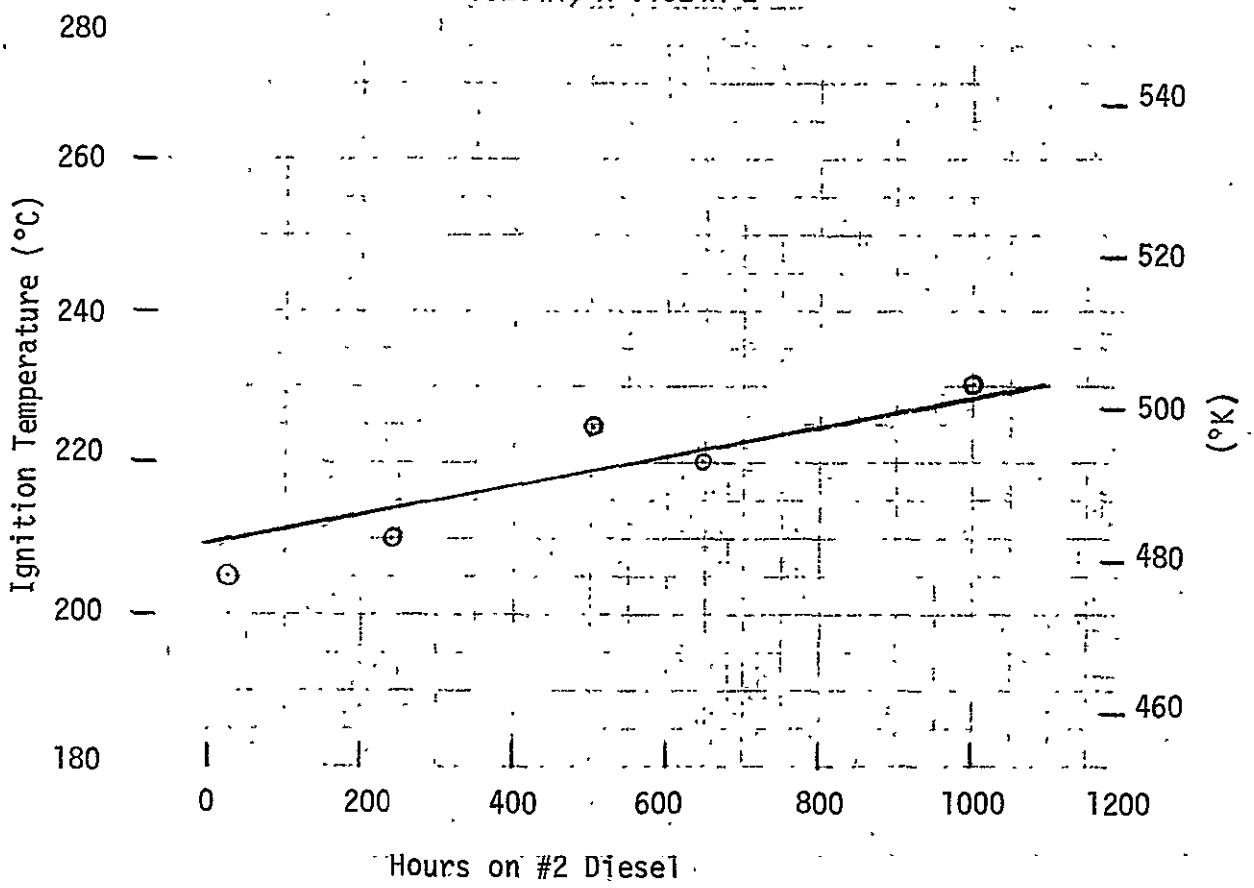
Run Conditions

Reference Velocity = 36.5 M/S

Feed CO = 4000 Vppm

Pressure = 1×10^5 N/M^2

Catalyst Core Dimensions = .0254M ø x .1524M L



Additional information can be obtained from Figure V-24 by plotting the mass transfer limited CO conversion, as shown in Figure V-26. This figure further confirms that the mass transfer limited conversion indeed declined rapidly during the first 250 hours of aging, but thereafter further decline is negligible for DXC-532. The decline in mass transfer conversion represents a 36% change in the apparent mass transfer area.

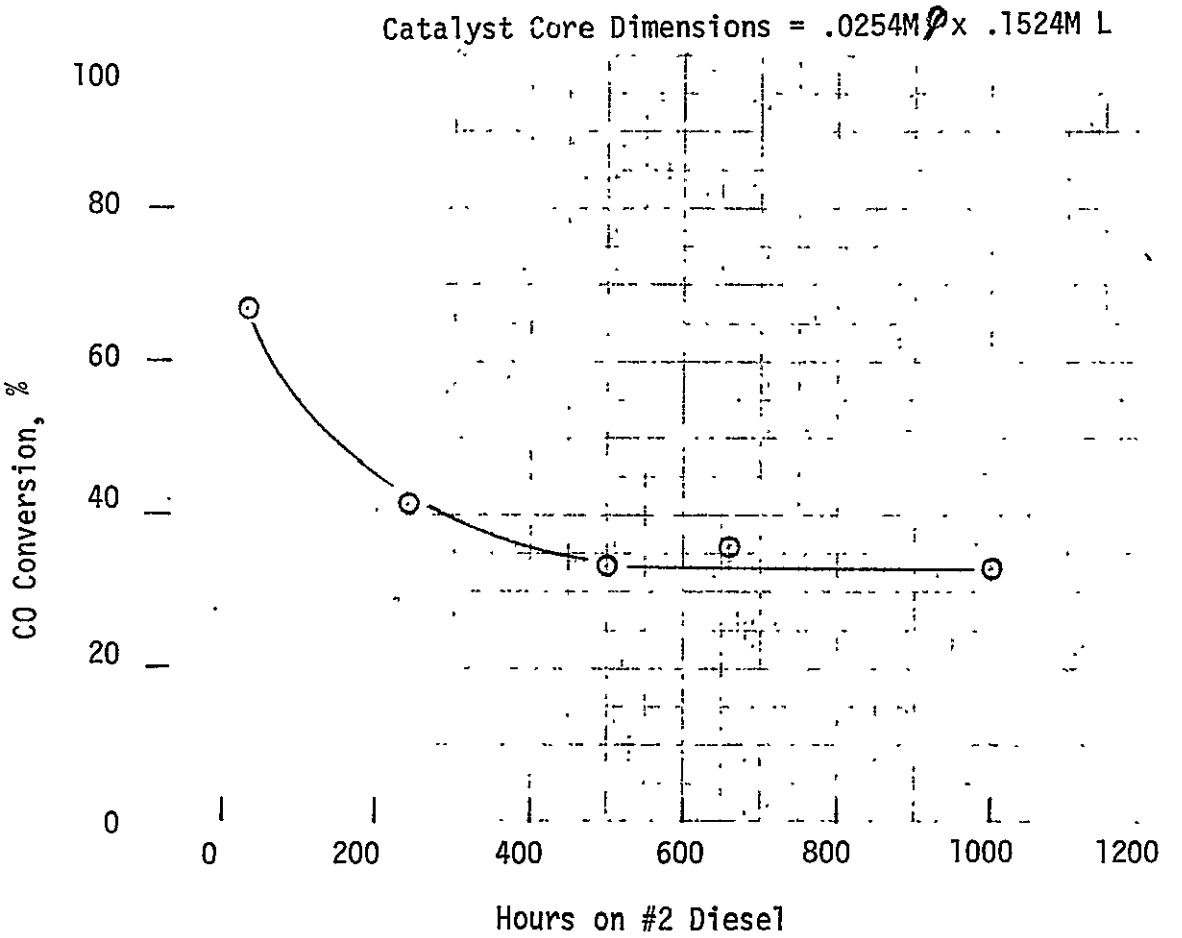
The CO activity results indicate that apparent mass transfer area appears to have stabilized on DXC-532 after 250 hours aging. However, the CO ignition temperature increases gradually during the entire 1000 hours.

c. Propane Parametric Study

The propane parametric studies conducted on catalyst core DXC-532 at the beginning of the life test provided information on the low emissions operating region of this catalyst with C. P. Propane. The final propane parametrics provided information on the effect of diesel aging time on the retention of catalytic activity for low emissions operation.

The responses of combustion efficiency from the 1/3 replicate factorial design are shown in Table V-10. Considering the

Figure V-26 Response of Mass Transfer Limited Conversion of Carbon Monoxide Conversion From Activity Tests On Catalyst Core DXC-532.



combustion efficiency responses for the initial parametrics, the initial region of low emissions operation is as follows:

Air Preheat Temperature:	$\geq$653°K
Adiabatic Operating Temperature:	$\geq$1449°K
Reference Velocity:	$\leq$30 M/S
Pressure:	$\leq 5 \times 10^5$ N/M^2

The low emissions operating region for DXC-532 with C. P. Propane is quite broad. The only regions of marginal operation are at low air preheat ($\leq$653°K) and low adiabatic flame temperature ($\leq$1449°K).

After the 1,000-hour life test, only seven parametric runs, as shown in Table V-11, were conducted on DXC-532. These runs were at operating conditions considered to have the highest probability of successful low emissions operation. The results indicated low hydrocarbon conversion for all seven experiments. Since the other 20 runs in the parametric matrix were at more stringent operating conditions, it was concluded that after 1,000 hours life testing, catalyst core DXC-532 had no acceptable region of low emissions operation for C. P. Propane, over the range of variables studied.

d. Analysis of Propane Parametrics

Detailed analysis of the initial propane parametrics on DXC-532 were conducted to determine a graphical representation and

TABLE V-11

Combustion Efficiency Response of Propane Parametrics
Before and After 1000 Hour Life Test on Catalyst Core DXB-532

Run #	Inlet Pressure (x 10^{-5}) N/M^2	Preheat Air Temperature °K	Reference Velocity M/S	Adiabatic Flame Temperature °K	Combustion Efficiency (%) Initial	Final
6-47A3	3.1	723	14.5	1477	99.89	
6-66A	3.1	723	14.5	1477		9.70
6-47B3R	5.1	653	15	1482	99.87	
6-47C3	5.1	723	14.5	1394	98.78	
6-47D3	5.1	813	22.7	1480	99.86	
6-47E3	3.1	813	30.87	1480	99.65	
6-47F3	1.2	718	14.4	1540	99.88	
6-66B	1.2	723	14.5	1545		17.73
4-134D3	3.1	658	23.8	1487	97.39	
6-55G3	3.1	723	31.3	1545	99.78	
4-135B3	3.1	653	16.17	1554	99.97	
6-66C	3.1	653	15.1	1554		4.65
4-134A3	1.3	715	21.5	1466	97.05	
6-55D3	1.2	653	21.59	1544	99.72	
6-54F3	5.1	718	30.87	1469	27.51	
6-55A3	3.1	723	22.83	1394	64.85	
6-49B3	1.2	813	14.4	1480	99.92	
6-66D	1.2	806	14.4	1473		23.82
6-49C3	3.1	808	14.33	1394	99.88	
6-49D3	5.1	808	14.52	1541	99.98	
6-66G	5.1	812	14.5	1541		11.23
6-49E3	5.1	723	22.77	1545	99.96	
6-54C3	5.1	653	32.3	1528	95.49	
6-50A3	1.2	811	30.96	1548	99.44	
6-66E	1.2	814	30.94	1551		13.11

TABLE V-11 (continued)

Combustion Efficiency Response of Propane Parametrics
Before and After 1000 Hour Life Test on Catalyst Core DXB-532

Run #	Inlet Pressure (x 10^{-5}) N/M^2	Preheat Air Temperature °K	Reference Velocity M/S	Adiabatic Flame Temperature °K	Combustion Efficiency (%) Initial	Final
6-56B3	1.2	721	22.79	1475	98.43	
4-134C3	1.2	653	13.0	1406	99.15	
6-50D3	3.1	653	32.07	1406	28.61	
6-55F3	1.2	658	33.7	1487	33.39	
6-50F3	3.1	813	22.66	1550	91.94	
6-66F	3.1	809	22.68	1546		9.33
4-134B	1.4	723	27.9	1394	37.88	
6-54A2	1.2	723	22.85	1474	99.23	
6-54D3	5.1	658	23.65	1411	40.97	
6-54E3	5.1	813	30.78	1399	37.86	
4-136A3	1.2	808	24.64	1394	93.62	

a statistical model to adequately describe the responses of combustion efficiency, CO emissions and pressure drop. The models considered in this study were multiple linear regressions of all first, second and third order variable interactions. These models were all of the following form: Combustion Efficiency = A + B (Reference Velocity) + C (Air Preheat Temperature) (Adiabatic Flame Temperature). This section contains a synopsis of the results obtained from these analyses.

1) Combustion Efficiency

Because of the usefulness of being able to predict satisfactory or unsatisfactory operation with C. P. Propane, a number of graphical techniques were tried to represent the combustion efficiency of catalyst core DXC-532. The details of the graphical approaches considered are found in Appendix D. In summary, no suitable graphical representation of the combustion efficiency response was found for DXC-532.

A stepwise multiple regression computer program was used to determine the best statistical model for C. P. Propane combustion efficiency. This program analyzes all the main effects and interactions and then presents only the most significant model as output. The most significant model consisted of interaction terms involving the main variables of reference velocity, air preheat temperature and adiabatic flame temperature. The multiple correlation

coefficient for this best model was 0.8356 but the standard error was 15.9% absolute. This indicates that a fair amount of scatter would result between predicted and actual results if this model were used as a predictive tool.

2) Carbon Monoxide Emissions

Employing a stepwise multiple regression computer routine, the best regression model consisted of interactions of the main variables of reference velocity, air preheat temperature and adiabatic flame temperature. The multiple correlation coefficient was 0.807 with a standard error of 295 vppm. This model is not a useful predictor because of the large standard error.

No satisfactory graphical presentation of the CO emissions data was found for the results on DXC-532.

3) Pressure Drop

Analysis of the pressure drop response from the propane parametrics on catalyst core DXC-532 resulted in excellent graphical representations and regression correlations for both isothermal and combustion conditions. The models that should be used for prediction of pressure drop are as follows:

Isothermal

$$\frac{\%\Delta P}{P} = \frac{0.0497V^{1.6}}{p^{0.548}}$$

Standard Error = 0.709%

Maximum Error = 1.99%

Correlation Coefficient = 0.993

Combustion

$$\frac{\%\Delta P}{P} = \frac{0.219V^{1.3}}{p^{0.77}}$$

Standard Error = 1.57%

Maximum Error = 3.16%

Correlation Coefficient = 0.9852

Where

P = Atm. (1×10^5 N/M^2)

V = M/S

The excellent agreement between predicted and experimental results is further indicated in Figure V-27.

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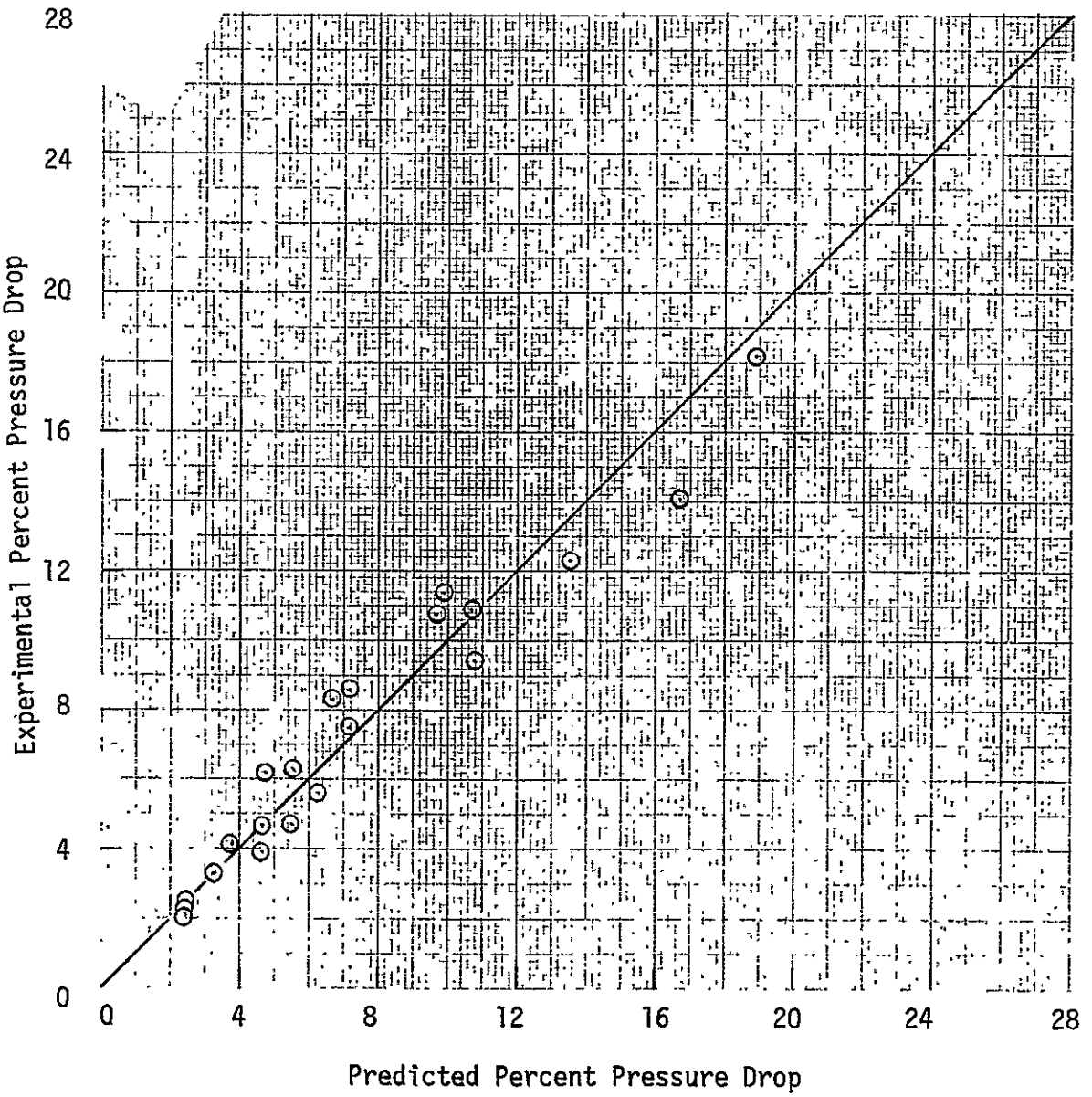
Figure V-27. Comparison of Experimental and Predicted Percent Pressure Drop of Catalyst Core DXC-532 (Combustion Condition).



VI. DISCUSSION OF TEST RESULTS AND SELECTION OF PREFERRED CATALYST CORE

In selecting the preferred catalyst core, the primary criteria were the maintenance of low emissions operation and physical durability of the catalyst core after 1,000 hours of aging with #2 diesel fuel. The secondary criteria considered, in the event the primary criteria could not detect significant differences, were the maintenance of carbon monoxide activity, the range of low emission performance on C. P. Propane and the maintenance of activity on C. P. Propane fuel.

A. LIFE TEST RESULTS

Overall, the results from the #2 diesel life test indicate that catalyst cores DXB-222 and DXC-532 are both capable of sustained operation at combustion operating temperatures. The support selected for the catalyst core appears quite durable despite operation at 1527°K.

However, there are some significant differences in the operation of the two catalyst cores to maintain this acceptable performance, as shown in Table VI-1. Catalyst core DXB-222 retains enough activity after 1,000 hours aging to attain low emissions operation at the preheat temperature of 633°K set at the start of the life test. However, the activity of DXC-532 has declined such that an air preheat temperature of 673°K is required at the end of the 1,000 hours to attain low emissions operation. Even with increased air preheat, downstream burning was still present for DXC-532 indicating incomplete combustion was occurring in the catalyst core. This increase in temperature of 40°K represents a significant decline in the activity of DXC-532 for diesel fuel.

TABLE VI-1

Comparison of Operating Conditions And
Test Responses After 1000 Hours Life Testing

	Catalyst Core	
	DXB-222	DXC-532
Operating Conditions:		
Air Preheat Temperature (°K)	628	663
Adiabatic Flame Temperature (°K)	1540	1585
Inlet Pressure (N/M^2)	1.1×10^5	1.1 x 1(
Reference Velocity (M/S)	12.9	13.8
Responses:		
Outlet Temperature (°K)		
.00635 M (1/4") Downstream	1470	1365
.03175 M (2-1/4") Downstream	1475	1450
Percent Pressure Drop (%)	8.6	7.9
Combustion Efficiency (%)	99.89	99.91
Emissions: (Nominally @ 12.5% O_2)*		
CO (Vppm)	60	42
UHC (Vppm)	1	0
NO_x (Vppm)	4.2	3.2

* Measured .1016 M (4") downstream with .00635M (1/4" φ) water cooled sampling probe.

For combustion applications with air preheat temperature considerably above 700°K, both catalyst core DXB-222 and DXC-532 possess the potential of functioning with low emissions for extended time periods. However, for air preheat temperatures between 630 and 700°K, or for transient engine conditions over a wide range of air preheat temperatures (e.g., 630 to 1000°K), only catalyst core DXB-222 appears to have suitable life characteristics.

The physical appearance of the catalyst cores and the analytical results indicated very little difference between DXB-222 and DXC-532. Unfortunately, catalyst core DXB-222 was exposed to very high temperatures during the final diesel parametrics causing some channels to collapse, probably contributing to a lower retention of BET surface area. In addition, this exposure to high temperatures could have vaporized any Pb that may have been deposited on DXB-222. Therefore, the lead deposited on DXC-532 may not be unique to this catalyst core but only indicative of a lower operating temperature. Since these analytical results are inconclusive, they were not considered further in selection of the preferred catalyst core. It should be noted that if indeed significantly more Pb was in the fuel used for the life test on DXC-532 then these aforementioned conclusions may not be completely valid.

B. PROPANE PARAMETRICS

The initial propane parametrics on both DXB-222 and DXC-532 gave essentially identical results. Both catalysts exhibited a very broad range of low emissions operation for C. P. Propane over the range of variables studies. After 1,000 hours aging, the activity towards low emissions operation declined significantly for both catalysts.

However, DXB-222 was at least active over some of the range of variables studied. Since propane fuel is a more difficult fuel to combust than #2 diesel, any decline in diesel activity would naturally reflect a significant decline in propane activity. Since DXC-532 lost some activity towards diesel fuel during life testing, it is not surprising that DXC-532 had lost its activity completely for low emissions operation with C. P. Propane.

C. CARBON MONOXIDE ACTIVITY TESTING

The CO activity tests for both DXB-222 and DXC-532 indicated very similar trends in that the most significant decrease in CO conversion occurred during the first 250 hours of life testing. The mass transfer limited CO conversion level for DXB-222 was 44% while DXC-532 lined-out at 35%.

D. DIESEL PARAMETRICS

The diesel parametrics, conducted with catalyst core DXB-222 after 1000 hours life testing, indicate that a very broad range of operation is possible with this catalyst which result in low emissions operation. The impurities in #2 diesel have not affected the performance of DXB-222.

In examining these results obtained on catalyst cores DXB-222 and DXC-532, and summarized in Table VI-2, it becomes apparent that the main difference is the loss in diesel activity that occurred on catalyst core DXC-532 during life testing. Since the life test was terminated at 1,000 hours, there is no supportive evidence that the diesel activity of catalyst core DXC-532 had indeed stabilized. Catalyst core DXB-222 had not lost any measurable activity for #2 diesel from these test results and gave very stable operation up to 1,000 hours of life testing. Based on these life test results, catalyst core DXB-222 possesses the potential for maintenance of low emission diesel operation beyond 1,000 hours over a wide range of operating conditions. Future work on extended life test and fuel durability studies, as well as scaled-up engine tests, should be conducted with catalyst core DXB-222 to obtain further data on its performance capabilities.

TABLE VI-2

Summary of Test Results on Catalyst Cores DXB-222 and DXC-532

#2 Diesel Life Test

Emissions: Same for both catalysts during the 1000 hour test.

Activity: For DXC-532, a 30-40°K higher inlet temperature was needed to initiate low emission combustion after 600 hours life testing.

Propane Parametric Studies

Initial Test: No difference.

After Aging: DXC-532 deactivated completely for high efficiency combustion. DXB-222 retained high efficiency combustion over a narrow range of operation.

CO Activity Test

1. DXB-222 retained about 44% mass transfer limited conversion while DXC-532 had 35% mass transfer limited conversion left after aging.

2. Significant deactivation of both catalyst cores apparently occurred between 24 and 250 hours of aging.

VII. CONCLUSIONS AND RECOMMENDATIONS

From the experimental test results obtained under this contract, the following conclusions were reached:

1. The two catalyst cores tested, DXB-222 and DXC-532, maintained extremely low emissions for 1,000 hours of continuous operation with #2 diesel fuel. Emissions were:

Unburned Hydrocarbons (C_3 vppm)	4
Carbon Monoxide (vppm)	50
Nitrogen Oxides (vppm)	4

2. Comparison of the steady state emissions for both catalyst cores after 1,000 hours aging were well below the 1977 and 1978 automotive standards and typically were as follows:

			Federal Standards (g/mi.)	
			1977	1978
Unburned Hydrocarbons	.04	g/mile	1.5	.41
Carbon Monoxide	.59	g/mile	15.	3.4
NO_x	.06	g/mile	2.0	.4

These emissions are calculated based on steady-state operation, assuming a fuel consumption of 10 miles/gallon.

3. Both catalyst cores can maintain their physical integrity for at least 1,000 hours of life testing at operating temperatures characteristic of catalytically-supported thermal combustion (ca. 1527°K).

4. Excellent predictive models were obtained for the pressure drop through both catalyst cores, using the propane parametric data. No simple linear models were found satisfactory for correlating combustion efficiency and emissions responses from the propane parametrics.

5. During the 1,000 hours life testing of DXB-222, no changes in operating conditions were required to maintain low emissions. The air preheat temperature had to be increased 40°K to maintain low emissions operation of DXC-532.

6. Catalyst core DXB-222 had not lost any measurable activity for #2 diesel and retained a broad range of low emissions operation with this fuel, exhibiting stable operation through 1,000 hours of testing.

7. The preferred catalyst core was selected as DXB-222 based on its broader operating range for #2 diesel fuel after 1,000 hours life testing.

8. Catalyst cores, DXB-222 and DXC-532, can operate for at least 1,000 hours under simulated steady state gas turbine operations, and yet maintain their durability and excellent low emissions performance.

9. The main difference between the two catalyst cores is the loss in diesel activity that occurred with catalyst core DXC-532 in life testing. Since the life test was terminated at 1,000 hours, there is no supportive evidence that the diesel activity of catalyst core DXC-532 had indeed stabilized.

It is recommended that additional life testing of DXB-222 be carried out at higher pressures, in order to more closely simulate gas turbine engine operating conditions. It is further recommended that a parallel effort be carried out to test DXB-222 in realistic combustion hardware.

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APPENDIX A

WORK STATEMENT

FOR TASKS I, II AND III

OF NAS3-19416

Contract NAS3-19416 EXHIBIT A

I. GENERAL REQUIREMENTS

Emission measurements shall be made of carbon monoxide (CO), carbon dioxide (CO_2), unburned hydrocarbons (HC) and oxides of nitrogen (NO_x). This shall be performed per SAE Standard ARP-1256, "Procedure for Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines". The following instrumentation and methods are required for testing of sub-scale catalytic substrates in Task III:

A. CARBON MONOXIDE AND CARBON DIOXIDE

Carbon monoxide and carbon dioxide shall be measured by the non-dispersive infrared (NDIR) method. Recommended accuracy is:

CO 0-100 ppm $\pm$ 2 percent full scale
0-500 ppm $\pm$ 1 percent full scale

CO_2 $\pm$ 1 percent full scale

B. OXIDES OF NITROGEN (NO_x)

The chemiluminescent method of optical NO detection shall be used. The instrument shall be provided with a switchable converter so that total NO and NO_2 may be measured.

C. HYDROCARBONS (HC)

Hydrocarbons shall be measured with a heated flame ionization detector (FID). Instrument and sample line temperatures shall be maintained at approximately 150°C. Accuracy shall be 1/2 ppm carbon on the 0-10 ppm scale.

II. SPECIFIC REQUIREMENTS

A. TASK I - SURVEY AND SELECTION OF CONTRACTORS' CATALYSTS AND CATALYTIC SUBSTRATES FOR PARAMETRIC AND ENDURANCE TESTING.

Within fourteen (14) days after the date of this contract, the Contractor shall review the results of his in-house screening tests performed on his catalysts and catalytic substrates. Based on the results of this review, the Contractor shall select and recommend three catalytic substrates for parametric and endurance testing in Task III. The selected items shall be the best candidates for low emission, catalytic combustion of hydrocarbon fuels at the operational conditions cited in Table I. The selected catalytic substrates shall reflect the best potential of success for a turbine engine catalytic combustor application.

In support of this selection, the Contractor shall provide to the NASA in-house screening test data, identification of the catalysts and substrates and the reasons and justification for selecting

and recommending the three catalytic substrates for parametric and endurance testing. The test data, catalyst and substrate identification and catalytic substrate identification and catalytic substrate selection shall be submitted to the NASA Contracting Officer for approval by the NASA Project Manager.

Five (5) days after this submittal, the Contractor shall present an oral discussion of the test results and recommendations to the NASA Project Manager at the Lewis Research Center. The proprietary information submitted to the Contracting Officer and presented in the oral discussion will be restricted and considered proprietary by NASA Lewis Research Center and EPA until February 1, 1977.

As a minimum, the information and recommendations submitted by the Contractor to the NASA Contracting Officer shall consider and include the following information:

1. Durability and life of the catalysts and substrate at the specified operation conditions.

2. Low emission (NO_x, CO and HC - refer to Table I) characteristics and operation at the specified operating conditions.

3. Ignition characteristics.

4. Cost of catalyst materials.

5. Availability of catalyst.

6. Compounds or elements which act as poisons to the catalysts.

7. Catalyst and substrate degradation.

8. Catalyst and substrate maximum operational temperature.

9. Developmental status.

10. Contractor's in-house screening test parameters (inlet and outlet temperature, inlet pressures, reference velocity, heat release rates, test fuels, test duration and fuel-air ratios).

11. In-house screening test results (NO_X, CO and HC emissions, combustion efficiency, ignition characteristics, $\Delta P/P$ and degradation, if any).

12. Identification of substrate materials.

13. Identification of catalyst including catalyst system constituents.

14. Differences between the screened and recommended catalytic substrates.

B. TASK II - TEST FACILITIES

Within thirty (30) days after date of this contract, the Contractor shall submit the following information to the NASA Project Manager for approval:

1. Five (5) copies of the test system layout.

2. Five (5) copies of assembly drawing, including a bill of materials and identifying and showing all instrumentation and components integral in the test system.

3. Five (5) copies of the test system schematics.

The test system layout shall include: Design pressure rating, maximum operational pressure and maximum air flow at 600, 800, and 1000°F inlet temperature and pressure of 1, 3 and 5 atmospheres.

After approval of the design drawings by the NASA Project Manager, the Contractor shall: (1) Proceed to procure and fabricate the necessary parts and items for assembly and modification of the existing test apparatus; (2) assembly the test apparatus; and, (3) perform operational check out tests.

C. TASK III - SUB-SCALE CATALYTIC SUBSTRATE PARAMETRIC AND ENDURANCE TESTING.

In this task the Contractor shall perform parametric and endurance testing with the three (3) catalytic substrates selected in Task I. Each sub-scale (1.0" O.D. nominal) candidate catalytic substrate shall be tested through a total operational test period of 1,000 hours. The objective of this task is to evaluate and establish the performance and emission characteristics of the three catalytic substrates through a range of operating conditions during the course of the parametric and endurance testing.

Within four (4) weeks after date of this contract, the Contractor shall submit three (3) copies of a test plan to the NASA Project Manager for approval. The test plan shall include:

1. Test objectives.

2. Detailed test procedures.

3. Testing sequence of the candidate catalytic substrates.

4. Schematic of test apparatus and location of installed instrumentation.

5. List of installed instrumentation.

6. Data to be recorded.

7. Test conditions.

8. Identification of the fuel(s) to be used.

9. Method of determining combustion efficiency.

10. Method of fuel-air premixing and distribution.

This submittal shall include: (1) Criteria for evaluating the performance and rating of the three candidate catalytic substrates during testing and at the end of the 1,000-hour test period; (2) criteria establishing failure or cause for rejection of the candidate catalytic substrate due to poor performance or degradation; (3) criteria for discerning and evaluating degradation of the catalyst(s) separately from that of the substrate material.

The sub-scale catalytic substrates shall be tested at steady state conditions through a total test period of 1,000 hours. The inlet operational parameters of fuel-air ratio, reference velocity, temperature and pressure are to be varied at scheduled intervals to establish emission characteristics through a broad operational range. The ignition temperature shall be determined for each catalytic substrate. An evaluation shall be made of the ignition temperature and emission characteristics of each catalytic substrate at specific check points in the test cycle to detect any rate of catalyst degradation (chemical or physical). This shall be performed at:

1. Beginning of test.

2. 250 hours of testing.

3. 500 hours of testing.

4. 750 hours of testing.

5. 1,000 hours of testing.

Each catalytic substrate shall be tested within the inlet pressure range of 1-5 atmospheres, inlet temperature range of 400-1000°F and outlet temperature range of 2000-2400°F.

For each catalyst, as a minimum, the test procedure shall include the following test points:

P_1	T_1 Inlet	T_2 Outlet
3 atm.	600°F	2000-2400°F
	1000°F	2000-2400°F
5 atm.	600°F	2000-2400°F
	1000°F	200-2400°F

Testing at each temperature shall include three different fuel-air ratios. The testing shall include a minimum average and

maximum reference velocity for each fuel-air ratio. As a part of the task, the Contractor shall measure the emissions (NO_x, CO, CO_2 and unburned hydrocarbons, inlet and outlet temperature, inlet pressure, $\Delta P/P$, fuel-air ratio, reference velocity, inlet air humidity, and auto ignition temperature. The combustion efficiency and heat release rate shall be computed for each test point. Testing can be performed with a gaseous fuel such as propane. The Contractor shall advise the NASA Project Manager of the extent to which the use of lead-free gasoline and JP-5 would affect the ranking of the catalyst. The Contractor shall promptly notify the NASA Project Manager if accidental damage of a catalytic substrate occurred or if poor performance, degradation, or failure is detected during the testing of any of the three candidate catalytic substrates.

The decision to continue testing of the affected test item will be made by the NASA Project Manager after a review of test data, condition of the catalytic substrate and recommendation by the Contractor.

Upon completion of the testing in this task, the Contractor shall review and evaluate the test results and examine the catalytic substrates for chemical and/or physical degradation. The Contractor shall submit three (3) copies of all test data and results, conclusions and recommendations to the NASA Project Manager for review and approval. Plots shall be provided for each catalytic substrate showing:

1. Effect of fuel-air ratio on combustion efficiency and emissions.

2. Effect of reference velocity on combustion efficiency and emissions.

3. Effect of inlet temperature and pressure on combustion efficiency and emissions.

4. Optimum low emission operating band.

APPENDIX B

COMPUTER PRINTOUTS

OF #2 DIESEL LIFE TESTS

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RUN IDENTIFICATION LIFE TEST FOR ENGELHARD CATALYST CORE DXB-222

LOGBOOK UNIT NO 6 BOOK 1 PP. 14-28 FUEL TYPE #2 DIESEL FUEL

	CATALYST	ID.	DIMENSION DIA. X LEN. CM	EQUIVALENT DIA. CM	HYDRAULIC DIA. CM	PERCENT OPEN AREA	SPACING
1	DXB-222	4039S 20	2.5 BY 7.6	2.29	0.09754	65.5	******
2	DXB-222	4039S 21	2.5 BY 7.6	2.29	0.09754	65.5	.635

	RUN #	HOURS ON FUEL	FUEL/AIR RATIO	INLET P ATM	PRESSURE DROP %	INLET T C	OUTLET T C	MAX. T C	MAX. T LOCATION INCHES	REF. VELOCITY INLET FACE M/SEC
1	6-33A	24.0	0.0000000	1.0374	3.6454	365.0	305.0	305.0	0.250	13.003
2	6-33A	64.0	0.0207060	1.1068	9.0206	300.0	1205.0	1205.0	0.250	12.700
3	6-35	254.0	0.0202754	1.0918	8.3804	300.0	1165.0	1165.0	0.250	12.873
4	6-37	518.0	0.0200172	1.0802	7.3926	365.0	1150.0	1150.0	0.250	13.113
5	6-39	751.0	0.0205338	1.0932	8.5226	360.0	1090.0	1115.0	2.250	12.857
6	6-39	970.0	0.0205338	1.0333	3.2558	355.0	360.0	360.0	0.250	13.495
7	6-39	998.0	0.0201893	1.0932	8.5226	355.0	1190.0	1190.0	0.250	12.755

RUN IDENTIFICATION LIFE TEST FOR ENGELHARD CATALYST CORE DXB-222

LOGBOOK UNIT NO 6 BOOK 1 PP. 14-28 FUEL TYPE #2 DIESEL FUEL

	CATALYST	ID.	DIMENSION DIA. X LEN. CM	EQUIVALENT DIA. CM	HYDRAULIC DIA. CM	PERCENT OPEN AREA	SPACING
1	DXB-222	40395 20	2.5 BY 7.6	2.29	0.09754	65.5	******
2	DXB-222	40395 21	2.5 BY 7.6	2.29	0.09754	65.5	.035

RUN #		HOURS ON FUEL	REYNOLDS # CHANNEL INLET	COMBUSTION EFFICIENCY %	HEAT RELEASE RATE KCAL/HR CM3 ATM	PERCENT ADIABATICITY %	EXHAUST GASES HC PPM	CO PPM	NOX PPM	CO2 %	O2 %
1	0-35A	24.0	370.072	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
2	0-35A	64.0	382.664	99.87	45.09	92.62	8.0	48.0		5.8	12.5
3	0-35	254.0	382.504	99.92	44.99	89.45	6.0	24.0	4.1	5.5	12.4
4	0-37	518.0	330.309	99.93	45.03	88.07	0.0	36.0	2.9	5.4	12.4
5	0-39	751.0	382.598	99.88	45.36	83.21	1.0	61.0	3.7	5.5	12.5
6	0-39	970.0	334.734	0.00	43.05	0.	0.0	0.0	0.0	0.0	0.0
7	0-39	998.0	384.605	99.89	44.76	93.03	0.0	60.0	3.8	5.6	12.5

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RUN IDENTIFICATION LIFE TEST FOR ENGELHARD CATALYST CORE DXC-532

LOGBOOK UNIT NO 6 BOOK 5 PP. 7-25 FUEL TYPE #2 DIESEL FUEL

	CATALYST	ID.	DIMENSION DIA. X LEN. CM	EQUIVALENT DIA. CM	HYDRAULIC DIA. CM	PERCENT OPEN AREA	SPACING
1	DXC-532	4051F 5	2.5 BY 7.0	2.20	0.09754	65.5	******
2	DXC-532	4051F 9	2.5 BY 7.0	2.20	0.09754	65.5	.035

	RUN #	HOURS ON FUEL	REYNOLDS # CHANNEL INLET	COMBUSTION EFFICIENCY %	HEAT RELEASE RATE KCAL/HR CM3 ATM	PERCENT ADIABATICITY %	EXHAUST GASES HC PPM	CO PPM	NOx PPM	CO2 %	O2 %
1	6-57A	24.0	384.004	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
2	6-57A	27.0	394.734	99.89	45.65	87.84	3.0	49.0	4.0	5.5	12.4
3	6-60B	324.0	396.969	99.81	46.59	80.58	2.5	95.0	3.0	5.5	12.9
4	6-60B	485.0	402.037	99.89	47.27	81.71	0.0	61.0	0.0	5.4	12.7
5	6-64	755.0	398.473	99.87	48.41	80.84	0.5	72.0	2.8	5.4	12.5
6	6-64	847.0	380.043	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
7	6-64	904.0	392.121	99.93	47.77	84.17	0.0	38.0	3.2	5.0	12.3

APPENDIX C

COMPUTER PRINTOUTS OF PROPANE PARAMETRICS

RUN IDENTIFICATION PROPANE PARAMETRIC STUDIES FOR DXB-222 (PART I) - MC 11/10/75

LOGBOOK UNIT NO. 5 BOOK 3 PP. 2,3,4 FUEL TYPE PROPANE

	CATALYST	ID.	DIMENSION DIA. X LEN. CM	EQUIVALENT DIA. CM	HYDRAULIC DIA. CM	PERCENT OPEN AREA	SPACING
1	DXB-222	4039S 16	2.5 BY 7.6	2.46	0.09754	65.5	******
2	DXB-222	4039S 17	2.5 BY 7.6	2.46	0.09754	65.5	.635

	RUN #	HOURS ON FUEL	FUEL/AIR RATIO	INLET P ATM	PRESSURE DROP %	INLET T C	OUTLET T C	MAX. T C	MAX. T LOCATION INCHES	REF. VELOCITY INLET FACE M/SEC
1	5-109A1	25.8	0.0000000	1.1973	9.3489	450.0	450.0	450.0	0.250	27.883
2	5-109A	25.8	0.0185213	1.3741	20.5979	450.0	1065.0	1080.0	1.125	24.591
3	5-109B1	25.8	0.0000000	1.1973	6.0487	448.0	448.0	448.0	0.250	20.396
4	5-109B	25.8	0.0209177	1.2789	13.7985	448.0	1138.0	1138.0	0.250	19.357
5	5-109C1	25.8	0.0000000	1.2041	10.7605	360.0	360.0	360.0	0.250	30.270
6	5-109C	25.8	0.0225194	1.2381	21.6992	375.0	790.0	790.0	0.250	30.583
7	5-109D1	25.8	0.0000000	1.1973	6.7993	365.0	365.0	365.0	0.250	22.500
8	5-109D	25.8	0.0249274	1.3469	15.0962	365.0	1220.0	1220.0	0.250	20.329
9	5-109E1	25.8	0.0000000	1.1973	3.7001	365.0	360.0	360.0	0.250	14.319
10	5-109E	25.8	0.0209174	1.2739	8.5793	365.0	1040.0	1060.0	1.125	13.589
11	5-109F1	25.8	0.0000000	1.1973	3.3801	445.0	434.0	434.0	0.250	12.897
12	5-109F	25.8	0.0230000	1.2041	8.2600	445.0	1208.0	1208.0	0.250	13.019
13	5-110A1	25.8	0.0000000	1.1973	3.5791	535.0	535.0	535.0	0.250	12.914
14	5-110A	25.8	0.0185211	1.2041	8.9596	535.0	1160.0	1160.0	0.250	12.998
15	5-110B1	25.8	0.0000000	1.1973	6.1739	530.0	530.0	530.0	0.250	20.178
16	5-110B	25.8	0.0162916	1.2041	14.2992	530.0	1000.0	1020.0	1.125	20.279
17	5-110C1	25.8	0.0000000	1.1973	9.3202	535.0	535.0	535.0	0.250	27.695
18	5-110C	25.8	0.0208375	1.3469	20.6934	535.0	1215.0	1215.0	0.250	24.956

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RUN IDENTIFICATION PROPANE PARAMETRIC STUDIES FOR DXB-222 (PART I) MC 11/10/75

LOGBOOK . UNIT NO 5 . BOOK . 3 . PP. 2,3,4 . . . FUEL TYPE . . PROPANE

	CATALYST	ID.	DIMENSION DIA. X.LEN. CM	EQUIVALENT DIA. CM	HYDRAULIC DIA. CM	PERCENT OPEN AREA	SPACING
1	DXB-222	40398 16	2.5 BY 7.6	2.46	0.09754	65.5	******
2	DXB-222	40398 17	2.5 BY 7.6	2.46	0.09754	65.5	.635

RUN #		HOURS ON FUEL	REYNOLDS # CHANNEL INLET	COMBUSTION EFFICIENCY %	HEAT RELEASE RATE KCAL/HR CM3 ATM	PERCENT ADIABATICITY %	EXHAUST GASES HC PPM	CO PPM	NOx PPM	CO2 %	O2 %
1	5-109A1	25.8	708.969	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.1
2	5-109A	25.8	722.102	97.57	56.16	93.56	6.0	839.0	0.3	3.9	15.0
3	5-109B1	25.8	521.031	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.1
4	5-109B	25.8	531.922	99.89	51.17	89.79	1.0	42.0	0.3	4.4	13.0
5	5-109C1	25.8	970.234	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.1
6	5-109C	25.8	975.937	49.65	48.08	99.97	7150.0	76.0	0.0	2.0	17.0
7	5-109D1	25.8	707.594	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.5
8	5-109D	25.8	725.242	99.94	72.22	93.49	6.0	10.0	0.3	4.0	12.0
9	5-109E1	25.8	450.293	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.5
10	5-109E	25.8	459.707	99.67	40.51	88.68	1.0	120.0	0.0	4.4	12.9
11	5-109F1	25.8	331.824	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.5
12	5-109F	25.8	339.457	99.89	37.95	91.27	4.0	36.0	0.0	4.6	12.0
13	5-110A1	25.8	271.824	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.9
14	5-110A	25.8	276.855	99.91	27.20	92.91	0.0	30.0	0.4	4.0	14.6
15	5-110B1	25.8	429.234	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.9
16	5-110B	25.8	436.230	94.95	35.75	86.08	73.0	1348.0	0.3	3.3	15.5
17	5-110C1	25.8	582.938	0.00	0.00	0.00	0.0	0.0	0.0	0.0	21.0
18	5-110C	25.8	595.086	99.86	58.63	90.92	4.0	43.0	0.2	4.0	14.0

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RUN IDENTIFICATION PROPANE PARAMEIRIC STUDIES FOR DXB-222 (PART II)

LOGBOOK UNIT NO 6 BOOK 1 PP. 11,12 FUEL TYPE PROPANE

	CATALYST	ID.	DIMENSION DIA. X LEN. CM	EQUIVALENT DIA. CM	HYDRAULIC DIA. CM	PERCENT OPEN AREA	SPACING
1	DXB-222	40395 16	2.5 BY 7.6	2.46	0.09754	65.5	******
2	DXB-222	40395 17	2.5 BY 7.6	2.46	0.09754	65.5	.035

	RUN #	HOURS ON FUEL	FUEL/AIR RATIO	INLET P ATM	PRESSURE DROP %	INLET T C	OUTLET T C	MAX. T C	MAX. T LOCATION INCHES	REF. VELOCITY INLET FACE M/SEC
1	6-20A1	25.8	0.0000000	3.0067	1.8597	461.0	461.0	461.0	0.250	13.132
2	6-20A	25.8	0.0205176	3.0339	3.9102	461.0	1203.0	1203.0	0.250	13.190
3	6-20B1	25.8	0.0000000	4.9999	1.5501	350.0	350.0	350.0	0.250	12.773
4	6-20B3	25.8	0.0000000	4.9999	1.5692	380.0	380.0	380.0	0.250	13.388
5	6-20C1	25.8	0.0000000	4.9999	1.4499	445.0	445.0	445.0	0.250	12.881
6	6-20C	25.8	0.0185211	4.9999	2.6601	445.0	940.0	1100.0	2.250	13.038
7	6-20D1	25.8	0.0000000	4.9999	2.8501	535.0	535.0	535.0	0.250	20.260
8	6-20D	25.8	0.0187607	4.9999	4.8998	535.0	1025.0	1200.0	2.250	20.510
9	6-20E1	25.8	0.0000000	2.9999	5.7800	530.0	530.0	530.0	0.250	27.453
10	6-20E	25.8	0.0187607	2.9999	10.3993	530.0	1065.0	1220.0	2.250	27.773
11	6-27A1	25.8	0.0000000	2.9999	3.6902	365.0	365.0	365.0	0.250	20.553
12	6-27A	25.8	0.0230803	2.9999	6.7001	365.0	970.0	1220.0	2.250	20.865
13	6-27B1	25.8	0.0000000	3.0067	5.9899	438.0	438.0	438.0	0.250	27.270
14	6-27B	25.8	0.0221183	2.9999	10.3199	438.0	998.0	1240.0	2.250	27.731
15	6-28A1	25.8	0.0000000	2.9999	3.7000	450.0	450.0	450.0	0.250	20.379
16	6-28A	25.8	0.0185211	2.9999	6.9801	450.0	925.0	1125.0	2.250	20.628
17	6-27F1	25.8	0.0000000	4.9999	4.8997	445.0	440.0	440.0	0.250	27.501
18	6-27F	25.8	0.0209177	4.9999	7.3000	445.0	680.0	695.0	2.250	27.119

RUN IDENTIFICATION PROPANE PARAMETRIC STUDIES FOR DXB-222 (PART II)

LOGBOOK UNIT NO 6 BOOK 1 PP. 11,12

FUEL TYPE PROPANE

	CATALYST	ID.	DIMENSION DIA. X LEN. CM	EQUIVALENT DIA. CM	HYDRAULIC DIA. CM	PERCENT OPEN AREA	SPACING
1	DXB-222	40395 16	2.5 BY 7.0	2.40	0.09754	65.5	******
2	DXB-222	40395 17	2.5 BY 7.0	2.40	0.09754	65.5	.635

	RUN #	HOURS ON FUEL	REYNOLDS # CHANNEL INLET	COMBUSTION EFFICIENCY %	HEAT RELEASE RATE KCAL/HR CM3 ATM	PERCENT ADIABATICITY %	EXHAUST GASES HC PPM	CO PPM	NOX PPM	CO2 %	O2 %
1	6-26A1	25.3	817.289	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.2
2	6-26A	25.8	834.055	99.96	33.63	98.49	0.0	14.0	0.0	4.5	14.0
3	6-26B1	25.3	1740.734	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.5
4	6-26B3	25.8	1690.183	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.5
5	6-26C1	25.3	1383.922	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.9
6	6-26C	25.8	1409.531	98.32	30.21	96.40	2.0	585.0	0.1	3.6	13.0
7	6-26D1	25.3	1780.875	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.1
8	6-26D	25.8	1814.281	99.93	43.48	97.69	1.0	21.0	0.0	4.0	15.0
9	6-26E1	25.8	1403.260	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.1
10	6-26E	25.8	1490.719	99.86	59.23	101.29	1.0	48.0	0.0	4.0	15.1
11	6-27A1	25.8	1619.531	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.1
12	6-27A	25.8	1656.891	99.88	68.68	99.97	0.0	53.0	0.0	5.0	13.1
13	6-27B1	25.8	1791.531	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.1
14	6-27B	25.8	1831.141	99.81	78.49	99.18	0.2	78.0	0.0	5.0	13.1
15	6-28A1	25.8	1298.344	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.4
16	6-28A	25.8	1322.391	99.61	48.09	98.19	0.0	137.0	0.0	4.0	15.0
17	6-27F1	25.8	2965.500	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.4
18	6-27F	25.8	2934.156	47.03	33.89	69.05	7000.0	57.0	0.0	1.9	19.3

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RUN IDENTIFICATION PROPANE PARAMETRIC STUDIES FOR DXB-222 (PART III) MC 11/6/75-11/11/75

LOGBOOK UNIT NO 5 , BOOK 3 PR. 5,6 - FUEL TYPE - PROPANE

	CATALYST	ID.	DIMENSION DIA. X. LEN. CM	EQUIVALENT DIA. CM	HYDRAULIC DIA. CM	PERCENT OPEN AREA	SPACING
1	DXB-222	4039S 20	2.5 BY 7.6	2.29	0.09754	65.5	******
2	DXB-222	4039S 21	2.5 BY 7.6	2.29	0.09754	65.5	.635

	RUN #	HOURS ON FUEL	FUEL/AIR RATIO	INLET P. ATM	PRESSURE DROP %	INLET T C	OUTLET T C	MAX. T C	MAX. T LOCATION INCHES	REF. VELOCITY INLET FACE M/SEC
1	5-112A1	25.0	0.0000000	1.1973	6.3789	435.0	435.0	435.0	0.250	21.326
2	5-112A	25.0	0.0209179	1.2108	15.1093	435.0	1145.0	1150.0	1.125	21.377
3	5-112B1	25.0	0.0000000	2.9999	1.8827	530.0	530.0	530.0	0.250	13.073
4	5-112B	25.0	0.0149409	2.9999	3.4913	530.0	1100.0	1100.0	0.250	13.202
5	5-112C1	25.0	0.0000000	2.9999	3.2146	530.0	530.0	530.0	0.250	20.243
6	5-112C	25.0	0.0195589	3.0135	6.5427	530.0	1228.0	1232.0	1.125	20.411
7	5-112D1	25.0	0.0000000	4.9999	1.3963	536.0	536.0	536.0	0.250	12.972
8	5-112D	25.0	0.0205178	5.0135	2.7190	536.0	1255.0	1255.0	0.250	13.111

RUN IDENTIFICATION PROPANE PARAMETRIC STUDIES FOR DXB-222 (PART III) MC 11/6/75-11/11/75

LOGBOOK . . UNIT NO 5 BOOK 3 PP. 5,6 FUEL TYPE PROPANE

	CATALYST	ID.	DIMENSION DIA. X LEN. CM	EQUIVALENT DIA. CM	HYDRAULIC DIA. CM	PERCENT OPEN AREA	SPACING
1	DXB-222	4039S 20	2.5 BY 7.6	2.29	0.09754	65.5	******
2	DXB-222	4039S 21	2.5 BY 7.6	2.29	0.09754	65.5	.635

	RUN #	HOURS ON FUEL	REYNOLDS # CHANNEL INLET	COMBUSTION EFFICIENCY %	HEAT RELEASE RATE KCAL/HR-CM3-ATM	PERCENT ADIABATICITY %	EXHAUST GASES HC PPM	CO PPM	NOx PPM	CO2 %	O2 %
1	5-112A1	25.0	561.898	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.3
2	5-112A	25.0	573.048	99.76	57.48	92.84	4.0	83.0	0.0	4.5	13.7
3	5-112B1	25.0	696.805	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.1
4	5-112B	25.0	707.211	99.93	22.48	103.12	2.0	15.0	0.0	3.5	15.0
5	5-112C1	25.0	1078.984	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.3
6	5-112C	25.0	1100.078	99.96	45.38	99.13	1.0	12.0	0.5	4.2	13.4
7	5-112D1	25.0	1137.828	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.5
8	5-112D	25.0	1161.172	99.96	30.33	97.41	3.0	5.0	0.0	4.1	14.1

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RUN IDENTIFICATION PROPANE PARAMETRIC STUDIES FOR DXB-222 (PART IV) NC 11/13/75-11/14/75

LOGBOOK UNIT NO 6 BOOK 1 PP. 14,15 FUEL TYPE PROPANE

	CATALYST	ID.	DIMENSION DIA. X LEN. CM	EQUIVALENT DIA. CM	HYDRAULIC DIA. CM	PERCENT OPEN AREA	SPACING
1	DXB-222	40395 20	2.5 BY 7.0	2.29	0.09754	65.5	******
2	DXB-222	40395 21	2.5 BY 7.0	2.29	0.09754	65.5	.635

	RUN #	HOURS ON FUEL	FUEL/AIR RATIO	INLET P ATM	PRESSURE DROP %	INLET T C	OUTLET T C	MAX. T C	MAX. T LOCATION INCHES	REF. VELOCITY INLET FACE M/SEC
1	6-31A1	25.0	0.0000000	1.1973	6.3872	455.0	455.0	455.0	0.250	21.928
2	6-31A	25.0	0.0209179	1.1973	15.5518	455.0	1165.0	1165.0	0.250	22.230
3	6-31B1	25.0	0.0000000	4.9999	3.4999	460.0	460.0	460.0	0.250	22.431
4	6-31B	25.0	0.0221186	4.3333	5.8315	460.0	1015.0	1240.0	2.250	26.260
5	6-31C1	25.0	0.0000000	2.9999	6.9826	360.0	360.0	360.0	0.250	30.193
6	6-31C	25.0	0.0201182	2.9932	10.6985	360.0	673.0	693.0	2.250	30.062
7	6-31D1	25.0	0.0000000	4.9999	3.6242	380.0	380.0	380.0	0.250	22.855
8	6-31D	25.0	0.0205176	5.0135	5.4997	380.0	665.0	695.0	2.250	23.102
9	6-31E1	25.0	0.0000000	4.9999	5.1866	535.0	535.0	535.0	0.250	29.968
10	6-31E	25.0	0.0157349	5.0135	6.8976	535.0	920.0	1090.0	2.250	30.196
11	6-31F1	25.0	0.0000000	4.9863	7.1018	392.0	392.0	392.0	0.250	31.808
12	6-31F	25.0	0.0229199	5.0067	11.4889	392.0	927.0	1219.0	2.250	32.157
13	4-92E	25.0	0.0000000	2.9999	2.2838	370.0	370.0	370.0	0.250	14.250
14	4-92E1	25.0	0.0238831	2.9999	4.9663	370.0	1252.0	1252.0	0.250	14.475

RUN IDENTIFICATION PROPANE PARAMETRIC STUDIES FOR DXB-222 (PART IV) MC 11/13/75-11/14/75

LOGBOOK UNIT NO 6 BOOK 1 PP. 14,15 FUEL TYPE PROPANE

	CATALYST	ID.	DIMENSION DIA. X LEN. CM.	EQUIVALENT DIA. CM.	HYDRAULIC DIA. CM	PERCENT OPEN AREA	SPACING
1	DXB-222	40395 20	2.5 BY 7.6	2.29	0.09754	65.5	******
2	DXB-222	40395 21	2.5 BY 7.6	2.29	0.09754	65.5	.635

RUN #	HOURS ON FULL	REYNOLDS # CHANNEL INLET	COMBUSTION EFFICIENCY %	HEAT RELEASE RATE KCAL/HR CM3 ATM	PERCENT ADIABATICITY %	EXHAUST GASES HC PPM	CO PPM	NOx PPM	CO2 %	O2 %
1	6-31A1	25.0	551.063	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.5
2	6-31A	25.0	562.536	99.74	58.12	92.70	0.0	102.0	0.0	4.3	14.0
3	6-31B1	25.0	2326.875	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.5
4	6-31B	25.0	2378.344	99.96	72.20	96.86	0.0	15.0	0.0	4.7	13.4
5	6-31C1	25.0	2411.156	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.5
6	6-31C	25.0	2459.656	44.19	39.30	99.02	7100.0	47.0	0.5	2.0	16.4
7	6-31D1	25.0	2885.406	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.5
8	6-31D	25.0	2944.625	38.29	25.36	106.83	8000.0	67.0	1.0	2.0	17.5
9	6-31E1	25.0	2634.183	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.4
10	6-31E	25.0	2675.656	99.23	53.41	96.51	4.0	220.0	0.0	2.9	16.0
11	6-31F1	25.0	3832.656	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.4
12	6-31F	25.0	3971.594	99.83	100.80	97.98	4.0	62.0	0.3	4.9	13.1
13	4-92E	25.0	1103.094	0.00	0.00	0.00	0.0	0.0	0.0	0.0	20.3
14	4-92E1	25.0	1134.547	99.94	48.92	100.19	7.5	5.5	0.4	4.3	13.2

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RUN IDENTIFICATION--NASA PROPANE PARAMETRIC STUDY FOR DXB-222 AFTER 1000 HOUR AGING MC 3/2/76

LOGBOOK UNIT NO 6 BOOK 1 PP. 30-37 FUEL TYPE PROPANE

	CATALYST	ID.	DIMENSION DIA. X LEN. CM	EQUIVALENT DIA. CM	HYDRAULIC DIA. CM	PERCENT OPEN AREA	SPACING
1	DXB-222	4039 S20	2.5 BY 7.6	2.27	0.09754	65.5	******
2	DXB-222	4039 S21	2.5 BY 7.6	2.27	0.09754	65.5	.635

	RUN #	HOURS ON FUEL	FUEL/AIR RATIO	INLET P ATM	PRESSURE DROP %	INLET T C	OUTLET T C	MAX. T C	MAX. T LOCATION INCHES	REF. VELOCITY INLET FACE M/SEC
1	6-41A1	1000.0	0.0000000	2.9999	1.8131	460.0	460.0	460.0	0.250	14.490
2	6-41A3	1000.0	0.0221186	2.9727	2.9102	460.0	955.0	1190.0	2.250	14.835
3	6-41B1	1000.0	0.0000000	4.9454	1.5472	380.0	380.0	380.0	0.250	14.965
4	6-41B2	1000.0	0.0230803	4.9454	1.5472	380.0	380.0	380.0	0.250	15.193
5	6-41C1	1000.0	0.0000000	4.9454	1.3099	450.0	450.0	450.0	0.250	14.450
6	6-41C3	1000.0	0.0189199	4.9794	1.5436	450.0	568.0	612.0	2.250	14.530
7	6-41D1	1000.0	0.0000000	4.9999	2.6620	535.0	535.0	535.0	0.250	22.361
8	6-41D3	1000.0	0.0187607	4.9999	0.0000	535.0	895.0	1150.0	2.250	22.638
9	6-41E1	1000.0	0.0000000	2.9999	6.8892	535.0	535.0	535.0	0.250	30.525
10	6-41E3	1000.0	0.0187609	2.9999	8.4396	535.0	945.0	1185.0	2.250	30.902
11	6-41F1	1000.0	0.0000000	1.1973	3.8766	435.0	435.0	435.0	0.250	14.028
12	6-41F3	1000.0	0.0230806	1.1973	9.6731	435.0	1145.0	1145.0	0.250	14.241
13	6-42A1	1000.0	0.0000000	2.9999	3.7712	380.0	380.0	380.0	0.250	23.236
14	6-42A2	1000.0	0.0230803	3.0135	5.0237	380.0	590.0	625.0	2.250	23.483
15	6-42B1	1000.0	0.0000000	2.9999	7.1978	450.0	450.0	450.0	0.250	30.649
16	6-42B3	1000.0	0.0230803	2.9999	9.8804	450.0	650.0	680.0	2.250	31.115
17	6-42C1	1000.0	0.0000000	2.9999	2.2838	360.0	360.0	360.0	0.250	14.321
18	6-42C3	1000.0	0.0253298	2.9999	0.0000	360.0	985.0	1240.0	2.250	14.560
19	6-42D1	1000.0	0.0000000	1.2041	6.7712	450.0	450.0	450.0	0.250	22.434
20	6-42D3	1000.0	0.0209177	1.2041	10.6462	450.0	710.0	730.0	2.250	22.742
21	6-42E1	1000.0	0.0000000	1.1973	7.7817	380.0	380.0	380.0	0.250	25.408
22	6-42E3	1000.0	0.0253296	1.1973	11.2051	380.0	630.0	660.0	2.250	25.833
23	6-42F1	1000.0	0.0000000	4.9999	6.2274	450.0	450.0	450.0	0.250	30.681
24	6-42F3	1000.0	0.0209177	4.9999	7.7656	450.0	580.0	610.0	2.250	31.104
25	6-43A1	1000.0	0.0000000	2.9999	4.4039	450.0	450.0	450.0	0.250	22.550
26	6-43A3	1000.0	0.0185213	2.9999	5.5500	450.0	590.0	610.0	2.250	22.325
27	6-43B1	1000.0	0.0000000	1.1973	4.0940	535.0	535.0	535.0	0.250	14.230
28	6-43B3	1000.0	0.0188403	1.1973	8.3583	535.0	1050.0	1050.0	0.250	14.407
29	6-43C1	1000.0	0.0000000	2.9999	2.1669	535.0	535.0	535.0	0.250	14.215
30	6-43C3	1000.0	0.0162914	2.9999	3.7361	535.0	865.0	1005.0	2.250	14.368

RUN IDENTIFICATION NASA PROPANE PARAMETRIC STUDY FOR DXB-222 AFTER 1000 HOUR AGING MC 3/2/76

LOGBOOK UNIT NO 6 BOOK 1 PP. 30-37 FUEL TYPE PROPANE

	CATALYST	ID.	DIMENSION DIA. X LEN. CM	EQUIVALENT DIA. CM	HYDRAULIC DIA. CM	PERCENT OPEN AREA	SPACING
1	DXB-222	4039 S20	2.5 BY 7.6	2.27	0.09754	65.5	******
2	DXB-222	4039 S21	2.5 BY 7.6	2.27	0.09754	65.5	.635

RUN #	HOURS ON FUEL	REYNOLDS # CHANNEL INLET	COMBUSTION EFFICIENCY %	HEAT RELEASE RATE KCAL/HR CM3 ATM	PERCENT ADIABATICITY %	EXHAUST GASES HC PPM	CO PPM	NOx PPM	CO2 %	O2 %
1	6-41A1	1000.0	901.820	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
2	6-41A3	1000.0	921.766	98.67	40.26	91.84	42.0	432.0	1.3	4.5	12.8
3	6-41B1	1000.0	1868.056	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
4	6-41B2	1000.0	1911.781	0.00	0.00		14600.0	0.0	0.0	0.0	20.0
5	6-41C1	1000.0	1517.594	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
6	6-41C3	1000.0	1546.297	18.65	6.48		9750.0	37.0	1.3	0.7	19.4
7	6-41D1	1000.0	1965.594	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
8	6-41D3	1000.0	2002.469	84.31	40.48		1000.0	2600.0	1.3	3.3	14.1
9	6-41E1	1000.0	1609.906	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
10	6-41E3	1000.0	1640.109	91.51	59.98		460.0	1650.0	1.3	3.7	14.4
11	6-41F1	1000.0	369.602	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
12	6-41F3	1000.0	378.129	99.70	42.16	84.62	35.0	28.0	1.3	4.5	13.0
13	6-42A1	1000.0	1760.047	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
14	6-42A2	1000.0	1800.656	24.54	18.55		11000.0	51.0	1.3	1.2	18.7
15	6-42B1	1000.0	1952.625	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
16	6-42B3	1000.0	1997.688	24.47	22.14		11000.0	81.0	1.3	1.3	18.4
17	6-42C1	1000.0	1143.672	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
18	6-42C3	1000.0	1172.641	99.58	52.77	95.13	3.0	191.0	1.3	5.2	12.4
19	6-42D1	1000.0	573.641	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
20	6-42D3	1000.0	585.641	37.58	22.56	96.91	8250.0	63.0	1.3	1.4	18.1
21	6-42E1	1000.0	768.117	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
22	6-42E3	1000.0	787.563	31.12	28.37	97.30	11000.0	60.0	1.3	1.3	18.2
23	6-42F1	1000.0	3257.750	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
24	6-42F3	1000.0	3325.875	16.87	13.85		11000.0	44.0	1.3	0.9	18.5
25	6-43A1	1000.0	1436.625	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
26	6-43A3	1000.0	1463.234	16.91	9.03		9750.0	40.0	1.3	0.8	18.8
27	6-43B1	1000.0	299.523	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
28	6-43B3	1000.0	305.160	99.61	30.57	75.60	34.0	36.0	1.3	3.7	14.6
29	6-43C1	1000.0	749.734	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
30	6-43C3	1000.0	761.953	88.65	23.50	83.58	800.0	1125.0	1.3	3.2	15.8

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RUN IDENTIFICATION NASA PROPANE PARAMETRIC STUDY FOR DXB-222 AFTER 1000 HOUR AGING (PART II) MC

LOGBOOK UNIT NO 6 BOOK 1 PP. 30-37 FUEL TYPE PROPANE

	CATALYST	ID.	DIMENSION DIA. X LEN. CM	EQUIVALENT DIA. CM	HYDRAULIC DIA. CM	PERCENT OPEN AREA	SPACING
1	DXB-222	4039 S20	2.5 BY 7.6	2.27	0.09754	65.5	******
2	DXB-222	4039 S21	2.5 BY 7.6	2.27	0.09754	65.5	.635

	RUN #	HOURS ON FUEL	FUEL/AIR RATIO	INLET P ATM	PRESSURE DROP %	INLET T C	OUTLET T C	MAX. T C	MAX. T LOCATION INCHES	REF. VELOCITY INLET FACE M/SEC
1	6-43D1	1000.0	0.0000000	4.9999	1.6748	535.0	535.0	535.0	0.250	14.269
2	6-43D3	1000.0	0.0221183	4.9999	2.6797	535.0	1215.0	1252.0	2.250	14.477
3	6-43E1	1000.0	0.0000000	4.9999	2.7951	455.0	455.0	455.0	0.250	22.642
4	6-43E3	1000.0	0.0229197	4.9999	3.3098	455.0	600.0	620.0	2.250	22.984
5	6-43F1	1000.0	0.0000000	4.9794	7.0788	385.0	385.0	385.0	0.250	32.042
6	6-43F3	1000.0	0.0253296	4.9999	10.1178	385.0	600.0	610.0	2.250	32.445
7	6-44A1	1000.0	0.0000000	1.1973	11.0349	535.0	535.0	535.0	0.250	30.550
8	6-44A4	1000.0	0.0225191	1.1973	22.0698	535.0	1210.0	1210.0	0.250	31.003
9	6-44B1	1000.0	0.0000000	1.1973	6.8097	450.0	450.0	450.0	0.250	22.561
10	6-44B3	1000.0	0.0209177	1.1973	10.6677	450.0	770.0	770.0	0.250	22.872
11	6-44C1	1000.0	0.0000000	1.1973	4.5494	380.0	380.0	380.0	0.250	16.172
12	6-44C3	1000.0	0.0206776	1.1973	6.9123	380.0	650.0	650.0	0.250	16.393
13	6-44D1	1000.0	0.0000000	2.9999	7.9755	380.0	380.0	380.0	0.250	31.641
14	6-44D3	1000.0	0.0206778	2.9999	10.0604	380.0	530.0	535.0	2.250	32.072
15	6-44E1	1000.0	0.0000000	1.1973	13.2686	380.0	380.0	380.0	0.250	34.501
16	6-44E3	1000.0	0.0230806	1.1973	17.8652	380.0	575.0	575.0	0.250	35.026
17	6-44F1	1000.0	0.0000000	2.9999	4.2321	535.0	535.0	535.0	0.250	22.361
18	6-44F3	1000.0	0.0209177	2.9999	5.6425	535.0	1020.0	1210.0	2.250	22.669
19	6-45A1	1000.0	0.0000000	1.1973	11.0535	450.0	450.0	450.0	0.250	30.639
20	6-45A3	1000.0	0.0185213	1.1973	14.8541	450.0	638.0	638.0	0.250	31.013
21	6-45B1	1000.0	0.0000000	1.1973	6.8097	450.0	450.0	450.0	0.250	22.561
22	6-45B3	1000.0	0.0209177	1.1973	10.1241	450.0	760.0	760.0	0.250	22.872
23	6-45C1	1000.0	0.0000000	4.9999	3.9262	405.0	405.0	405.0	0.250	24.125
24	6-45C3	1000.0	0.0206776	4.9999	4.1262	405.0	405.0	405.0	0.250	24.454
25	6-45D1	1000.0	0.0000000	4.9999	5.7794	535.0	535.0	535.0	0.250	30.454
26	6-45D3	1000.0	0.0162914	4.9999	6.6306	535.0	650.0	650.0	0.250	30.781
27	6-45E1	1000.0	0.0000000	1.1973	7.2712	535.0	535.0	535.0	0.250	22.412
28	6-45E3	1000.0	0.0162916	1.1973	10.8463	535.0	920.0	985.0	2.250	22.653

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RUN IDENTIFICATION NASA PROPANE PARAMETRIC STUDY FOR DXB-222 AFTER 1000 HOUR AGING (PART II) MC

LOGBOOK UNIT NO 6 BOOK 1 PP. 30-37 FUEL TYPE PROPANE

	CATALYST	ID.	DIMENSION DIA. X LEN. CM	EQUIVALENT DIA. CM	HYDRAULIC DIA. CM	PERCENT OPEN AREA	SPACING
1	DXB-222	4039 S20	2.5 BY 7.6	2.27	0.09754	65.5	******
2	DXB-222	4039 S21	2.5 BY 7.6	2.27	0.09754	65.5	.635

RUN #		HOURS ON FUEL	REYNOLDS # CHANNEL INLET	COMBUSTION EFFICIENCY %	HEAT RELEASE RATE KCAL/HR CM3 ATM	PERCENT ADIABATICITY %	EXHAUST GASES HC PPM	CO PPM	NOx PPM	CO2 %	O2 %
1	6-43D1	1000.0	1254.250	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
2	6-43D3	1000.0	1281.969	99.95	36.10	90.80	4.0	9.0	1.3	4.3	13.9
3	6-43E1	1000.0	2376.156	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
4	6-43E3	1000.0	2430.594	13.69	9.03		12500.0	43.0	1.3	1.0	18.1
5	6-43F1	1000.0	3976.813	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
6	6-43F3	1000.0	4077.500	21.77	24.73		12500.0	49.0	1.3	0.7	18.7
7	6-44A1	1000.0	643.023	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
8	6-44A4	1000.0	657.516	99.61	78.43	84.41	20.0	107.0	1.3	4.5	12.7
9	6-44B1	1000.0	573.641	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
10	6-44B3	1000.0	585.641	35.96	21.71		8450.0	105.0	1.3	1.5	17.6
11	6-44C1	1000.0	488.895	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
12	6-44C3	1000.0	499.000	31.17	14.76		9000.0	50.0	1.3	1.3	18.1
13	6-44D1	1000.0	2396.688	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
14	6-44D3	1000.0	2446.250	12.14	11.25		11500.0	30.0	1.3	0.7	19.0
15	6-44E1	1000.0	1042.984	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
16	6-44E3	1000.0	1067.062	21.14	23.84		11500.0	40.0	1.3	0.9	18.9
17	6-44F1	1000.0	1179.359	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
18	6-44F3	1000.0	1204.031	99.81	53.44	89.98	14.0	32.0	1.3	4.6	14.1
19	6-45A1	1000.0	779.023	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
20	6-45A3	1000.0	793.438	23.26	16.89		9000.0	50.0	1.3	0.9	18.6
21	6-45B1	1000.0	573.641	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
22	6-45B3	1000.0	585.641	35.58	21.48		8500.0	105.0	1.3	1.4	18.0
23	6-45C1	1000.0	2857.313	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
24	6-45C3	1000.0	2916.313	0.00	0.00		13100.0	0.0	0.0	0.0	20.0
25	6-45D1	1000.0	2676.938	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
26	6-45D3	1000.0	2720.531	17.74	10.07		8500.0	43.0	1.3	0.6	19.8
27	6-45E1	1000.0	471.746	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
28	6-45E3	1000.0	479.426	82.45	34.46	91.19	600.0	3650.0	1.3	2.6	15.7

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RUN IDENTIFICATION: PROPANE PARAMATRIC STUDY FOR DXC-532 (PART I) -MC- 4/20/76

LOGBOOK UNIT NO 0 BOOK 1 PP 40-46 FUEL TYPE PROPANE

	CATALYST	ID.	DIMENSION DIA. X LEN. CM	EQUIVALENT DIA. CM	HYDRAULIC DIA. CM	PERCENT OPEN AREA	SPACING
1	DXC-532	4051 F3	2.5 BY 7.6	2.25	0.09754	65.5	******
2	DXC-532	4051 F8	2.5 BY 7.6	2.25	0.09754	65.5	.635

RUN #		HOURS ON FUEL	FUEL/AIR RATIO	INLET P ATM	PRESSURE DROP %	INLET T C	OUTLET T C	MAX. T C	MAX. T LOCATION INCHES	REF. VELOCITY INLET FACE M/SEC
1	0-47A1	24.0	0.0000000	2.9999	1.6634	450.0	450.0	450.0	0.250	14.288
2	0-47A3	24.0	0.0209978	2.9999	3.2719	450.0	1070.0	1190.0	2.250	14.486
3	0-47B1R	24.0	0.0000000	4.9794	1.5037	378.0	378.0	378.0	0.250	14.835
4	0-47B3R	24.0	0.0230806	4.9999	2.5623	378.0	1005.0	1205.0	2.250	15.000
5	0-47C1	24.0	0.0000000	4.9454	1.3794	450.0	450.0	450.0	0.250	14.429
6	0-47C3	24.0	0.0185213	4.9794	2.0713	450.0	930.0	1090.0	2.250	14.506
7	0-47D1	24.0	0.0000000	4.9794	2.7400	535.0	535.0	535.0	0.250	22.454
8	0-47D3	24.0	0.0187607	4.9794	3.9428	535.0	1040.0	1180.0	2.250	22.732
9	6-47E1	24.0	0.0000000	3.0067		535.0	535.0	535.0	0.250	30.492
10	0-47E3	24.0	0.0187604	3.0067		535.0	1045.0	1205.0	2.250	30.869
11	0-47F1	24.0	0.0000000	1.1973		445.0	445.0	445.0	0.250	14.214
12	0-47F3	24.0	0.0230803	1.1973	6.2559	445.0	1165.0	1165.0	0.250	14.430
13	0-49B1	24.0	0.0000000	1.1973		535.0	535.0	535.0	0.250	14.228
14	0-49B3	24.0	0.0188403	1.1973	4.6868	535.0	1060.0	1060.0	0.250	14.405
15	0-49C1	24.0	0.0000000	3.0067	1.8948	535.0	535.0	535.0	0.250	14.182
16	0-49C3	24.0	0.0162914	3.0067		535.0	925.0	1050.0	2.250	14.334
17	0-49D1	24.0	0.0000000	5.0135	1.4136	535.0	535.0	535.0	0.250	14.229
18	0-49D3	24.0	0.0209973	4.9794	2.2187	535.0	1158.0	1243.0	2.250	14.525
19	0-49E1	24.0	0.0000000	4.9999		450.0	450.0	450.0	0.250	22.486
20	0-49E3	24.0	0.0230806	5.0135	4.6126	450.0	1032.0	1218.0	2.250	22.766
21	0-50A1	24.0	0.0000000	1.1973	10.2821	535.0	535.0	535.0	0.250	30.540
22	0-50A3	24.0	0.0209177	1.1973	14.0337	535.0	1030.0	1180.0	2.250	30.961
23	0-50B1	24.0	0.0000000	2.9999		380.0	380.0	380.0	0.250	31.642
24	0-50B3	24.0	0.0206778	2.9999		380.0	590.0	590.0	0.250	32.074
25	0-50F1	24.0	0.0000000	2.9999	3.2719	535.0	535.0	535.0	0.250	22.351
26	0-50F3	24.0	0.0209177	2.9999		535.0	1035.0	1215.0	2.250	22.660

RUN IDENTIFICATION - PROPANE PARAMETRIC STUDY FOR DXC-532 (PART I) -MC- 4/20/76

LOGBOOK - UNIT NO 6 BOOK 1 PP. 40-46 FUEL TYPE PROPANE

	CATALYST	ID.	DIMENSION DIA. X LEN. CM	EQUIVALENT DIA. CM	HYDRAULIC DIA. CM	PERCENT OPEN AREA	SPACING
1	DXC-532	4051 F3	2.5 BY 7.6	2.25	0.09754	65.5	******
2	DXC-532	4051 F8	2.5 BY 7.6	2.25	0.09754	65.5	.635

	RUN #	HOURS ON FUEL	REYNOLDS # CHANNEL INLET	COMBUSTION EFFICIENCY %	HEAT RELEASE RATE KCAL/HR CM3 ATM	PERCENT ADIABATICITY %	EXHAUST GASES HC PPM	CO PPM	NOx PPM	CO2 %	O2 %
1	6-47A1	24.0	910.312	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
2	6-47A3	24.0	929.414	99.89	38.33	96.02	11.0	11.0	2.0	4.7	13.6
3	6-47B1R	24.0	1074.934	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
4	6-47B3R	24.0	1918.219	99.87	48.38	97.01	7.0	35.0	1.4	4.8	13.2
5	6-47C1	24.0	1515.469	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
6	6-47C3	24.0	1543.531	98.78	33.54	93.89	27.0	350.0	1.5	4.0	14.4
7	6-47D1	24.0	1965.703	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
8	6-47D3	24.0	2002.578	99.86	48.15	94.82	3.0	40.0	1.6	4.0	14.4
9	6-47E1	24.0	1611.844	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
10	6-47E3	24.0	1642.063	99.65	65.25	98.71	1.0	122.0	2.7	4.1	14.0
11	6-47F1	24.0	365.687	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
12	6-47F3	24.0	374.125	99.88	42.21	85.87	11.0	17.0	1.8	4.7	12.6
13	6-49B1	24.0	299.480	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
14	6-49B3	24.0	305.117	99.92	30.66		5.0	12.0	2.6	3.7	14.3
15	6-49C1	24.0	749.641	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
16	6-49C3	24.0	761.859	99.88	26.41	86.15	1.0	35.0	3.1	3.5	15.6
17	6-49D1	24.0	1254.138	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
18	6-49D3	24.0	1230.500	99.98	34.43	93.90	2.0	0.0	2.2	4.5	14.0
19	6-49E1	24.0	2387.656	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
20	6-49E3	24.0	2442.750	99.96	66.18	91.04	2.0	12.0	2.2	5.1	13.4
21	6-50A1	24.0	642.828	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
22	6-50A3	24.0	656.273	99.44	72.71	86.31	8.0	200.0	2.4	4.3	13.6
23	6-50D1	24.0	2396.813	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
24	6-50D3	24.0	2446.344	28.01	26.51	94.66	9340.0	35.0	3.1	1.0	19.0
25	6-50F1	24.0	1178.844	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
26	6-50F3	24.0	1203.500	99.94	53.48	90.53	0.0	23.0	2.6	4.3	14.0

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RUN IDENTIFICATION PROPANE PARAMETRIC STUDY FOR DXC-532 (PART II) -IC- 4/21/76

LOGBOOK — UNIT NO 4 BOOK 4 PP. 14-17 FUEL TYPE PROPANE

	CATALYST	ID.	DIMENSION DIA. X LEN. CM	EQUIVALENT DIA. CM	HYDRAULIC DIA. CM	PERCENT OPEN AREA	SPACING
1	DXC-532	4051 F5	2.5 BY 7.6	2.25	0.09754	65.5	******
2	DXC-532	4051 F9	2.5 BY 7.6	2.25	0.09754	65.5	.035

	RUN #	HOURS ON FUEL	FUEL/AIR RATIO	INLET P ATM	PRESSURE DROP %	INLET T C	OUTLET T C	MAX. T C	MAX. T LOCATION INCHES	REF. VELOCITY INLET FACE M/SEC
1	4-134A1	24.0	0.0000000	1.1973	6.3646	442.0	442.0	442.0	0.250	22.294
2	4-134A3	24.0	0.0209179	1.2585	10.7869	442.0	1098.0	1120.0	2.120	21.502
3	4-134B1	24.0	0.0000000	1.2721	9.2855	450.0	450.0	450.0	0.250	28.849
4	4-134B3	24.0	0.0185211	1.3333	12.2278	450.0	767.0	770.0	2.120	27.801
5	4-134C1	24.0	0.0000000	1.1973	3.1588	380.0	380.0	380.0	0.250	12.817
6	4-134C1	24.0	0.0206771	1.1973	6.2538	380.0	1060.0	1060.0	0.250	12.992
7	4-134D1	24.0	0.0000000	2.9999	4.5472	385.0	385.0	385.0	0.250	23.416
8	4-134D3	24.0	0.0230963	2.9999	8.2637	385.0	1062.0	1177.0	2.120	23.772
9	4-135B1	24.0	0.0000000	2.9999	1.8295	380.0	380.0	380.0	0.250	15.901
10	4-135B3	24.0	0.0253296	2.9999	4.1043	380.0	1180.0	1235.0	2.120	16.167
11	4-136A1	24.0	0.0000000	1.1973		535.0	535.0	535.0	0.250	24.514
12	4-136A3	24.0	0.0162914	1.2041		535.0	1000.0	1010.0	2.120	24.636

RUN IDENTIFICATION: PROPANE PARAMETRIC STUDY FOR DXC-532 (PART II) -MC- 4/21/76

LOGBOOK UNIT NO 4 BOOK 4 PP. 14-17 FUEL TYPE PROPANE

	CATALYST	ID.	DIMENSION DIA. X LEN. CM	EQUIVALENT DIA. CM	HYDRAULIC DIA. CM	PERCENT OPEN AREA	SPACING
1	DXC-532	4051 F5	2.5 BY 7.0	2.25	0.09754	65.5	******
2	DXC-532	4051 F9	2.5 BY 7.0	2.25	0.09754	65.5	.635

	RUN #	HOURS ON FUEL	REYNOLDS # CHANNEL INLET	COMBUSTION EFFICIENCY %	HEAT RELEASE RATE KCAL/HR CM3 ATM	PERCENT ADIABATICITY %	EXHAUST GASES HC PPM	CO PPM	NOx PPM	CO2 %	O2 %
1	4-134A1	24.0	577.672	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
2	4-134A3	24.0	589.750	97.05	55.69	90.66	5.0	1157.0	3.4	4.2	13.9
3	4-134B1	24.0	779.383	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
4	4-134B3	24.0	793.613	37.88	24.70		7275.0	73.0	2.0	1.6	18.1
5	4-134C1	24.0	387.477	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
6	4-134C1	24.0	395.480	99.15	37.21	88.46	5.0	320.0	1.9	4.3	13.8
7	4-134D1	24.0	1750.875	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
8	4-134D3	24.0	1791.281	97.39	74.03	95.39	55.0	980.0	2.0	4.9	13.0
9	4-135B1	24.0	1204.484	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
10	4-135B3	24.0	1234.984	99.97	57.02	92.51	1.0	13.0	2.2	5.5	12.1
11	4-136A1	24.0	515.984	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
12	4-136A3	24.0	524.391	99.62	45.28		4.0	106.0	1.0	3.5	15.2

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RUN IDENTIFICATION PROPANE PARAMETRIC STUDY FOR DXC-532 (PARTIII) -MC- 4/21/76

LOGBOOK UNIT NO 6 BOOK 5 PP. 2-5 FUEL TYPE PROPANE

	CATALYST	ID.	DIMENSION DIA. X LEN. CM	EQUIVALENT DIA. CM	HYDRAULIC DIA. CM	PERCENT OPEN AREA	SPACING
1	DXC-532	4051 F5	2.5 BY 7.6	2.25	0.09754	65.5	******
2	DXC-532	4051 F9	2.5 BY 7.6	2.25	0.09754	65.5	.635

	RUN #	HOURS ON FUEL	FUEL/AIR RATIO	INLET P ATM	PRESSURE DROP %	INLET T C	OUTLET T C	MAX. T C	MAX. T LOCATION INCHES	REF. VELOCITY INLET FACE M/SEC
1	6-54A1	24.0	0.0000000	1.1973	6.0303	450.0	450.0	450.0	0.250	22.543
2	6-54A2	24.0	0.0209179	1.1973	9.4495	450.0	915.0	1060.0	2.250	22.854
3	6-54C1	24.0	0.0000000	4.9794		380.0	380.0	380.0	0.250	31.786
4	6-54C3	24.0	0.0245256	4.9794		380.0	935.0	1165.0	2.250	32.301
5	6-54D1	24.0	0.0000000	4.9794		380.0	380.0	380.0	0.250	23.333
6	6-54D3	24.0	0.0206773	4.9794		380.0	760.0	760.0	0.250	23.652
7	6-54E1	24.0	0.0000000	4.9999	5.9577	535.0	535.0	535.0	0.250	30.457
8	6-54E3	24.0	0.0162914	4.9999	7.5201	535.0	715.0	715.0	0.250	30.784
9	6-54F1	24.0	0.0000000	4.9999	6.8860	445.0	445.0	445.0	0.250	30.469
10	6-54F3	24.0	0.0199580	4.9999	8.6182	445.0	650.0	650.0	0.250	30.870
11	6-55A1	24.0	0.0000000	2.9999	4.1035	450.0	450.0	450.0	0.250	22.557
12	6-55A3	24.0	0.0185213	2.9999	5.5909	450.0	815.0	865.0	2.250	22.832
13	6-55C1	24.0	0.0000000	2.9999	7.0430	450.0	450.0	450.0	0.250	30.648
14	6-55C3	24.0	0.0230806	2.9999	11.4241	450.0	1035.0	1215.0	2.250	31.115
15	6-55D1	24.0	0.0000000	1.1973	5.9749	380.0	380.0	380.0	0.250	21.240
16	6-55D3	24.0	0.0253298	1.1973		380.0	1165.0	1180.0	2.250	21.595
17	6-55F1	24.0	0.0000000	1.1973	11.2565	385.0	385.0	385.0	0.250	33.211
18	6-55F3	24.0	0.0230806	1.1973	18.2034	385.0	675.0	680.0	2.250	33.717
19	6-56B1	24.0	0.0000000	1.1973	6.6147	448.0	448.0	448.0	0.250	22.481
20	6-56B3	24.0	0.0209179	1.1973	10.8668	448.0	930.0	1070.0	2.250	22.791

RUN IDENTIFICATION PROPANE PARAMETRIC STUDY FOR DXC-532 (PARTIII) -MC- 4/21/76

LOGBOOK UNIT NO 6 BOOK 5 PP. 2-5 FUEL TYPE PROPANE

	CATALYST	ID.	DIMENSION DIA. X LEN. CM	EQUIVALENT DIA. CM	HYDRAULIC DIA. CM.	PERCENT OPEN AREA	SPACING
1	DXC-532	4051 F5	2.5 BY 7.6	2.25	0.09754	65.5	******
2	DXC-532	4051 F9	2.5 BY 7.6	2.25	0.09754	65.5	.635

	RUN #	HOURS ON FUEL	REYNOLDS # CHANNEL INLET	COMBUSTION EFFICIENCY %	HEAT RELEASE RATE KCAL/HR CM3 ATM	PERCENT ADIABATICITY %	EXHAUST GASES HC PPM	CO PPM	NOx PPM	CO2 %	O2 %
1	6-54A1	24.0	573.203	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
2	6-54A2	24.0	585.180	99.23	59.86	79.95	0.0	305.0	2.3	4.2	13.6
3	6-54C1	24.0	3996.531	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
4	6-54C3	24.0	4094.469	95.49	105.43	91.42	145.0	1660.0	4.0	4.2	13.5
5	6-54D1	24.0	2933.719	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
6	6-54D3	24.0	2994.406	40.97	27.99		7700.0	100.0	2.0	1.6	18.3
7	6-54E1	24.0	2677.156	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
8	6-54E3	24.0	2720.781	37.86	21.50	79.43	6400.0	93.0	3.2	0.0	19.2
9	6-54F1	24.0	3273.594	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
10	6-54F3	24.0	3338.906	27.51	21.55	100.89	9150.0	60.0	4.0	1.0	18.3
11	6-55A1	24.0	1437.125	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
12	6-55A3	24.0	1463.734	64.85	34.66	92.73	3250.0	2640.0	2.0	2.5	16.7
13	6-55C1	24.0	1952.578	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
14	6-55C3	24.0	1997.641	99.78	90.28	91.45	6.0	80.0	4.0	4.7	13.5
15	6-55D1	24.0	642.094	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
16	6-55D3	24.0	658.359	99.72	75.98	86.77	9.0	105.0	2.5	5.1	12.5
17	6-55F1	24.0	991.047	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
18	6-55F3	24.0	1013.906	33.39	35.97	103.69	9700.0	75.0	4.0	1.6	17.5
19	6-56B1	24.0	574.297	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
20	6-56B3	24.0	580.305	98.43	59.37	82.14	5.0	610.0	2.2	4.2	13.9

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RUN IDENTIFICATION PROPANE PARAMETRIC STUDIES FOR DXC-532 AFTER 1000 HOUR AGING -MC- 6/14/76

LOGBOOK UNIT NO 6 BOOK 5 PP. 28,29,30 FUEL TYPE PROPANE

	CATALYST	ID.	DIMENSION DIA. X LEN. CM	EQUIVALENT DIA. CM	HYDRAULIC DIA. CM	PERCENT OPEN AREA	SPACING
1	DXC-532	4051 F9	2.5 BY 7.6	2.24	0.09754	65.5	******
2	DXC-532	4051 F5	2.5 BY 7.6	2.24	0.09754	65.5	.635

	RUN #	HOURS ON FUEL	FUEL/AIR RATIO	INLET P ATM	PRESSURE DROP %	INLET T C	OUTLET T C	MAX. T C	MAX. T LOCATION INCHES	REF. VELOCITY INLET FACE M/SEC.
1	6-66A1	1005.0	0.0000000	2.9727	1.7240	450.0	450.0	450.0	0.250	14.478
2	6-66A3	1005.0	0.0209978	3.0067	1.9258	450.0	508.0	508.0	0.250	14.512
3	6-66B1	1005.0	0.0000000	1.1700	3.5890	450.0	450.0	450.0	0.250	14.697
4	6-66B3	1005.0	0.0230806	1.2041	4.1912	450.0	560.0	560.0	0.250	14.499
5	6-66C1	1005.0	0.0000000	3.0067	1.8131	380.0	380.0	380.0	0.250	14.822
6	6-66C3	1005.0	0.0253296	3.0067	2.0214	380.0	405.0	410.0	2.250	15.069
7	6-66D1	1005.0	0.0000000	1.1973	3.4807	535.0	535.0	535.0	0.250	14.273
8	6-66D3	1005.0	0.0187607	1.2041	4.0729	535.0	620.0	620.0	0.250	14.367
9	6-66E1	1005.0	0.0000000	1.1973	9.4495	535.0	535.0	535.0	0.250	30.643
10	6-66E3	1005.0	0.0209174	1.2041	10.5015	535.0	630.0	650.0	2.250	30.936
11	6-66F1	1005.0	0.0000000	3.0067	3.2318	535.0	535.0	535.0	0.250	22.370
12	6-66F3	1005.0	0.0209177	3.0067	3.6965	535.0	598.0	618.0	2.250	22.678
13	6-66G1	1005.0	0.0000000	5.0135	1.3274	535.0	535.0	535.0	0.250	14.265
14	6-66G3	1005.0	0.0209174	4.9999	1.4376	535.0	605.0	615.0	2.250	14.502

RUN IDENTIFICATION PROPANE PARAMETRIC STUDIES FOR DXC-532 AFTER 1000 HOUR AGING -MC- 6/14/76

LOGBOOK UNIT NO 6 BOOK 5 PP: 28,29,30 FUEL TYPE PROPANE

	CATALYST	ID.	DIMENSION DIA. X LEN. CM	EQUIVALENT DIA. CM	HYDRAULIC DIA. CM	PERCENT OPEN AREA	SPACING
1	DXC-532	4051 F9	2.5 BY 7.6	2.24	0.09754	65.5	******
2	DXC-532	4051 F5	2.5 BY 7.6	2.24	0.09754	65.5	.635

	RUN #	HOURS ON FUEL	REYNOLDS # CHANNEL INLET	COMBUSTION EFFICIENCY %	HEAT RELEASE RATE KCAL/HR CM3 ATM	PERCENT ADIABATICITY %	EXHAUST GASES HC PPM	CO PPM	NOx PPM	CO2 %	O2 %
1	6-66A1	1005.0	914.016	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
2	6-66A3	1005.0	933.195	9.70	3.73		12000.0	30.0	1.5	0.4	20.0
3	6-66B1	1005.0	365.191	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
4	6-66B3	1005.0	373.621	17.73	7.48		12000.0	34.3	1.5	0.7	18.7
5	6-66C1	1005.0	1125.250	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
6	6-66C3	1005.0	1153.766	4.65	2.47		15250.0	19.3	1.1	0.2	20.1
7	6-66D1	1005.0	300.430	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
8	6-66D3	1005.0	306.066	23.82	7.26		9050.0	46.4	2.0	0.6	19.5
9	6-66E1	1005.0	645.000	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
10	6-66E3	1005.0	659.484	13.11	9.58		11500.0	39.5	1.6	0.5	19.4
11	6-66F1	1005.0	1182.531	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
12	6-66F3	1005.0	1207.250	9.33	5.00		12000.0	40.6	2.1	0.4	20.0
13	6-66G1	1005.0	1257.391	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
14	6-66G3	1005.0	1283.672	11.23	3.85	94.76	11750.0	34.7	2.5	0.3	19.9

APPENDIX D

DETAILS OF GRAPHICAL ANALYSIS OF PROPANE PARAMETRIC DATA FOR DXB-222 AND DXC-532

In the analysis of the results from the propane parametrics on catalyst cores DXB-222 and DXC-532, an extensive attempt was made to obtain a suitable graphical representation of the propane combustion efficiency as a function of the four main control variables (i.e., air preheat temperature, operating pressure, reference velocity and adiabatic flame temperature). The standard graphical techniques considering first, second and third order interactions were unsuccessful. However, a plotting routine considering average responses proved to be quite successful. For the sake of completeness in this report, the graphical analysis for the propane combustion efficiency on catalyst core DXB-222 is presented. Similar analyses were made with the data on combustion efficiency of DXC-532 and only the plots of average responses clearly represented the data.

A. FIRST ORDER INTERACTIONS

The initial analysis involved plotting the propane combustion efficiency from the initial parametrics on catalyst core DXB-222 as a function of the main control variables. Figures D-1, D-2, D-3 and D-4 indicate that no satisfactory presentation of the data is possible based on the first order interactions.

B. HIGH ORDER INTERACTIONS

Since a first order or non-interacting combination of variables proved unsuccessful, a number of second and third order combinations of variables were tried with varying degrees of success.

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Figure D-1 Combustion Efficiency Versus Air Preheat Temperature For Catalyst Core DXB-222 (Initial Propane Parametric).

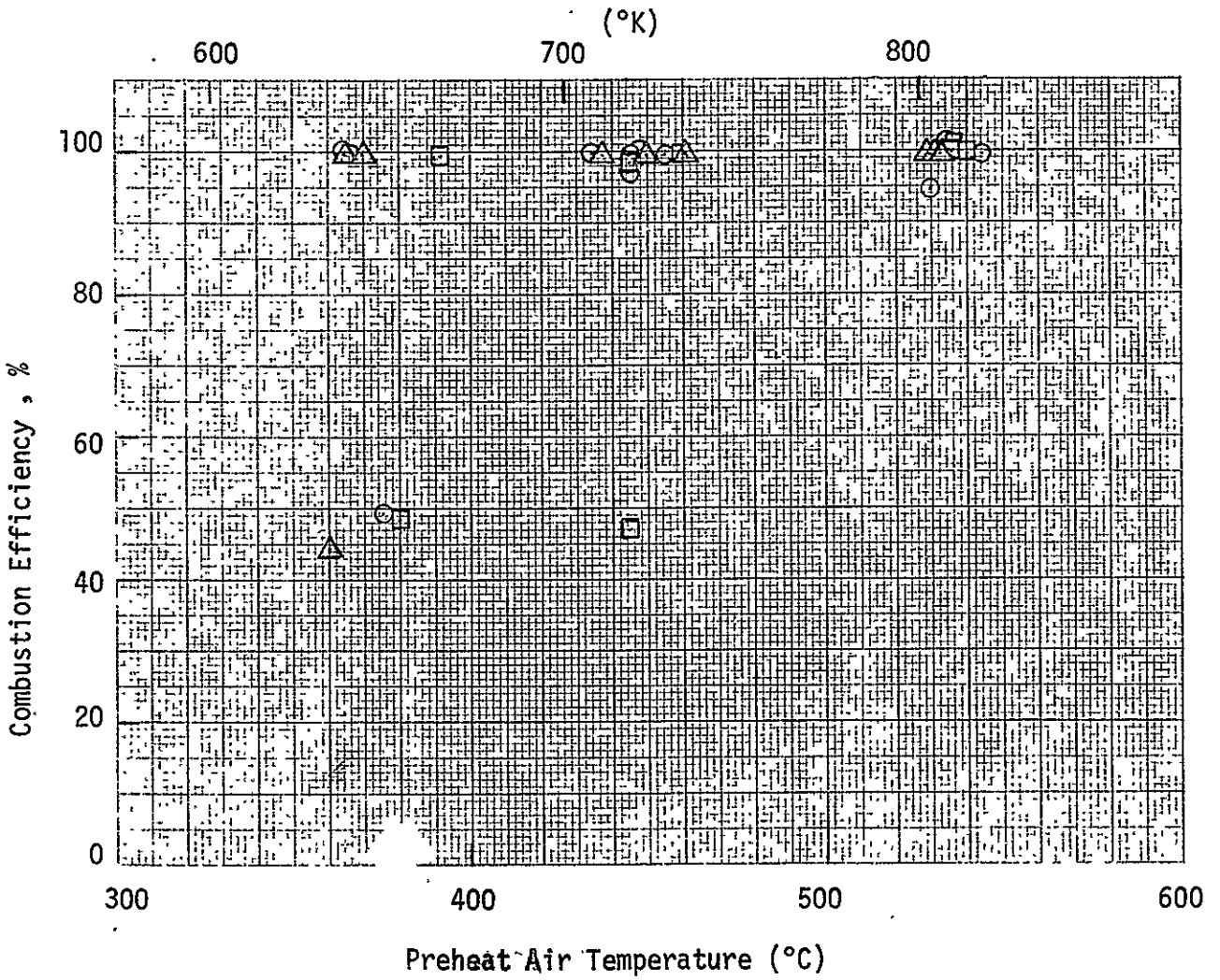

Figure D-2 Combustion Efficiency Versus Reference Velocity for Catalyst Core DXB-222 (Initial Propane Parametric).

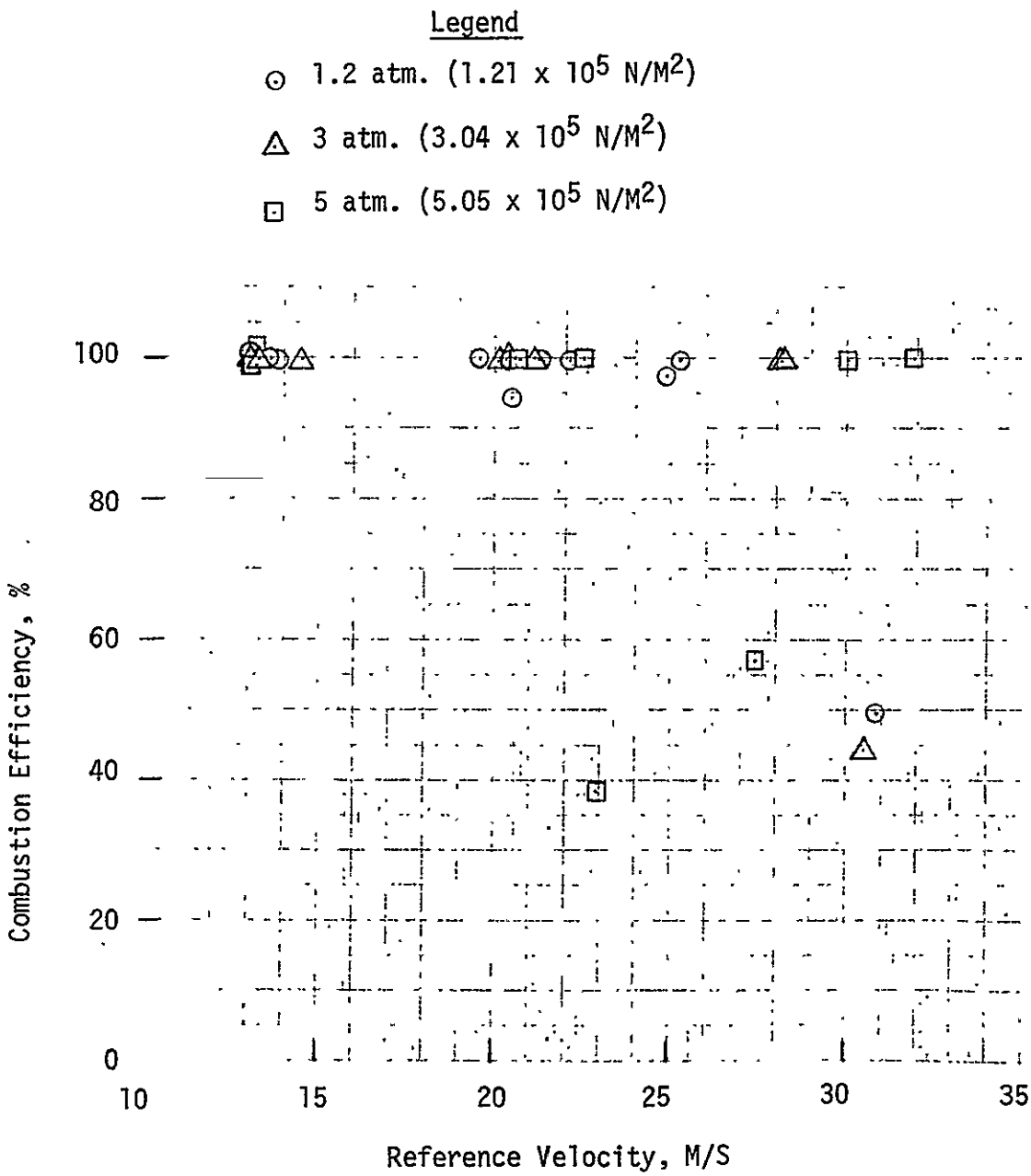

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Figure D-3 Combustion Efficiency Versus Operating Pressure For Catalyst Core DXB-222 (Initial Propane Parametric).

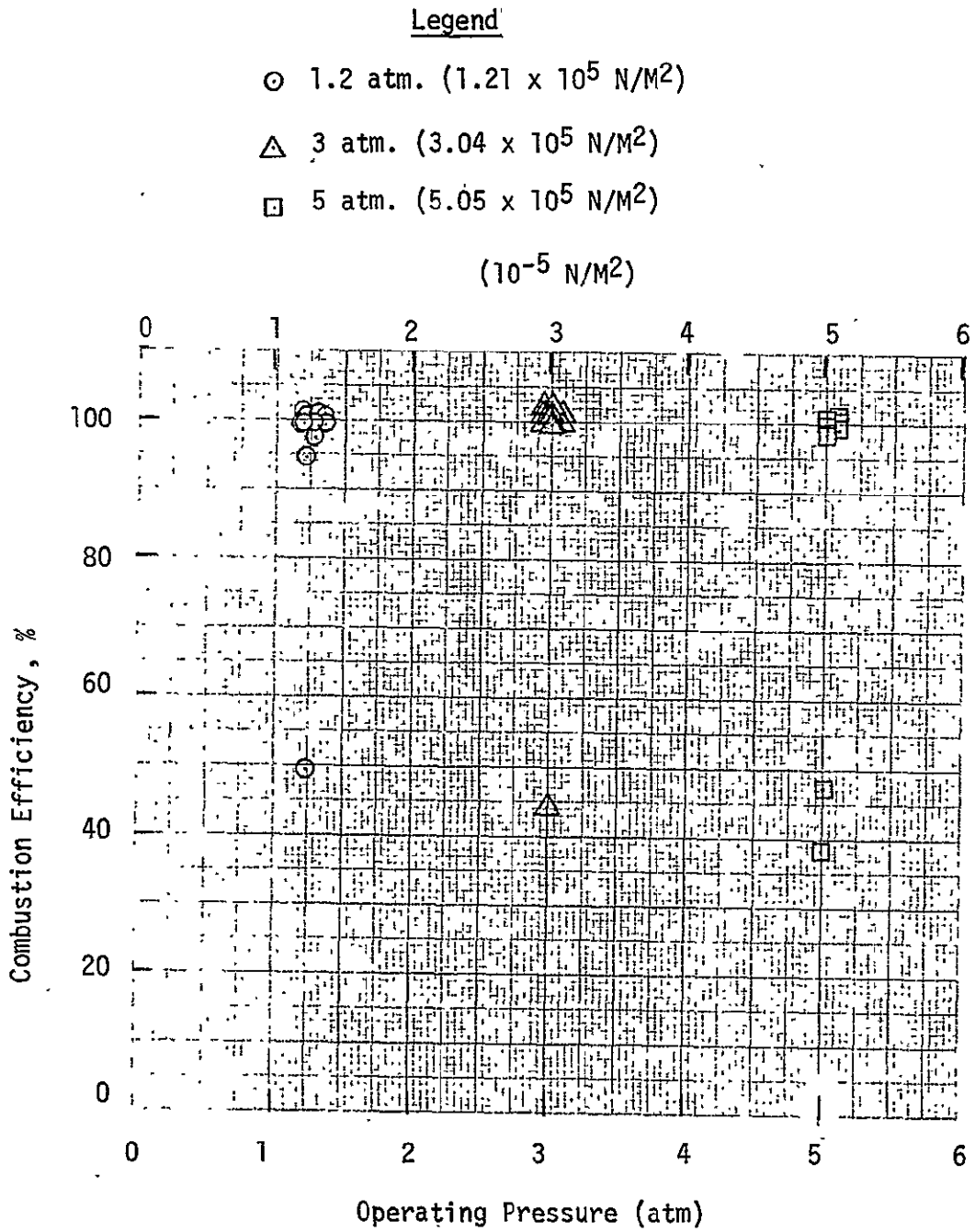

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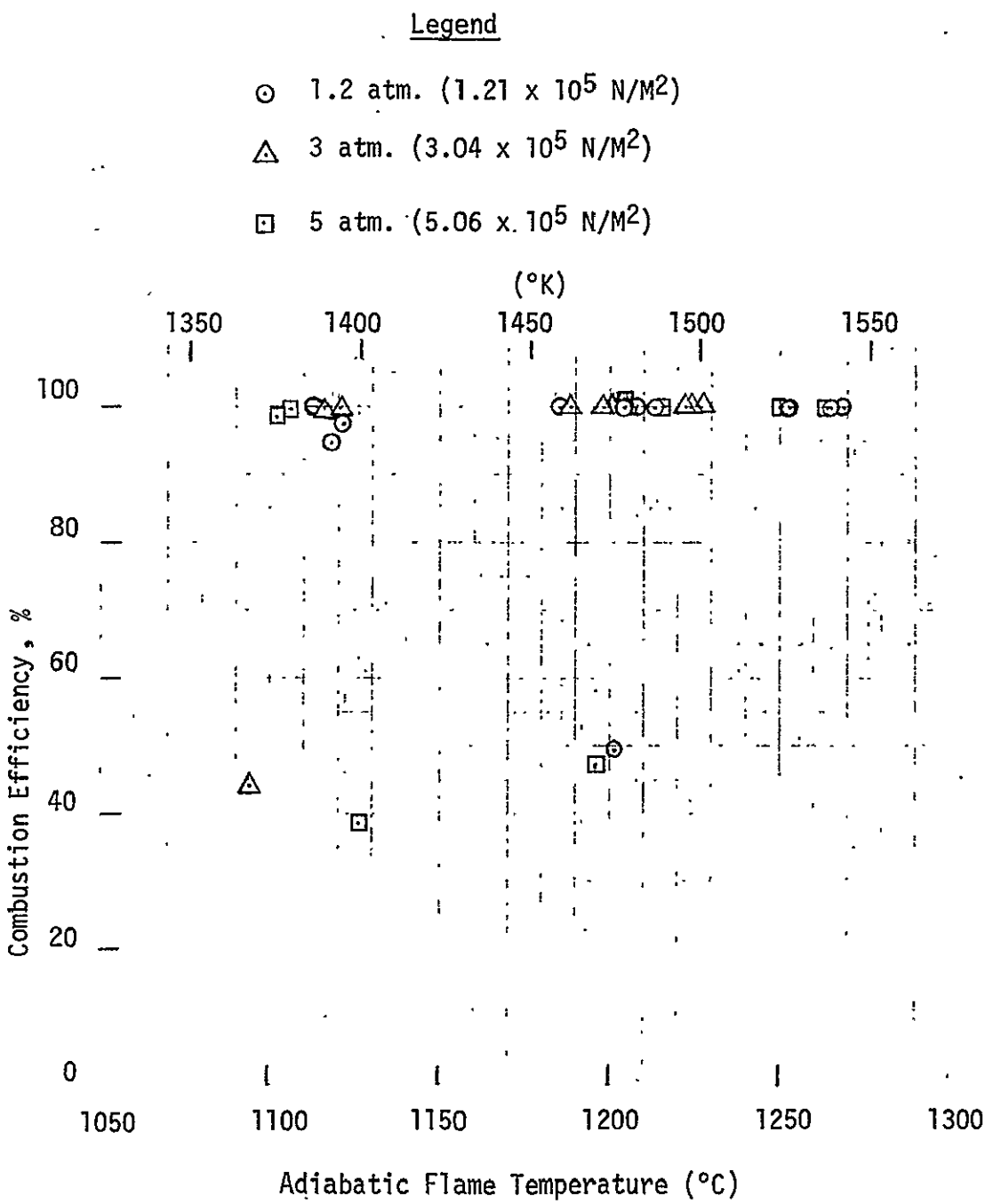
Figure D-4 Combustion Efficiency Versus Adiabatic Operating Temperature For Catalyst Core DXB-222 (Initial Propane Parametric).



The best representation of the data is shown in Figure D-5, which is a plot of propane combustion efficiency versus the product of the air preheat temperature and the adiabatic flame temperature divided by the reference velocity. Again, this graphical presentation has an overlapping region below abscissa values of 40,000 $°K^2/M/S$. Above this region, high combustion efficiency is depicted but below 40,000 $°K^2/M/S$, multiple values are depicted.

C. AVERAGE RESPONSES

A plotting routine which proved to be most successful involved plotting the average response of combustion efficiency at each of the true levels of a single control variable. This, in effect, neglects the simultaneous changes that occur in the other three control variables. The examination of the average responses from a statistical experimental design is a common technique used to determine significant trends of the responses versus functions of the control variables.

The plots showing the average responses are shown in Figures D-6 and D-7. This technique gives the clearest graphical interpretation of the results from the propane parametrics. The response of average combustion efficiency to air preheat, reference velocity and adiabatic operating temperature are similar to results found in previous studies (ref. 1, 2). Operating pressure appears to have a minor effect as shown.

Figure D-5 Combustion Efficiency Versus Combinded Independent Variables for Catalyst Core DXB-222. (Initial Propane Parametric)

Note: The numbers designate Run Serials.

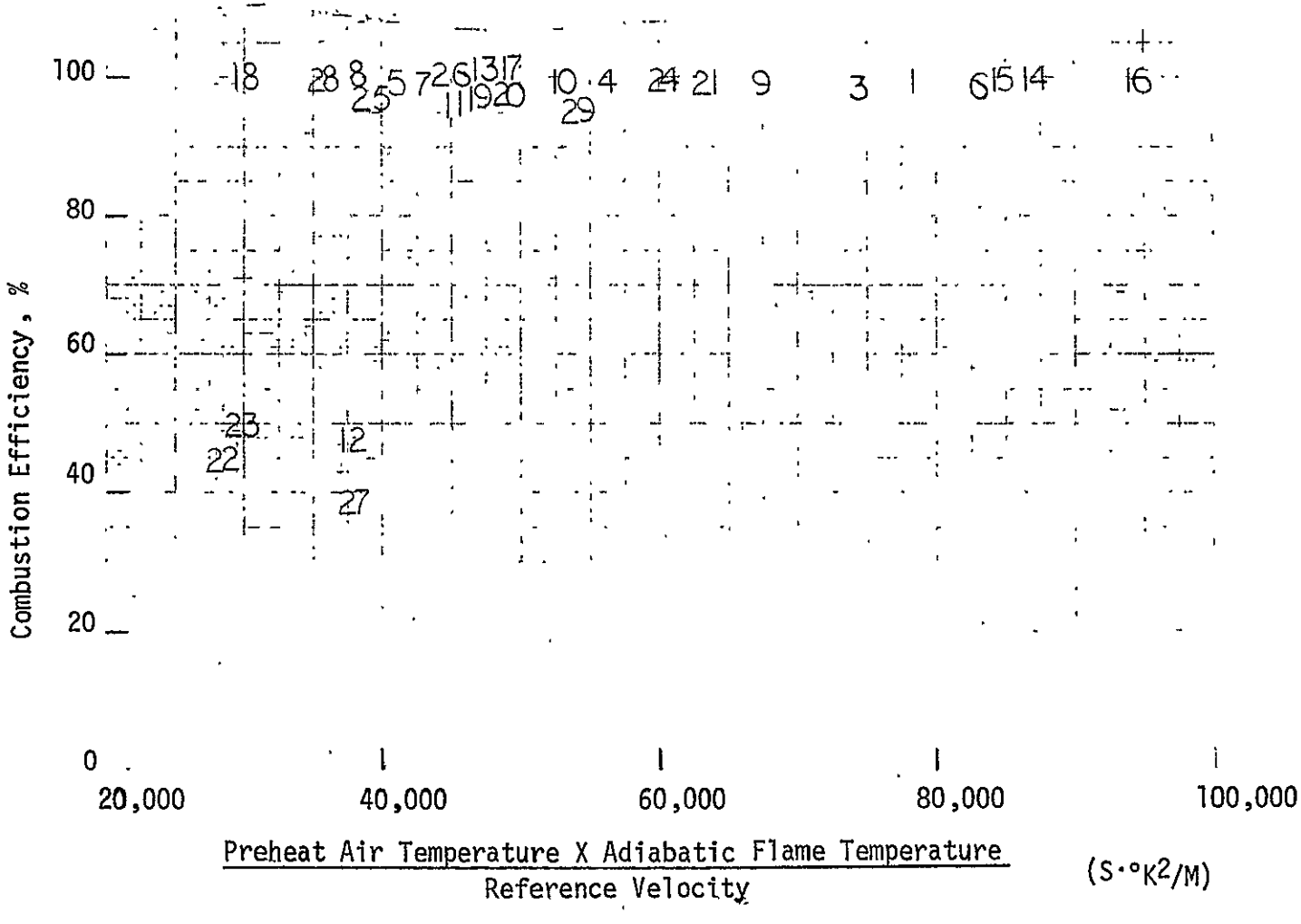
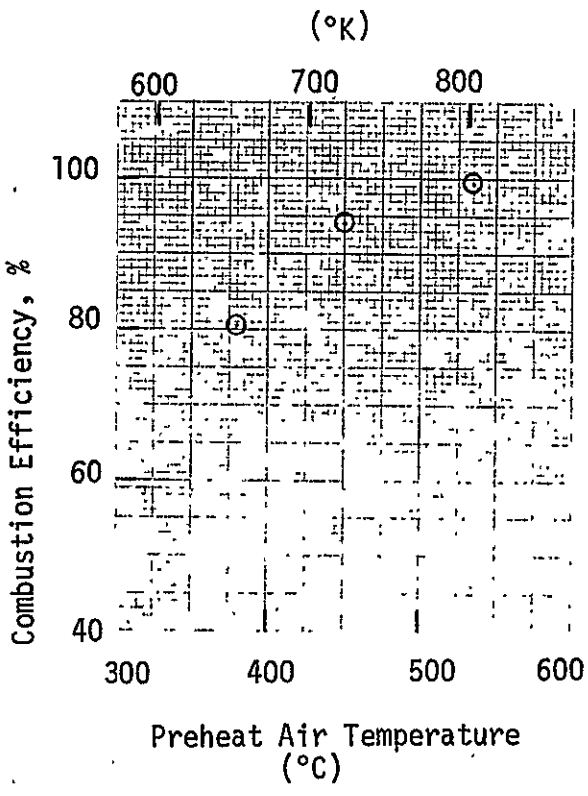


Figure D-6 Averaged Response of Combustion Efficiency Versus Preheat Air Temperature And Operating Pressure For Catalyst Core DXB-222 (Initial Propane Parametric).



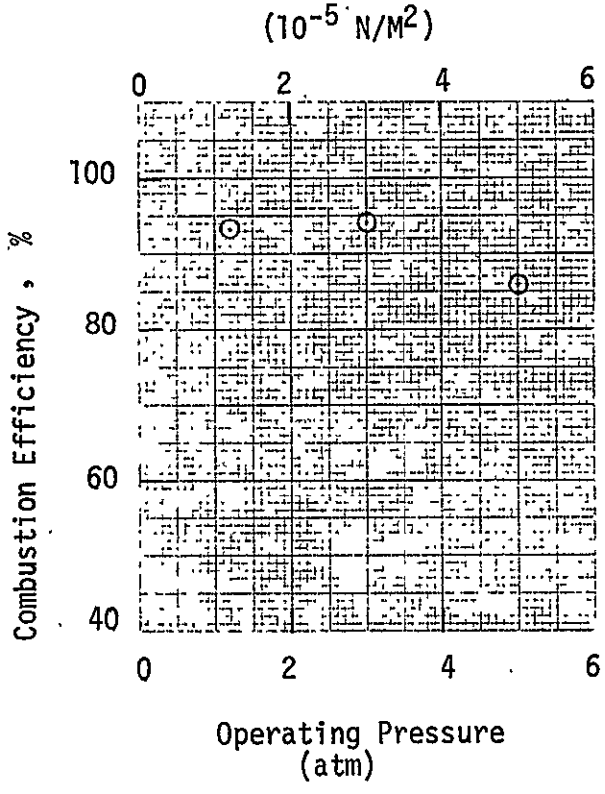
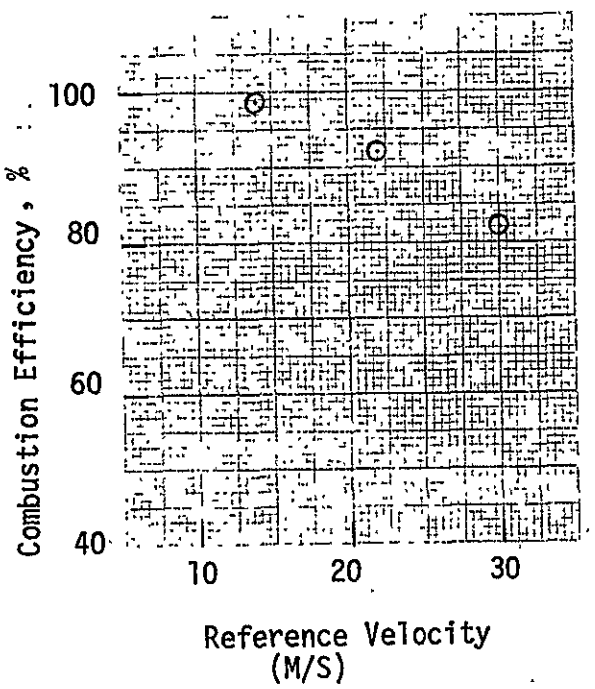
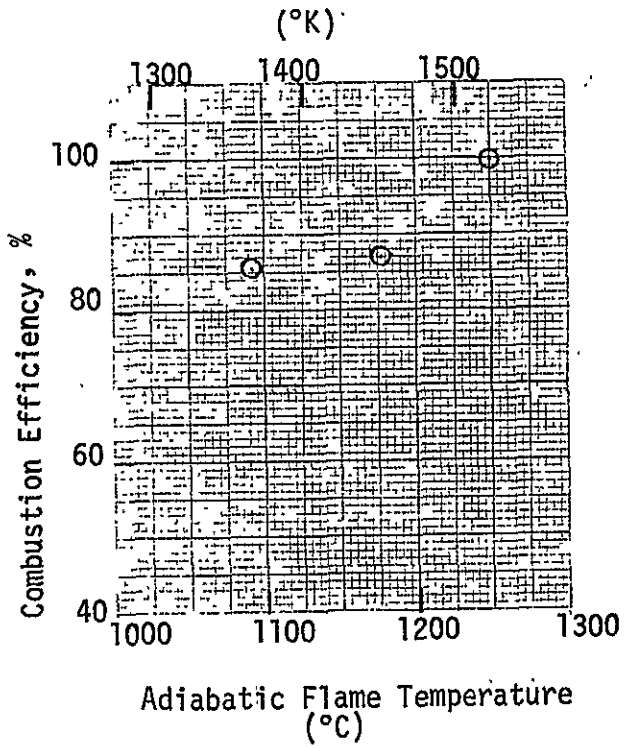


Figure D-7 Averaged Response Of Combustion Efficiency Versus Reference Velocity and Adiabatic Operating Temperature For Catalyst Core DXB-222 (Initial Propane Parametric)





APPENDIX E

DETAILED OPERATING INSTRUCTIONS

I. LIFE TEST

II. ACTIVITY TESTING

III. PARAMETRIC TESTING

IV. ANALYTICAL EQUIPMENT

V. CATALYST CHARGING

VI. UNIT SHUTDOWN

VII. ROUTINE DATA REDUCTION

VIII. DATA ANALYSIS (MISCELLANEOUS CALCULATIONS)

STANDARD OPERATING PROCEDURES

I. LIFE TEST PROCEDURE

A. START-UP PROCEDURES

1. Set Up Reactor Conditions

a. Switch on power to every instrument.

b. Set air supply pressure at 50 psig with air regulator.

c. Set air flow rate on automatic control loop at 416 scfh (32 lb./hr.).

d. Set air preheat SCR controller at 360°C reactor inlet temperature.

e. Select furnace to be used and open valves for flow.

f. While unit is heating, check safety shutdown system for performance (refer to Safety Shutdown).

g. Calibrate analytical train as shown in "Analytical Start-Up Section".

h. When the inlet temperature is lined out within ± 5°C of control point, take a set of readings for "no fuel" conditions.

i. Make sure the automatic level control on the vent cooler system is turned on and functioning properly.

2. Fuel Presentation

a. Set liquid fuel pump to give 447 cc/hr. #2 diesel fuel. This is an A/F wgt. ratio of 38/1.

b. Bring liquid feed on slowly by having bypass valve open and fuel feed line closed. With bypass open, slowly open fuel feed line valve. When fuel feed line is fully open, close the bypass line.

c. Once a day the fuel flow should be checked by flowing through the calibrated flow through gauge glass. Record results under comments on log sheet.

II. ACTIVITY TEST PROCEDURE

A. INTRODUCTION

For each catalyst core an activity test will be taken at 0, 250, 500, 750 and 1,000 hours of life testing. The test procedure is as follows:

1. Set the air flow using the air flow rotameter at 1088 scfh.

2. Preheat the air to the previous test ignition temperature. For virgin catalyst, begin at 180°C.

3. Using C. P. carbon monoxide (at 4000 ppm in feed stream) as the activity test fuel, determine ignition temperature by stepping in 20°C temperature increases until ignition occurs. While increasing temperature, fuel (CO) should be off.

4. After ignition is obtained, proceed in 40°C increments to obtain conversion data. Remember that background data should be taken before fuel is brought on.

5. Stop conversion data at 400°C inlet temperature.

III. PARAMETRIC TESTING

A. INTRODUCTION

Parametric tests will be performed on each catalyst core at 0 and 1,000 hours of life testing using C. P. Propane. The following procedures should be followed:

1. Start-Up

a. Set air flow rate as specified in operating instructions. Set pressure at 70 psig on rotameter.

b. Set air preheat temperature as specified in operating instructions.

c. Select furnace (or furnaces) to be used and open valves for flow.

d. Calibrate analytical train as shown in "Analytical Start-Up Section".

e. Set reactor operating pressure given in operating instructions by adjusting valve on reactor vent line.

f. When the inlet temperature is lined out within ± 5°C of control point, take a set of readings for "no fuel" conditions.

2. Fuel Presentation

This procedure should be followed for any gaseous fuel runs in which the anticipated outlet temperature is over 1000°C. The basic idea is to bring in fuel slowly and do not ever overshoot the fuel.

a. Check FID calibration against the standard. Select the one closest to the desired fuel level you want to set.

b. Adjust the inlet sample flow to obtain about the same flow (∿4 scfh) as when you calibrate it.

c. Check the back pressure gauge and make sure it reads 4.5 psig exactly.

d. FID should read zero. If not, zero it with zero gas.

e. Check the pressure in the fuel line between the metering valve and solenoid valves. If high pressure is found, bleed it off.

f. Open the solenoid valves and set fuel pressure regulation to the desired pressure.

g. Turn recorder chart on and open the metering valve slowly.

h. Bring in the fuel to 3/4 of the final setting according to the FID. Wait for the outlet temperature to turn such that it is beginning to line-out (about 10 minutes). Then, gradually increase the fuel to the specified level. Note that there is a time delay between the change of the setting of the valve and the FID response. Therefore, every change that is made should give you sufficient time (at least one minute) to line out on recorder.

i. At no time should the outlet temperature exceed 1260°C. If it is likely to occur, shut fuel off and report to the engineer.

j. After fuel is set, mark the chart and turn off inlet sample stream and recorder chart. If there is any doubt about the inlet fuel concentration during the run, it should be rechecked.

IV. ANALYTICAL EQUIPMENT PROCEDURES

Start-Up Procedures for CO, CO_2, NO/NO_x, O_2 and FID Analyzers

A. GENERAL

1. Power-switch on on FID and Beckman Console - Also NO/NO_x. This is for warming up the units electrical circuits.

2. Turn off house air on N_2 at the back of the unit that was on for overnight purge.

3. Selector valves at the control panel should be in closed position to prevent any leaks or flow surges. Then turn on all tanks and one zero air tank.

B. CONSOLE PANEL

1. Open CO purge valve to give a flow of 7.0 on rotameter.

2. Sample valve calibration valve should be in calibration position.

3. Turn on pump and open span valve $CO/CO_2/O_2$ also to give flow of 7.0.

4. Turn CO and CO_2 analyzers from the tune position to Range -1.

5. Selector valve Lo-CO, Hi-CO should be in Hi-CO position.

6. CO and CO_2 chopper switches on.

7. Selector valve span zero, 1, 2 and 3 should be in zero position to zero analyzers.

8. Recorders off-on switch should be in on position. Check pens on recorders by turning recorder chart switch on to see if pens write. (If pens don't write, use thin wire or suction bottle to draw ink through tip.)

9. Check filter paper in pancake valve on sample line and change if necessary.

10. O_2 analyzer should be on Range 25.

C. CALIBRATION PROCEDURE FOR CO ANALYZER

1. Range 1 calibration (CO span gas from 500 to 5000 ppm).

a. From control panel select span gas labelled CO 1.

b. On console selector valve span zero, 1, 2 and 3 should be turned to CO #2 position.

c. Control flow through rotameter to setting of 7.0 by regulating $CO/CO_2/O_2$ span valve.

d. At this point you can actually calibrate on any gas from 500 to 5000 ppm.

e. Check the reading at the meter which corresponds to the span gas at Range 1. Verify at CO curve.

f. If reading is not verified, adjust gain potentiometer to verify curve.

2. Range 2 calibration (CO span gas from 50 to 500 ppm).

a. From the control panel select span gas labelled CO 2.

b. Hi-CO, Lo-CO selector valve should be in Lo-CO position.

c. Regulate flow setting at 7.0 by adjusting CO-CO_2-O_2 span valve if necessary.

d. At this point you are actually calibrating any gas from 50-500 R 2, 0-50 R 3.

e. Check the meter reading and at CO curve for Range 2. Verify reading.

f. If reading is not verified according to reference curve, open and pull out analyzer and adjust potentiometer labeled D for R 2 to verify curve.

3. Range 3 calibration (CO span gas from 0 to 50).

a. From control panel select span gas labeled CO 3.

b. Follow Steps b through e as in Range 2 calibration.

c. If reading is not verified according to reference curve, open and pull out analyzer and adjust potentiometer labeled as R 3 to verify curve.

D. CALIBRATION OF CO_2 ANALYZER

1. Range 1 calibration (any CO_2 span gas from 2.5% to 15%).

a. From the control panel select span gas labeled CO_2-1.

b. On console selector valve span zero 1, 2 and 3 should be turned to CO_2 #1 position.

c. Control flow through rotameter to setting of 7.0 by regulating $CO/CO_2/O_2$ span valve on console.

d. At this point you are calibrating on any gas from 2.5% to 15%.

e. Check the reading at the meter which corresponds to the span gas at Range 1. Verify at CO_2 curve. If not verified, adjust gain potentiometer.

2. <u>Range 2 calibration (any CO_2 gas from 0 to 2.5% CO_2).</u>

a. From the control panel select span gas labeled CO_2-2.

b. Regulate from console a flow of 7.0 setting by adjusting $CO/CO_2/O_2$ span valve, if necessary.

c. If reading is not verified according to reference curve, open and pull out analyzer and adjust potentiometer labeled as R-2 to verify curve.

3. Range 3 calibration is not in use.

E. O_2 ANALYZER CALIBRATION

Note: All readings are taken on Range 25 unless otherwise specified.

1. Select the gas from the control panel (zero-air).

2. Span selector valve zero, 1, 2 and 3 should be at span 3. Verify flow to 7.0 setting on console by regulating $CO/CO_2/O_2$ span valve.

3. Verify reading on meter by calibrating zero air to 21%.

4. After calibrating selector valve span zero, 1, 2 and 3 should be back to zero position (zero instrument).

5. Verify zero readings on $CO/CO_2/O_2$ analyzers.

F. SET UP FOR SAMPLING - BECKMAN CONSOLE ($CO/CO_2/O_2$)

1. Selector valve, sample calibrate goes to sample position.

2. Lo-CO and Hi-CO valve goes to Hi-CO position. Also CO analyzer to R 1.

3. Shut off $CO/CO_2/O_2$ span valves on console.

4. Verify rotameter flow at 7.0 by means of $CO/CO_2/O_2$ sample valves on console.

5. Open valve that is marked Unit #2, #3, #4 or #5 respectively for sampling to Beckman Console.

6. Read and record data. (If not reading, notify engineer). Mark charts for easy data retrieval on each sample.

G. NO/NO_X ANALYZER CALIBRATION

1. NO_X sample valve on console fully open. Close NO_X span valve on console.

2. NO mode selector switch in zero position to zero analyzer with range switch preferably on Range 10. (If not zeroed, adjust zero knob).

3. Open door to analyzer to see if there is a flow setting of 8.0 on bypass rotameter, 20 psig ozone and 4 psig sample. Let door stay open.

4. From the control panel select respective span gas, preferably NO 3 (gas is 4.2 ppm).

5. On analyzer turn NO mode switch to read sample. Flow on bypass rotameter should read 4.0 setting. (If flow is too great, regulate to 4.0 setting by NO_X sample valve on console. If flow is too small, regulate to 4.0 setting only when sampling for NO/NO_X by adjusting $CO/CO_2/O_2$ sample valve on console. NO_X sample should be fully open.

6. On analyzer turn NO mode switch to read span. From console open slowly NO_X span valve so as to give a flow of 4.0 setting on bypass rotameter.

7. Switch back and forth NO mode selector switch from span to sample. (Do this three times giving each time to respond). All pressures and flows should remain the same. Leave switch in span position.

8. Close door to analyzer and whatever gas is selected will read at meter. Adjust reading to calibration gas if incorrect by using span knob.

9. The above procedures are done for NO_X gas also in NO_X mode side.

10. Use the above standard procedure for any other calibration gas selecting, of course, the appropriate calibration range.

11. When calibration is finished, leave NO mode or NO_X mode switch in zero position. Turn off NO_X span valve on console.

12. Turn to sample position only when sampling.

H. FID ANALYZER (402) CALIBRATION

1. Ignition Procedure

a. After air and fuel are turned on fron tanks (cylinders), ignition is made by pushing up (or down) ignition button and listening for popping sound, indicating that flame is lit.

2. Calibration Procedure

a. At this time sample pump can be turned on in back of analyzer and air and fuel adjusted to 25 psig each. Sample pressure regulator should be at 4 psig. Make sure to check pressure gauge zero reading before adjusting to 4 psig. Any offset on zero should be added to 4 to get correct actual pressure.

b. At this time zero air or house N_2 is flowing through the unit and temperature of oven is stable at 350 to 375°F.

c. Zero analyzer by turning range multiplier switch to Range 10 and let set for awhile (if not zeroed, use zero adjustment knob to zero).

d. When zero is OK, turn range multiplier switch to 5000. Close zero air valve at lower left corner and slowly open span gas valve.

e. From control panel select gas marked HC-1 (15,000 or 19,000 ppm). All pressures should be the same as in Step #2.

f. If meter does not read according to calibration standard, adjust gas by using span knob. (Ex. for a 19,000 ppm gas meter should read 3.8 x 5,000 - 19,000.0 ppm).

g. All other calibration gas HC-2 and HC-3 are done the same way as HC-1, but on the appropriate range. (Ex. for a 20 ppm gas meter should read 4.0 x 5 = 20.0 ppm or 2.0 x 10 = 20.0 ppm).

h. After calibration normal override switch goes to normal. Sample calibrate valve turn to sample and zero and span valve closed.

i. Range multiplier switch to 5000. You are now sampling from whatever unit you selected.

j. At control panel turn all selector valves at NO selection.

I. CONSOLE SHUTDOWN PROCEDURES

1. Daily Shutdown

a. Sample pump off.

b. $CO-CO_2$ choppers off.

c. All charts- off.

d. NO/NO_x sample valve, NO_x span valve, $CO-CO_2-O_2$ span valve, CO purge closed.

e. All tanks - off.

f. NO/NO_x analyzer left on, NO mode selector valve to NO sample position.

g. Sample calibrate valve, to sample position.

h. Lo-CO - Hi-CO valve, adjusted at mid-position, so as to give a flow to both CO cells.

i. Turn on house air (N_2) at the back of the unit, by adjusting metering valve to give a flow to all analyzers.

j. Verify the flow by observing rotameters in front to read anywhere from 0 - 7.0.

k. Analyzers $CO-CO_2$ goes to tune position.

l. FID analyzers pump off.

m. FID analyzers sample calibrate valve goes to calibrate position. FID analyzers normal override switch to override position.

n. FID air regulator to 0-5 psig.

o. FID analyzer, sample regulator to 2 psig.

p. FID analyzer, zero house air (N_2) flow through analyzer for purging.

q. All valves go to non-selecting position at control panel.

V. CATALYST CHARGING

The catalyst charging procedure is a very important step in the evaluation of each catalyst. A proper job will insure correct pressure drop measurements and prevent reactor bypassing. Monitor the pressure drop control charts during tests to detect failure of packing. Abrupt changes in pressure drop may indicate that fiberfrax has become loose and repacking is needed.

A. Weigh catalyst and record dimensions (diameter, length, number of full channels). Apply a 1/4" wide layer of ceramic cement around the middle periphery of the catalyst core to prevent bypassing.

Wrap a layer of fiberfrax, recessed 1/4" from each end, around the catalyst core.

B. Place the catalyst core in the metal holder, pushing the catalyst core into the bottom of the holder. Inspect catalyst core in holder and make sure no fiberfrax has slipped and is covering channels. If so, remove and start over again.

C. Remove all fiberfrax from reactor that may be stuck to the reactor wall from previous tests.

D. Wrap fiberfrax around catalyst holder and insert in reactor. Make sure the fiberfrax wrapping provides a snug fit. Set air flow at 1000 scfh and see if holder stays in place. If not, remove, rewrap and place in reactor. Retest at 1000 scfh for bypassing.

E. Insert holder pin through reactor wall and pull down the holder flush with this pin. A schematic showing the placement of the packed catalysts in the reactor is shown in Figure -1.

F. Secure reactor flanges, thermocouples, etc. for testing. Pressure test reactor at 50 psig for 30 minutes for leak checks.

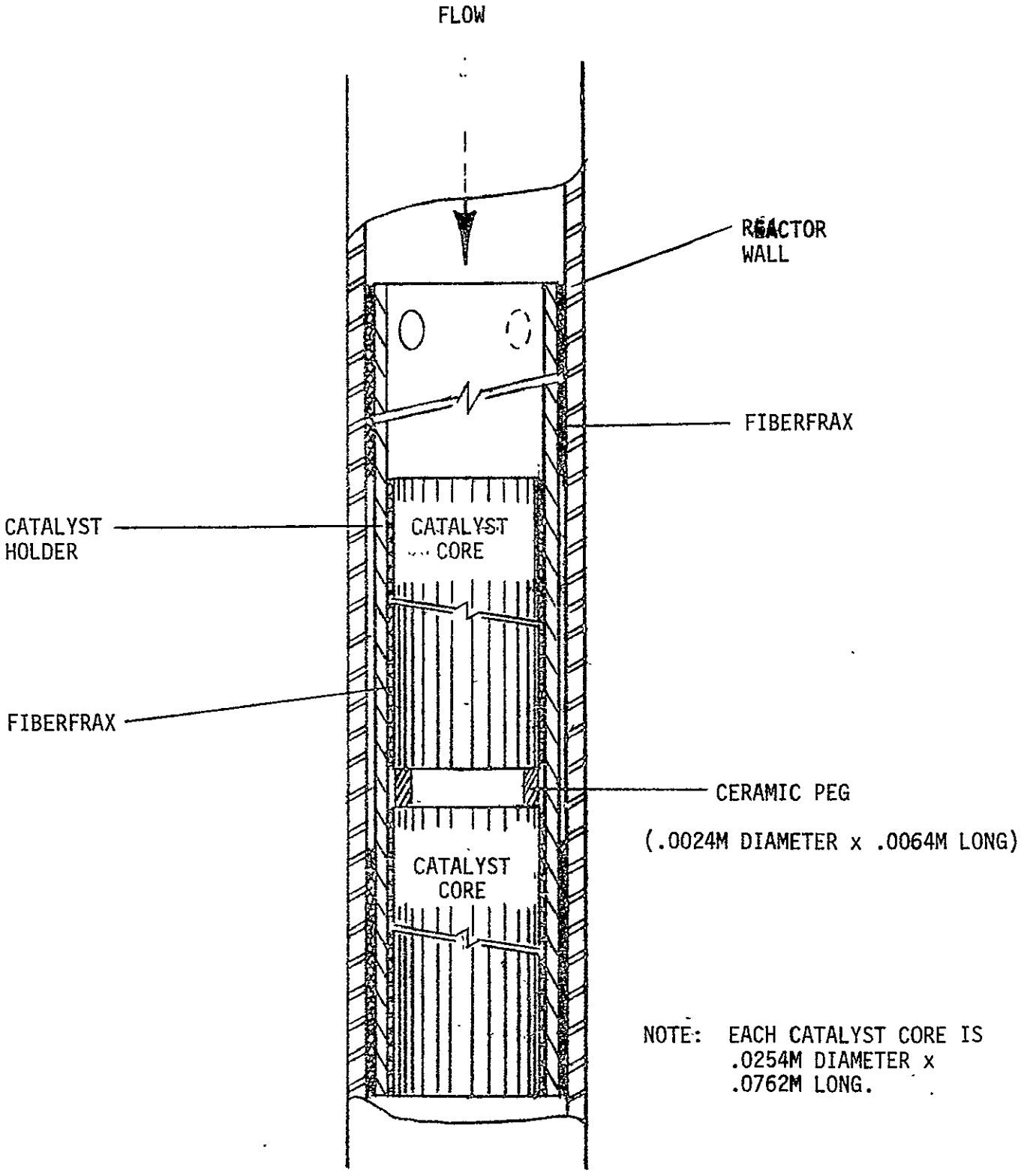


Figure E-1: Schematic Showing Details of Packing of Test Catalyst Cores

VI. UNIT SAFETY SHUTDOWN

A. INTRODUCTION

The unit shutdown is designed for operating personnel safety and for protecting the catalyst core from process upsets. When an automatic shutdown occurs, the fuel line solenoids cut off fuel to the reactor and air preheat. If the cause of the shutdown is removed, the air preheat is restored but the fuel must be reset manually.

Before resetting the fuel the technician should determine the cause of the shutdown, correct the problem and record the occurrence on the logsheet. Always bring fuel back on "on bypass" as standard operating procedure.

The proper functioning of the shutdown system should be checked every 500 hours of life testing. Use the check list in Attachment I. Problems should be corrected and noted in the log sheet.

VII. ROUTINE DATA REDUCTION

Data was processed using the following procedure:

A. Data recorded on standard log sheets.

B. The data is transferred from the log sheets to standardized computer forms with subsequent keypunching.

C. Data is inputted to computer and reduced on CATCOM computer programs.

D. Computer output in tabular form and plots.

This entire sequence is handled by technicians in the CATCOM group.

A subroutine is also available for taking the reduced data and providing plots. This is used routinely for life tests to detect trends with operation time (e.g., emissions plotted vs. operating time). For life tests, the operating time is defined as the time on stream at life test conditions.

The routine data reduction program performs the calculations listed in Table E-1 with the nomenclature explained in Table E-2. Because of the fact that a one-inch core is removed from the catalyst block, the outside channels are ineffective in converting the fuel. This is taken into account by defining an effective catalyst core diameter based on the ratio of the number of open channels actually in the 1" diam. test core compared with the calculated number of channels. Note that the reference velocity, the space velocity, Reynolds' number and heat release rate all contain this correction factor.

The combustion efficiency is calculated on fuel conversion for this study and not on a heat balance. Similarly, the heat release rate is based on hydrocarbon conversion and not a heat balance.

For 1" diam. laboratory test rigs, the percent adiabaticity is a very important guide post. It represents the percent heat loss in the reactor. This is inherent in small test rigs because of the high surface to volume ratio available for heat transfer to the atmosphere. The calculation shows how much the actual measured temperature rise across the catalyst core deviates from the calculated adiabatic temperature rise based on heats of combustion and hydrocarbon conversion levels.

TABLE E-1

EQUATIONS FOR DATA REDUCTION COMPUTER PROGRAM

- Reference Velocity: $= [A/\rho A + F/\rho F]/[E/CI]$
- Space Velocity: $= [A/\rho A + F/\rho F]/[C/CI][L]$
- Emissions: CO, NO_x, UHC = PPM [M/MW]/[A+F/F]
- Combustion Efficiency: $\frac{100 \times HCI \times NC \times 10^6 - [CO + 3HC]}{HCI \times NC \times 10^6}$
- Percent Adiabaticity: $= (T_0 - T_I)/(T_{OD} - T_I) \times 100$
- Reynolds' Number: $= (A + F)Dh/[C/C_I]\mu$
- Heat Release Rate: $= FQ\ F_C/[C/C_I]$
- Carbon Balance: $= (IC - OC)/IC \times 100$
- Hydraulic Diameter: = (Channel Cross Section Area)/(Wetted Perimeter)
- Equivalent Diameter: $= [C/C_I]^{1/2}\ [4/\pi]$
- Percent Pressure Drop: $([P_{IN} - P_{OUT}]/[P_{IN}]) \cdot [100]$

TABLE E-2

NOMENCLATURE FOR DATA REDUCTION

A - Air mass flow rate

F - Fuel mass flow rate

C - Actual number of open channels in 1" Ø catalyst core

C_I - Theoretical number of channels per area for catalyst core

ρA - Density of air

ρF - Density of fuel

L - Catalyst core length

PPM - Parts per million of emission as measured in exhaust

M - Emission molecular weight

MW - Exhaust mixture molecular weight

HCI - Mole fraction of fuel in feed

NC - Number of carbons in fuel

CO - ppm of carbon monoxide in exhaust

HC - ppm of hydrocarbons measured as propane in exhaust

T_O - Measured outlet catalyst core temperature

T_I - Measured inlet catalyst core temperature

T_{od} - Calculated adiabatic temperature rise for air/fuel ratio in feed (adiabatic flame temperature)

D_c - Equivalent honeycomb diameter calculated from number of open channels in 1" Ø catalyst core

μ - Gas mixture viscosity

F_C - Conversion of fuel in catalyst core

P_I - Inlet pressure to catalyst core

IC - Number of carbon atoms in feed

OC - Number of carbon atoms in exhaust

D_h - Hydraulic diameter

V_r - Reference velocity

VIII. DATA ANALYSIS (MISCELLANEOUS CALCULATIONS)

Supplementing the routine data reduction were miscellaneous calculations for

A. Emissions Index

B. Adiabatic Flame Temperature

Because of their importance, these calculations are detailed below.

A. EMISSIONS INDEX

Emissions in grams/mile were calculated using Equation (1) (refer to Table E-2 for nomenclature).

$$(1) \quad (\text{g/mile}) = \frac{[A/29 + F/199][PPM \times 10^{-6}][MW]}{\frac{F}{\rho_F} \times \left[\frac{2.642 \times 10^{-4}\ \text{gallons}}{\text{cc}}\right] \times \frac{10\ \text{miles}}{\text{gallon}}}$$

Example Calculation:

For UHC as C_3H_8

and A/F = 38/1

MW = 44

PPM = 3.8

ρ_F = .864 g/cc

(g/mile) = 0.072

B. ADIABATIC FLAME TEMPERATURE CALCULATION

1. Basis: Feed Air/Fuel Ratio

Material Balance

To complete the material balance the stoichiometry of the diesel oil combustion must be known. Using the analytical results for

- API gravity of 34.4
- 50% distillation temperature of 523°K

the molecular weight of diesel oil is calculated using the method in Reference 9 as 192 grams/gram-mole. For carbon/hydrogen ratio of .566 (obtained by analysis), a formula of $C_{13.93}H_{24.61}$ is calculated for the #2 diesel fuel. The stoichiometry for diesel oil combustion can then be represented by:

$$C_{13.93}H_{24.61} + 20.08\ O_2 \rightarrow 13.93\ CO_2 + 12.30\ H_2O$$

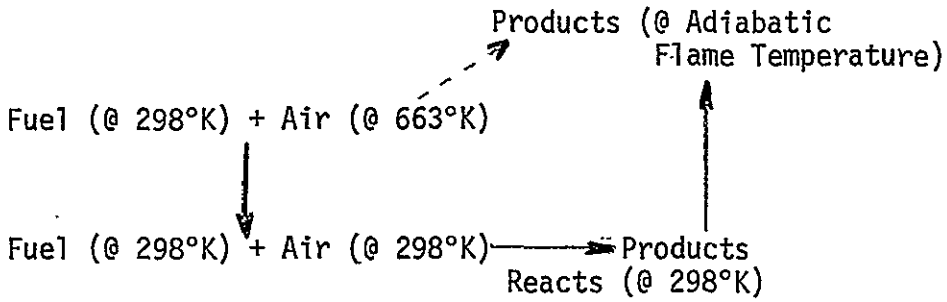
In the life tests on DXB-222 and DXC-532, the typical air/fuel ratio of 38/1 results in the following molar balance:

Component	Feed (%)	Product (%)
#2 Diesel	0.396	-
O_2	20.92	12.71
N_2	78.69	77.12
CO_2	-	5.39
H_2O	-	4.77

The mean molecular weight of the product is 29.04

Energy Balance

The adiabatic flame temperature is calculated using the assumption shown schematically:



The calculation involves assuming an adiabatic flame temperature to obtain the mean molar heat capacities of the product gases for use in Equation (1).

(1) (Heat content of products at adiabatic flame temperature)
+ Heat of combustion at 298°K
- (Heat content of feed at feed temperature)
= 0

The calculated adiabatic flame temperature is then compared to the assumed and a trial and error solution is used to converge to the final solutions. Using this technique, an adiabatic flame temperature of 1527°K is obtained for an air/fuel weight of 38/1.

Sample Calculation:

Step (1) Assume adiabatic flame temperature of 1527°K

Step (2) Mean molar heat capacity of product

Component	Mole Percent	*Pure Component Mean Molar Heat Capacity @ 1527°K (kcal/kg·°K)	Heat Capacity Contribution (kcal/kg·°K)
CO_2	5.39	12.32	.664
H_2O	4.77	9.6	.458
O_2	12.71	8.1	1.03
N_2	77.12	7.67	5.915
Mean Molar Heat Capacity of Products from 298°K to 1527°K			8.067 $\frac{kcal}{kg \cdot °K}$

(*from Reference 9)

Step (3) The mean molar heat capacity of air from 298°K to 633°K is 7.12 $\frac{kcal}{kg \cdot °K}$ (from Reference 9).

Step (4) The overall energy balance is

(1 mole basis in feed)

$$(1.02\ \frac{kg\cdot moles}{Hr.})(8.067\ \frac{kcal}{kg\cdot °K})(T_{AD} - 298°K)$$

$$+ (.00396\ \frac{kg\cdot moles}{Hr.})(-1.957 \times 10^6\ kcal/kg\cdot mole)$$

$$- (.9961\ \frac{kg\cdot mole}{Hr.})(7.12\ \frac{kcal}{kg\cdot °K})(633 - 298°K)$$

$$= 0$$

$$T_{AD} = 1528°K$$

Therefore, the assumed adiabatic flame temperature of 1527°K is within 1°K of the calculated value. This is well within the accuracy of the calculation method.

2. Basis: CO_2 Vent Gas Analysis

Another technique that is frequently used in calculating the adiabatic flame temperature is based on the CO_2 produced in the combustion process. The steps used in this calculation are:

a. Using the CO_2 vent gas analysis and the stoichiometry of the combustion reaction, back calculate the corresponding feed component material balance.

b. Using the material balance results, calculate the feed air/fuel weight ratio.

c. With the calculated air/fuel ratio perform an energy balance calculation to obtain the adiabatic flame temperature. This last step is an iterative process as explained in Appendix E-VII-B-1.

The equations for stoichiometry and the energy balance are identical to those contained in Appendix E-VII-B-1.

Analysis of the CO_2 control charts maintained during the life tests of DXB-222 and DXC-532 showed the following:

Catalyst Core	Mean of CO_2 Vent Gas Analysis Over 1,000 Hours	Standard Deviation of of CO_2 Vent Gas Analysis Over 1,000 Hours
DXB-222	5.46 %	.11%
DXC-532	5.53%	.11%

Using these results to make a material and energy balance for the adiabatic combustion gave:

Catalyst Core	Adiabatic Flame Temperature Based on Mean CO_2 Analysis	Range of Flame Temperature at 95% Confidence Range
DXB-222	1533°K	1499 - 1565°K
DXC-532	1545°K	1511 - 1575°K

This data indicates that during the course of the life tests, temperatures ranged from approximately 1505°K (2294°K) to 1570°K (2366°F).

TABLE E-3

GLOSSARY OF TERMS

Catalytic Combustor: Flange to flange assembly of catalytic combustion equipment, including fuel presentation system, ignition system and catalytic substrate, including provision for instrumentation.

Catalytic Core (Catalyst Core): Composite of catalyst and catalyst support.

Catalyst Support: Structure upon which the catalyst is supported.

Catalyst: Active catalytic material.

Full Scale: Applies to components, equipment and test rigs for testing under simulated gas turbine engine conditions.

Sub-scale: Applies to components, equipment and test rigs for testing on a one-inch diameter catalytic bed scale.

Test Rig: Facility used for test and evaluation of catalytic combustors.

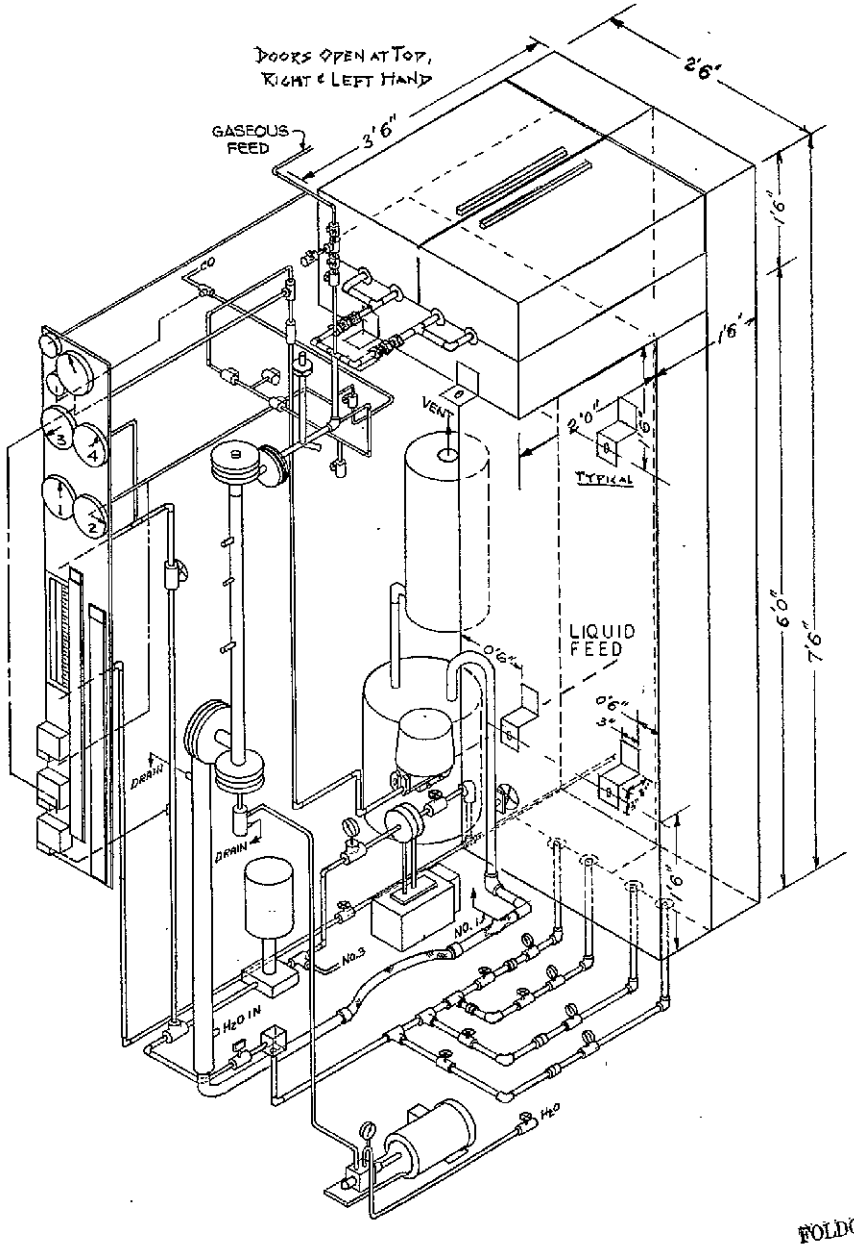
Ignition Temperature: The temperature at which spontaneous catalytic combustion occurs for a given fuel/air catalytic core combination.

Space Velocity: Volumetric flow rate of reactants per volume of catalyst core. NTP refers to 298°K and atmospheric pressure.

APPENDIX F

DESIGN DRAWINGS

FOR NASA TEST RIG



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GENERAL NOTES

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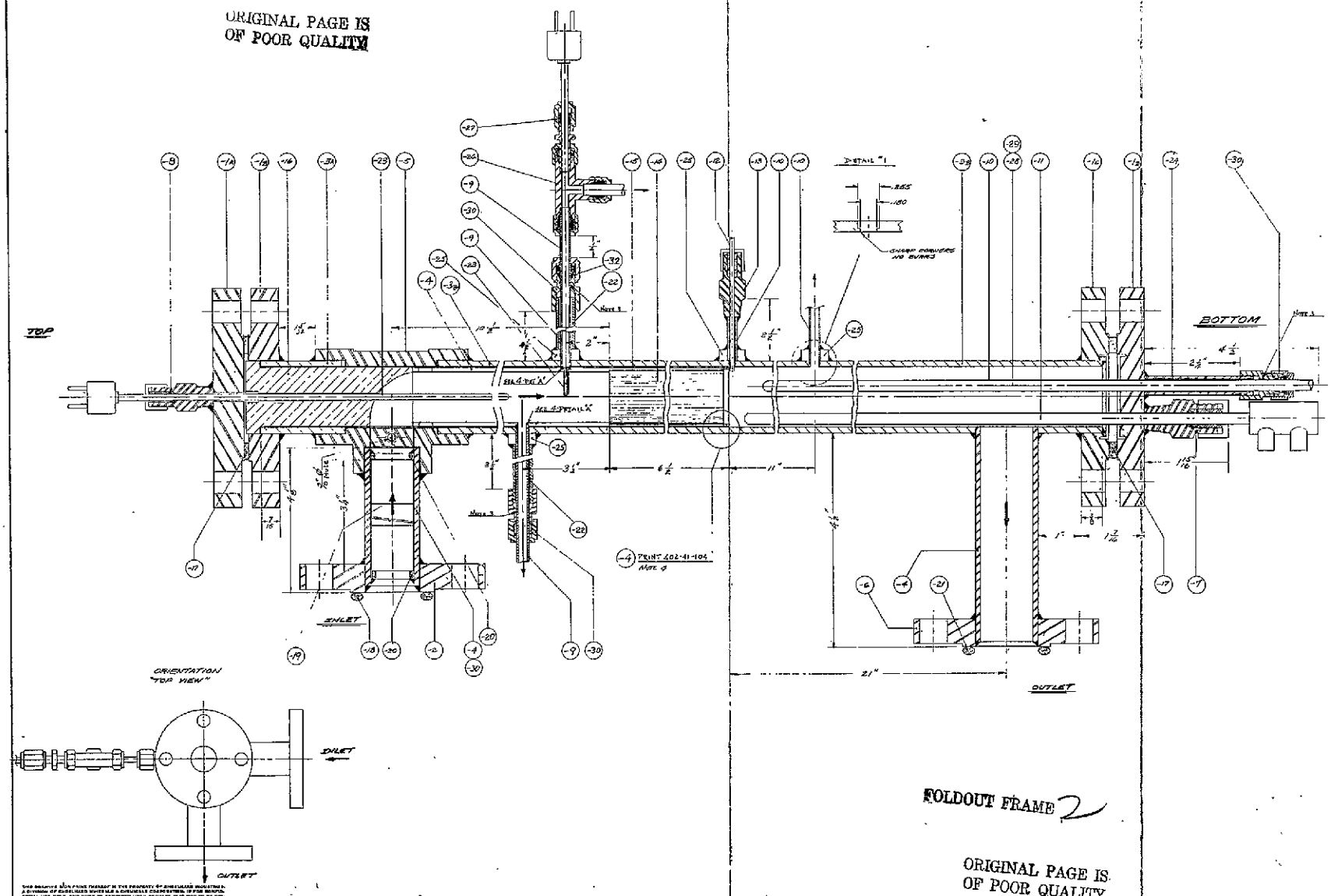

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FOLDOUT FRAME 2

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GENERAL NOTES

1. ALL BASIC NUMBER ITEMS ARE DESIGNED BY THE NUMBER 402
2. REACTOR TO BE DESIGNED FOR 5 ATM WORKING PRESSURE AT 2300°F USING 1 INCH DIAMETER PELLETS. USE TO 6 INCHES IN 5 ATM.
3. CATALYST PART MUST BE FLEXIBLE TO SUPPORT THERM. PARTS, PELLETS, NOT TO BE AT PLASTIC TEMPERATURES.
4. CONTACT [illegible] TO BE MADE [illegible] AS SHOWN [illegible] ADDITIONAL CONTACT [illegible] PRESSURE [illegible] PELLETS [illegible] MAKE ALL THERM. PARTS [illegible] ALL ALTERNATE USE [illegible] 5 ATM [illegible] THE [illegible] PELLETS [illegible] 6 INCHES.

REFERENCE DRAWINGS

DWG NO	TITLE
402-41-101	P & I DIAGRAM - HIGH
402-41-102	FUEL FEED SYSTEM
402-41-103	REACTOR DETAILS
402-41-104	REACTOR DETAILS
402-41-105	SCHEMATIC OF SAFETY ACTUATIONS
	BILL OF MATERIALS

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CKD		APPD	

TITLE
REACTOR, 5 ATMOSPHERES
2300°F, 1" DIA. CATALYST
CONTRACT NAS 5-1946

LOCATION | SCALE

JOB NO | DWG NO A-402-41-101 | REV NO 1

APPENDIX G

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