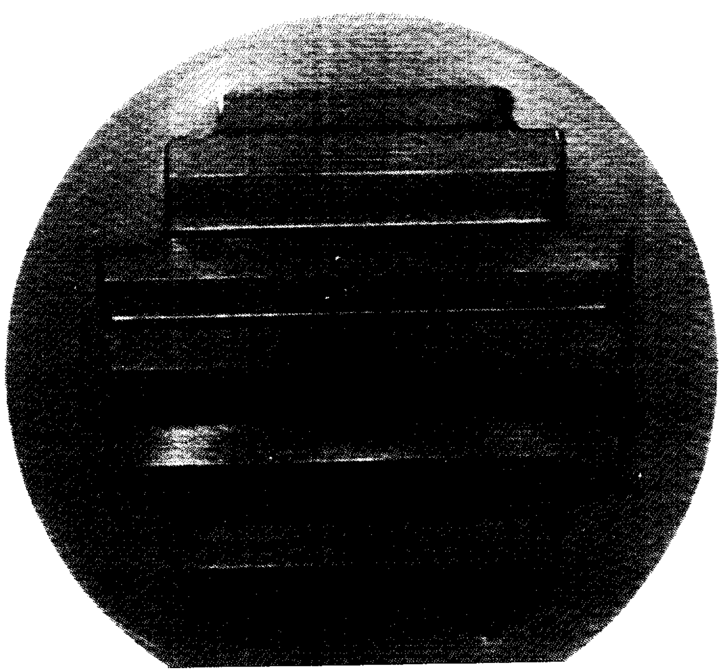
CR-184195

Carbon Deposition Model For Oxygen-Hydrocarbon Combustion

Contract NAS 8-34715
Bimonthly Progress Report 2427-BM-6
October 1988

Prepared for:
National Aeronautics And Space Administration
George C. Marshall Space Flight Center

By:
J.A. Bossard



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Aerojet
TechSystems
Company

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Carbon Deposition Model For Oxygen-Hydrocarbon Combustion

Contract NAS 8-34715

Bimonthly Progress Report

Prepared For

NASA/George C. Marshall Space Flight Center
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INTRODUCTION

This report describes Aerojet TechSystems Company's (ATC) progress and current status for the follow-on program for Contract NAS 8-34715, "Carbon Deposition Model for Oxygen-Hydrocarbon Combustion."

The status report is comprised of six subsections: A, Objectives; B, Approach; C, Schedule; D, Task Descriptions; E, Current Status. Appendix A contains the CER Package. The Liquid-Liquid Coax Injector Concept Review is found in Appendix B. For the purposes of the present Status Report, the original study refers to Report No. 2427-PP, 28 May 1982, the added scope program refers to Report No. 2427PP, September 1985, and the follow-on program to the present discussion.

Understanding how and why soot is formed with certain hydrocarbon rocket propellants is pertinent to the selection of the best hydrocarbon fuel for future engines as well as the selection of the engine cycle and operating conditions. Prior to the original Carbon Deposition program a consistent set of data had not been generated over a wide range of operating conditions. The original program generated this consistent set of data with LO_2/RP-1 propellants over a wide range of operating conditions using subscale hardware. The range of conditions covered both main chamber and fuel-rich preburner or gas generator operating conditions.

In the original program, deposition on the combustion chamber wall was investigated under main chamber operating conditions at mixture ratios of 2.0 to 4.0 and chamber pressures of 1000 to 1500 psia. The results from this effort indicated a lack of significant carbon deposition on the chamber wall with LO_2/RP-1 propellants. These results showed that chamber designs cannot depend on carbon deposition to reduce the "clean wall" heat flux for chamber pressures over 1000 psia and for combustion efficiencies greater than 95%.

An added scope program focused on carbon deposition in gas generators and preburners. This program included propane and methane testing and comparisons to the RP-1 database. The preburner test data from the added scope program revealed that methane gives a C^* performance within 10% of the value predicted by the One Dimensional Equilibrium (ODE) program, while propane and RP-1 test data are within 14% and 40%, respectively, of their ODE predicted C* performances. Both propane and methane exhibited C* performances between 3000 to 4000 fps, while RP-1 showed C* performances between 1600 to 3000 fps. Gas temperatures were highest for propane (1100 to 1900°F) (866 to 1311 K) while with both methane and RP-1 between 800 to 1300°F (700 to 977 K). Methane produced no carbon, while both RP-1 and propane deposited carbon above a certain threshold mixture ratio.

The results indicated that LO_2/RP-1 cannot be operated in the desirable temperature range (1400 - 1600°F) for gas generators without incurring substantial carbon buildup. On the other hand, LO_2/propane can be operated in the desired temperature range up to a maximum of 1500°F (1088 K), without carbon buildup. Operation with LO_2/methane is unrestricted over the desired gas generator operating temperature range. At the conclusion of the added scope test program, there were questions over the carbon deposition characteristics of high propellant injection density systems. The original and added scope programs used low propellant injection density gas generators. The desire to support full scale gas generator studies resulted in the recommendation to test high injection density gas generators on the follow-on program. In addition, at the conclusion of the added scope program it was recommended that additional testing be conducted using liquefied natural gas (LNG) to determine carbon buildup characteristics of low purity methane fuel, and that fuel-rich tests be conducted using propane to further define the sharp transition from no carbon buildup to excessive buildup. Also, it was recommended that the fuel chemistry for both propane and methane be incorporated into the Fuel Rich Combustion Model.

A. OBJECTIVES

The objectives of this follow-on contract are to use the existing hardware to verify and extend the database generated on the original test programs. The data to be obtained is the carbon deposition characteristics when methane is used at injection densities comparable to full scale values. The data base will be extended to include LNG testing at low injection densities for gas generator/preburner conditions. The testing shall be performed at mixture ratios between 0.25 and 0.60, and at chamber pressures between 750 and 1500 psia.

Introduction (cont.)

B. APPROACH

Aerojet TechSystems Company (ATC) will conduct a five task follow-on program to extend the carbon deposition database to include the use of LNG at low injection densities and methane at injection densities that replicate full scale gas generator operation with as much fidelity as is possible within the current hardware constraints. The LNG testing will be performed using the existing hardware. The high injection density methane testing will be performed by high injection flow rate constructing a new injector to meet the requirements. This injector will be used in conjunction with the existing carbon deposition hardware to evaluate carbon deposition of LO_2/methane as a function of mixture ratio and chamber pressure.

C. PROGRAM SCHEDULE

The program schedule includes 23 additional tests in Task III. Fifteen of the tests are scheduled for the high injection density testing and the remaining eight tests will occur during the LNG test series. The test activity and its accompanying support activities are shown in Figure 1. The scheduled technical period of performance is 20 months including one and one half months to obtain NASA/MSFC final report approval prior to publication. Timephasing and the task interrelationships are described in the next section.

D. DETAILED TASK DESCRIPTIONS

In support of the test activity, Task III, several activities must be completed: 1) gas generator requirements review; 2) hardware design and fabrication; 3) facility preparation and testing; 4) data analysis, and 5) reporting. This section describes in detail the scope of effort that will be performed on each task and its associated timephasing.

1. <u>Task 1 - Requirements</u>

The requirements review will be performed in two parts. At the program inception the existing Carbon Deposition hardware will be evaluated to determine the feasibility of using the existing turbine simulator, turbulence ring,

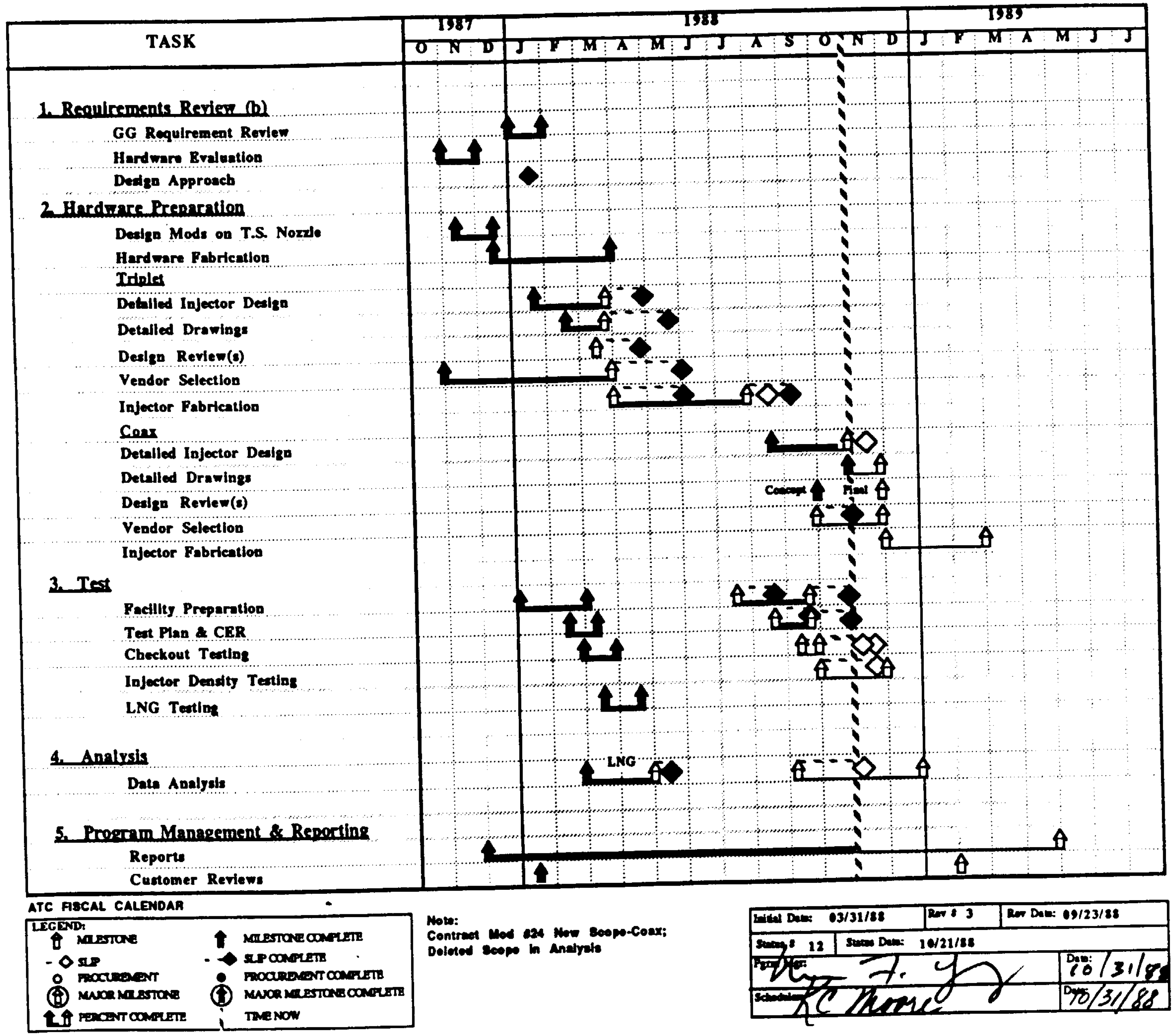

Figure 1. Program Schedule

and exit nozzles with the increased flow rates. Life analysis predictions and verification of the existing hardware will be performed and will be based on the testing performed to date. The open literature will be reviewed to determine the applicable injection density to be used with the Carbon Deposition hardware to simulate full scale gas generators. The task will conclude with a conceptual Design Review where an overview of the gas generator requirements and hardware evaluation will be presented. The task outputs will be a conceptual design approach for the injector, recommended test conditions, and determination of the adequacy of using the existing hardware for the higher flowrates.

2. Task 2 - Design and Fabrication of Experimental Hardware

Hardware design is scheduled to begin at program inception. This is possible because: (1) existing hardware is used as much as possible, (2) additional hardware pieces conform to existing hardware interfaces, (3) new hardware requirements were defined prior to program initiation, and (4) additional hardware requirements are less stringent than the original water-cooled designs. Wherever possible the hardware designs are direct derivatives of designs successfully demonstrated in one of the current or recently completed Aerojet LO_2/Hydrocarbon contracts. This has been done intentionally to provide justification of a design concept prior to its use.

The objective of this task is to produce detailed drawings for fabrication of the additional test hardware. The task involves analyses and mechanical design activity. This section describes the factors considered during the design stage, the supporting analyses, and the design details and features of the original hardware and, the new, uncooled hardware.

Three basic test assemblies are planned, one to simulate gas generator or preburner at low injection density conditions consistent with the current database and two at high injector densities. The two high injection density injectors are of the triplet and coax designs. To obtain the maximum experimental test data at minimum cost, the proposed test hardware is of modular design. The bolted module concept provides the greatest test hardware flexibility. Many of the components of the preburner assembly are interchangeable.

D, Detailed Task Descriptions (cont.)

a. Hardware Preparation

The hardware preparation will be performed in two parts. Beginning in the middle of program month two, the design modifications to existing hardware (turbine simulator, turbulence ring, and exit nozzle) will be performed. During this period the access port will be designed. Its function is to provide access to the upstream side of the turbine simulator to permit photographic documentation of carbon buildup after each test.

The detailed injector design will begin in month four. The design modifications to the existing injector manifold and faceplate will be performed. The injector faceplate design will incorporate elements as similar as possible to those identified for use in full scale, state-of-the-art LO_2/hydrocarbon booster engines. Detail drawings of the injector shall be prepared and existing drawings modified as required. Completion of the drawing package will be supported by the Project Office, Design, Thermodynamic and Stress analysis, and producibility. A Final Design Review of the injector will be conducted with the participation of the Project Office, Design, Analysis, Producibility, the Development Labs, Drafting, "A" Test Area, and Data Services.

b. Hardware Fabrication

A list of test hardware to be fabricated or modified for the follow-on contract is shown in Table I. Hardware fabrication will be initiated in the middle of the third program month. Fabrication of the high injection density injector was begun at the start of program month eight and will be completed by the end of program month eleven. Fab of the liq/liq coax is planned to begin in program month fourteen and be completed after month seventeen.

Test hardware will be fabricated at Aerojet TechSystems' approved vendor shops. Vendors will be selected on the basis of schedule requirements, quality requirements, and cost. The project engineer will coordinate the fabrication effort utilizing the Task 2 engineering drawings produced by the mechanical design department.

TABLE I

CARBON DEPOSITION STUDY ADDED SCOPE HARDWARE LIST

	Quantity
Preburner/Gas Generator	2
Turbine Simulator	2
Exit Nozzle	1
Turbulence Ring	1
Access Port	1

D, Detailed Task Descriptions (cont.)

3. Task 3 - Testing

Testing will be divided into five activities: (1) facility preparation, (2) test planning and critical experiment reviews, (3) checkout tests, (4) high injection density carbon deposition tests, and (5) LNG carbon deposition testing. Hardware facility preparation for the high injection density testing will begin in the middle of the tenth program month. The facility preparation and test planning will be conducted with a critical experiment review in the middle of the eleventh program month. Checkout for the high injection density testing is scheduled for the twelfth month. The high injection density carbon deposition testing is scheduled to begin at the start of the thirteenth month. Two months are allocated to the test series. Facility preparation for the LNG testing began on the third program month. The test planning was concluded at the end of the fifth month with a critical experiment review.

4. Task 4 - Data Analysis

Task 4 is scheduled to begin in the thirteenth program month and be completed at the end of the sixteenth month.

The objective of this task is to perform detailed data analysis. The data analysis effort will include: (1) comparison of measured and predicted combustion (C*) efficiency and combustion gas temperature, (2) flow data analysis to infer turbine simulator C_DA and carbon deposition rate, and (3) comparison of the results with the existing database.

5. Task 5 - Reporting

Eight bimonthly technical status reports will be published; eleven monthly fiscal reports will be distributed. Two program status reviews will be conducted as shown in Figure 1. The program final report draft will be submitted 30 days after completion of the program technical effort. Another 45 days will be scheduled for NASA review and subsequent ATC publication.

E. CURRENT STATUS

High Injection Density Injector

Originally scheduled for completion at the beginning of August, the high injection density injector was finally completed on 9/14/88. The schedule slip of 6 weeks was due largely due to a failure of the braze process by which the injector faceplate is attached to the body. This problem was solved after a delay of about 3 weeks. The remainder of the schedule slippage resulted from schedule slippages on the part of the fabrication vendors. Once the injector was completed, the final step was the proof test. This test was performed by attaching the backflush fixture and the injector and pressurizing with water. A schematic of this arrangement is shown in Figure 2. The proof test was completed on 9/14/88 with the injector being proof to 3300 psi. A leak check using GN_2 was also performed. The injector was pressurized with 100 psi nitrogen and held for 2 minutes. Because of the inability to separately seal-off the ox and fuel circuits at the faceplate, both circuits were checked simultaneously at the same pressure. With the completion of the proof and leak checks, the carbon deposition program high injection density injector was finished.

High Injection Density Testing

Although some work could be done, the majority of the preparation work required for the high injection density testing had to wait until the injector was completed. The first tasks were to perform a pattern check and measure the Kw values for both the ox and fuel circuits on the injector. The pattern check showed a good pattern on both ox and fuel circuits. Photographs of the pattern check are shown in Figure 3. The Kw measured for the fuel circuit was within 4% of the predicted value of .578 vs. .615, while the ox circuit Kw was within 2% of predicted, .155 vs. .157.

After the Kw measurements, the injector was cleaned to Level 400 and was then ready for installation. The injector was attached to the front end of the test

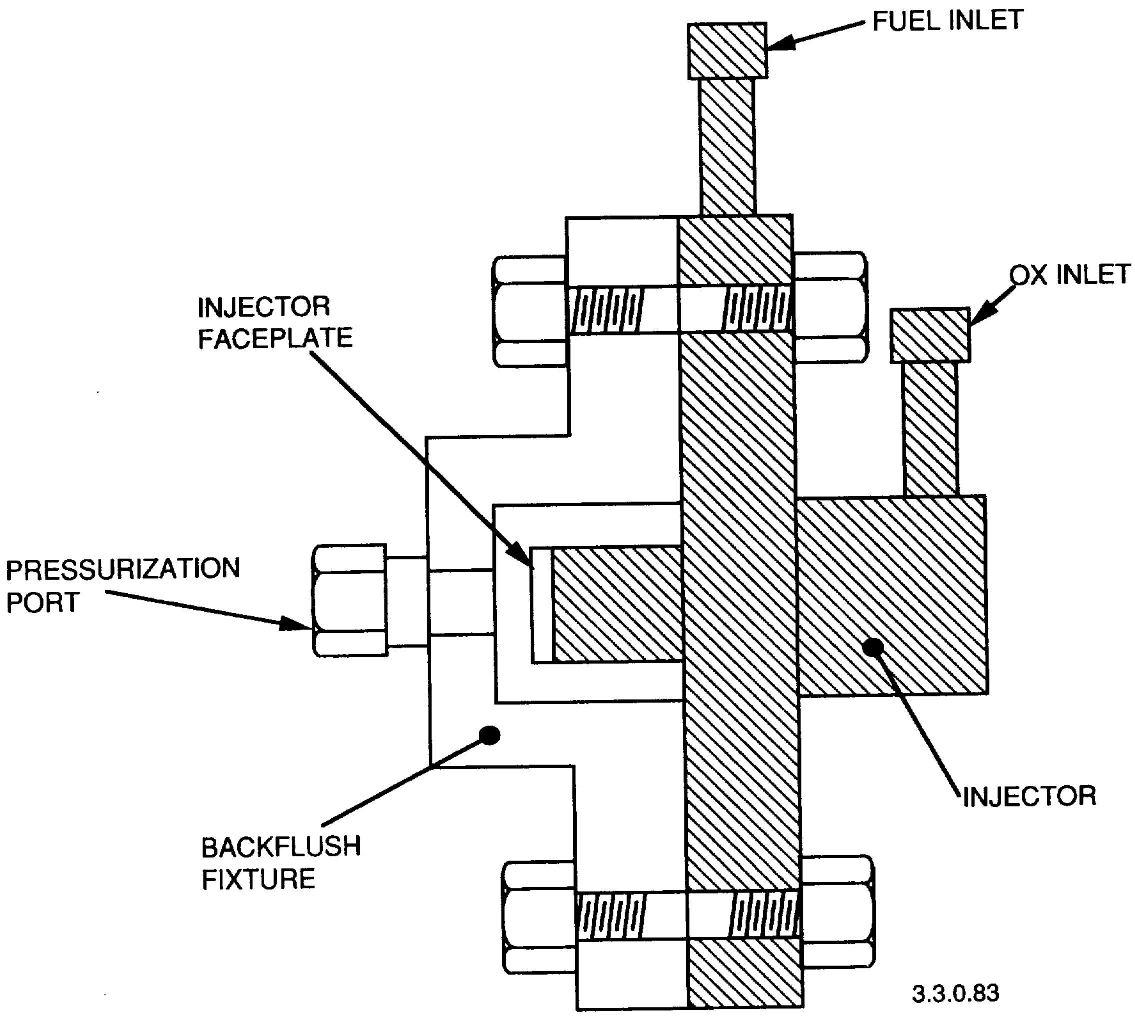

Figure 2. Proof Test Schematic

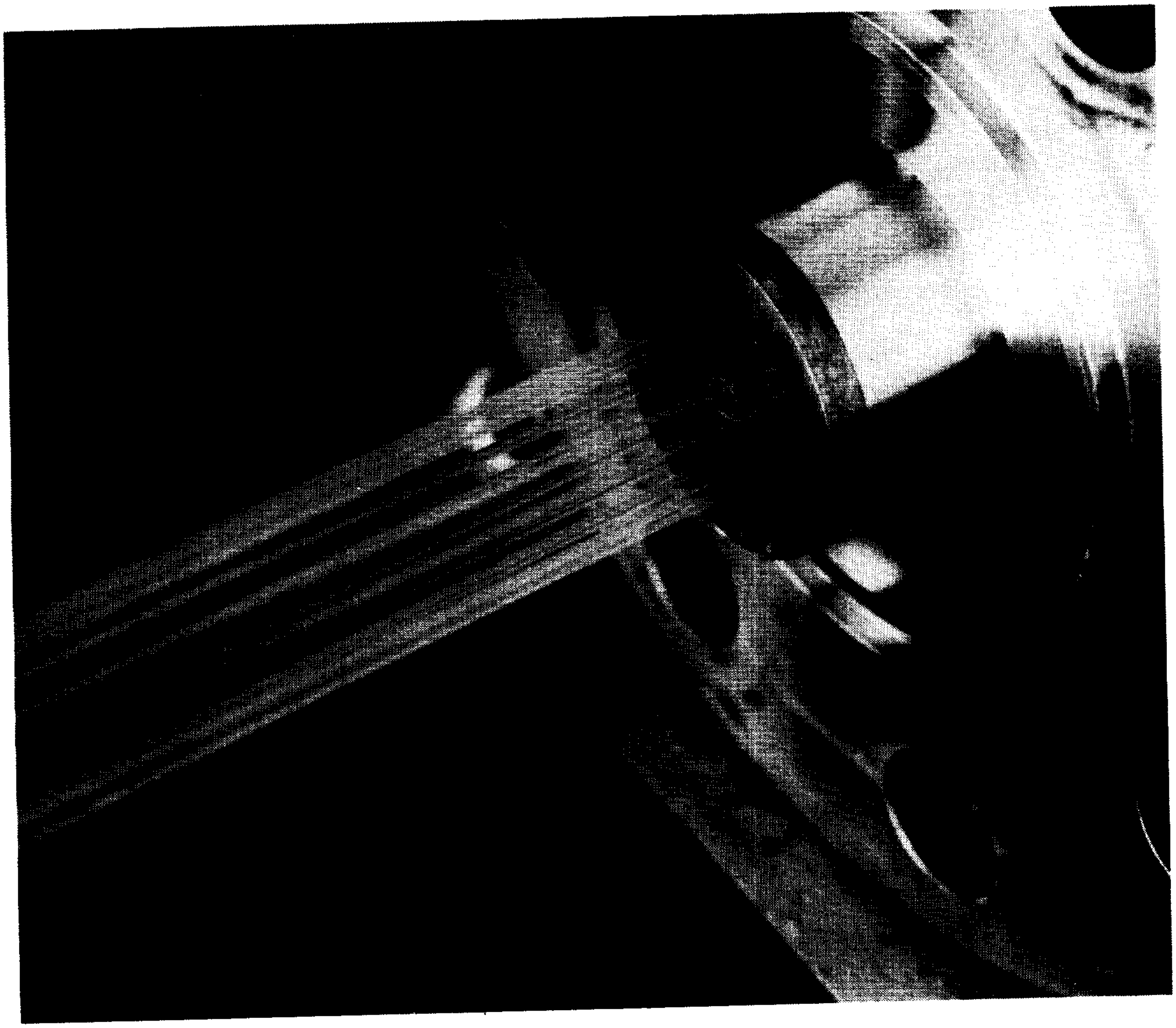

Figure 3A. Ox Circuit

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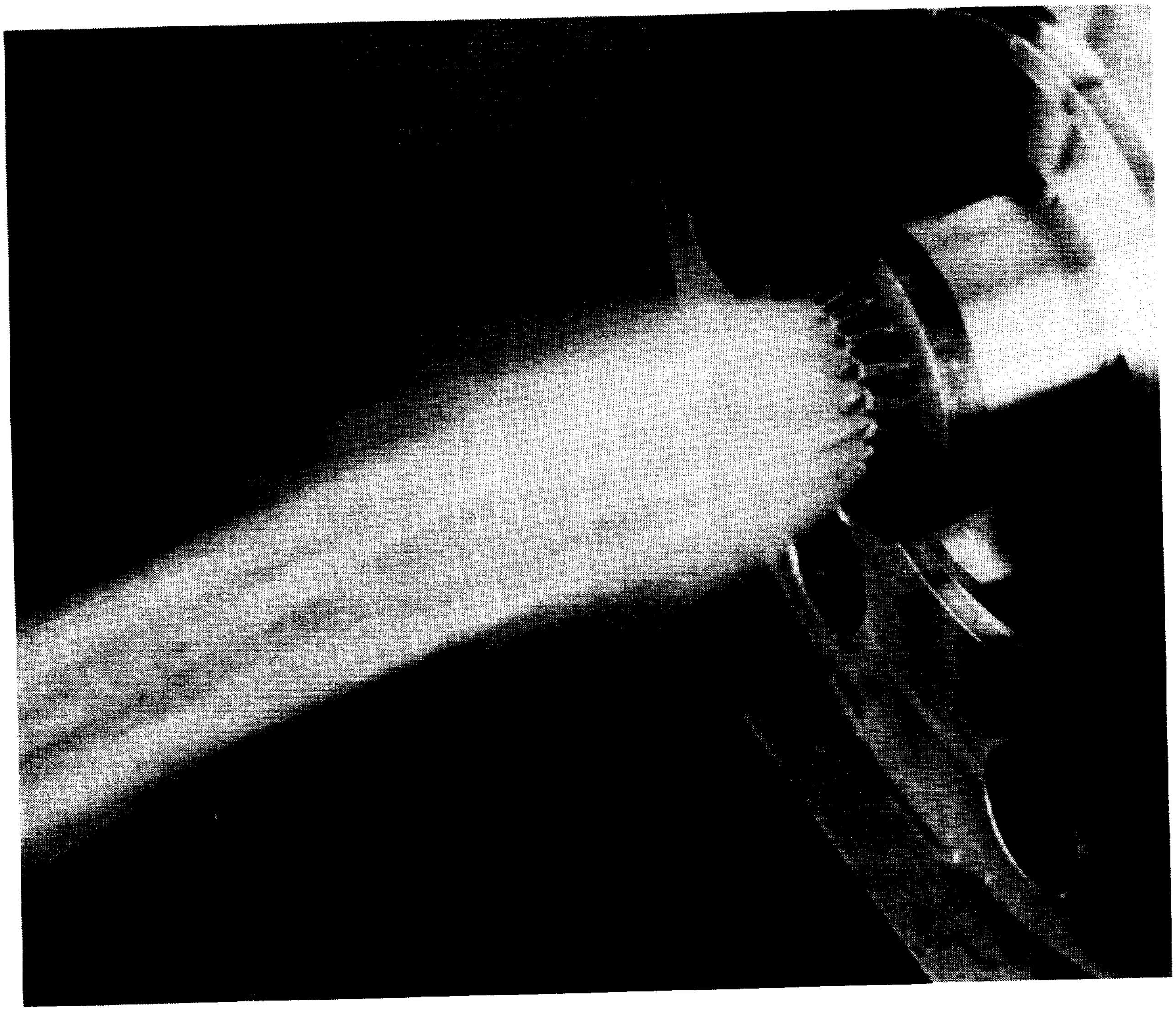

Figure 3B. Fuel Circuit

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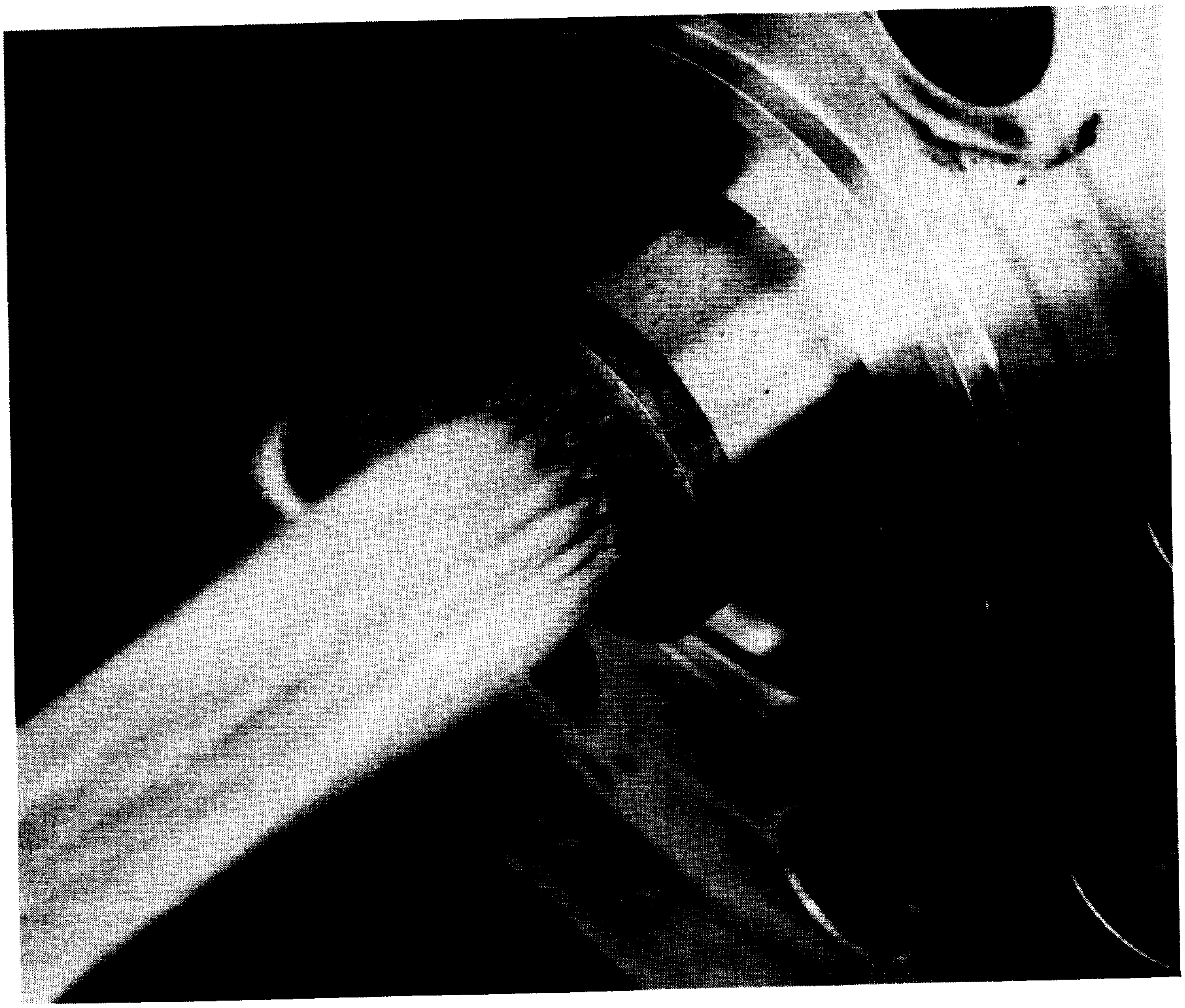
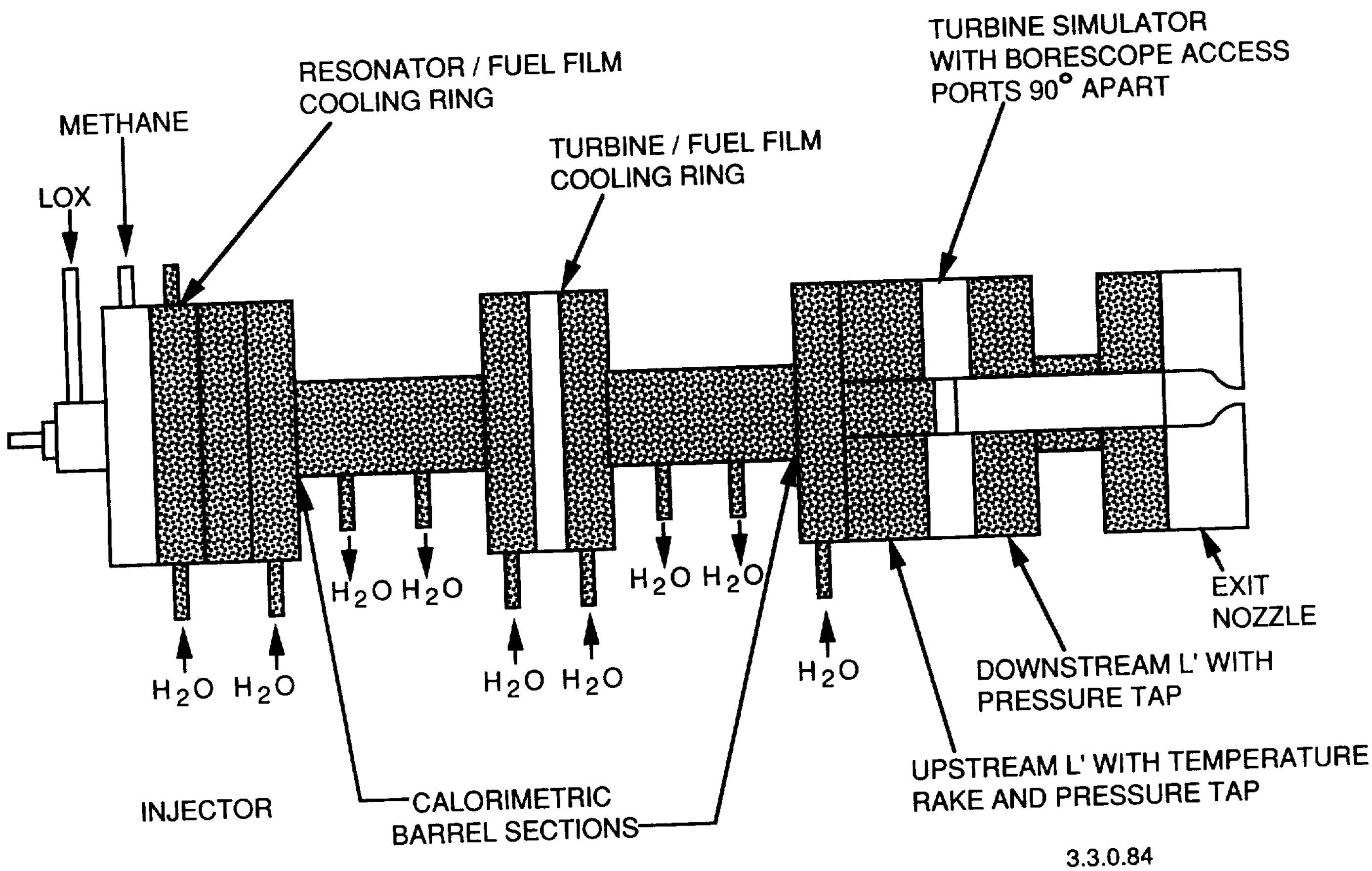


Figure 3C. Both Ox and Fuel Circuits

apparatus; subsequent pieces of the modular hardware were bolted into place, as shown in Figure 4. A total of 5 new pieces of hardware were installed to accommodate the high flowrate testing, relative to the previous methane and LNG testing. These were the injector, turbulence ring insert, upstream L' section, turbine simulator, and the exit nozzle. The pieces underwent, with the exception of the L' section, an enlargement of their respective flow areas. Boroscope ports into the upstream L' section were enlarged from 1/4" to 1/2", allowing the passage of a larger boroscope. Some of the thermocouples in the L' section were damaged during this machining process. These were removed and replaced, and more durable fittings were welded into place. Additionally, pitting on the O-ring surfaces of the L' section had not allowed proper sealing of the test apparatus, a problem compounded by the use of metal O-rings. The O-ring surfaces were machined to remove the pitting, which eliminated the problem. For the test apparatus itself, the only major refitting, other than the modular components mentioned, was that of the fuel and ox supply lines. Since the flow rates are 10 times higher than the previous testing, it was necessary to install larger lines. These lines transport propellant from the fuel and ox run tanks to the injector. The ox line went from a 1/2" line to a 3/4" line, which also required a larger flowmeter. The fuel line went from 1" to 1-1/2" line, and a filter and larger flowmeter were also installed. To accommodate the gas sampling to be done during the testing, a gas sampling system was installed. This consisted of a liter bottle made from 2" schedule 40 pipe, fitted with end caps and a pressure gauge. Hand valves on both ends allowed the bottle to be removed and taken to the Gas Chromatograph Lab. Solenoid valves in series with the hand valves allowed the bottle to be filled from the control room while the test was in progress. Figure 5 shows this arrangement. The boroscope apparatus for taking internal photographs remains largely as it was in the previous LNG testing, with the exception that the enlarged ports of the upstream L' section allows the use of a larger boroscope. The apparatus will accept both the video camera and a 35 mm camera.

Since the flowrates of this test series are considerably larger than that of the previous tests, the test durations have become limited by the fuel run tank capacity. The fuel run tank can hold 150 gallons of propellant, or about 440 lbm of liquid methane. This means that at the maximum fuel flowrate of 13.7 lbm/sec, the duration of the test is slightly over 32 seconds. The maximum test duration however is



NOTE: SKETCH NOT TO SCALE
Unshaded parts are new hardware

Figure 4. Assembly Schematic

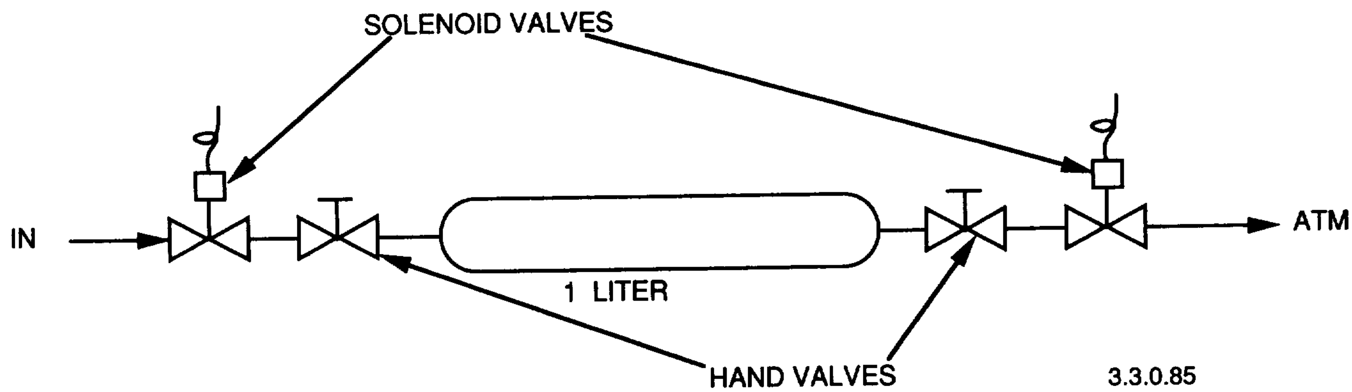


Figure 5. Gas Sampling System

about 100 seconds. All other tests fall in between these durations. These test durations, because of the very high flow rates, will provide sufficient time to determine whether carbon deposition is occurring. At this writing, the test control sequence will be programmed with the calculated fuel depletion time. This will allow the most reliable test run.

The entire test series was reviewed and examined at a Critical Experiment Review (CER) held on 5 October 1988. The review package is found in Appendix A. Currently, it is anticipated that the testing will be completed by mid November, two weeks ahead of schedule and in spite of the six week delay of the high injection density injector.

Liquid-Liquid Coax Injector

Concurrent with the testing being done, work on the liquid-liquid coaxial injector is nearing completion. A concept review for the injector design was held on 30 September 1988. Appendix B contains the Concept Review Handout and the action item list. In general, the review was successful and the design was well received. Nevertheless, a number of action items came out of the review. All proved to be resolvable and the closeout of the items is imminent. The final design review is currently scheduled for 18 November 1988. At this review, the final design will be approved and, pending the closeout of any resulting action items, the liquid-liquid coax injector will be ready for fabrication. Figure 6 shows the current coax injector schedule. The drawings for the injector will be completed after the final design review and prior to the fabrication phase.

F. PROBLEMS

There were no problems during this reporting period.

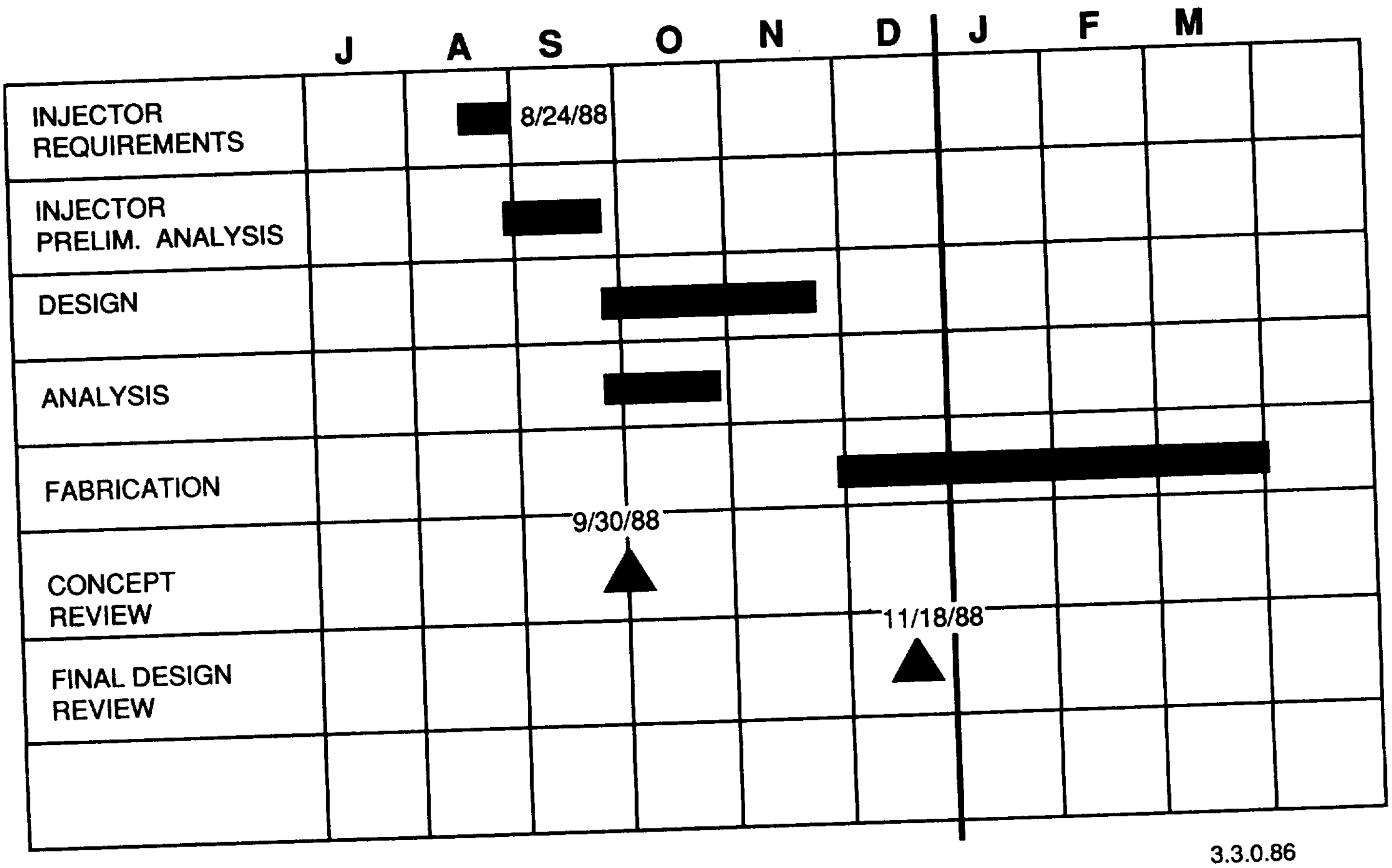


Figure 6. Coax Injector Schedule

APPENDIX A

CRITICAL EXPERIMENT REVIEW

AEROJET TechSystems COMPANY

CRITICAL EXPERIMENT REVIEW

CARBON DEPOSITION OF LOX/METHANE

NUMBER 10006

05 OCTOBER 1988

AEROJET TechSystems COMPANY

CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

AGENDA

INTRODUCTION/TEST OBJECTIVE........WERLING

TEST HARDWARE........BOSSARD

TEST MATRIX........BOSSARD

FACILITY OVERVIEW........KELLER

INSTRUMENTATION........THOMPSON

INJECTOR FLOW REQUIREMENTS........KELLER

IGNITER OPERATING CONDITIONS........KELLER

OPERATING SEQUENCE........THOMPSON

KILL PARAMETERS........THOMPSON

DATA REQUIREMENTS........BOSSARD

PHOTOGRAPHY........BOSSARD

ENVIRONMENTAL........KELLER

OPERATING PROCEDURES........KELLER

SCHEDULE........WERLING

ACTION ITEM REVIEW........WERLING

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AEROJET TechSystems COMPANY

CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

INTRODUCTION

- o CARBON DEPOSITION MODEL FOR OXYGEN - HYDROCARBON COMBUSTION
  - o LIQUID OXYGEN - METHANE
- o SECOND FOLLOW-ON CONTRACT FOR PROGRAM
  - o 1982 - BOTH MAIN ENGINE AND PREBURNER MODEL TESTING
    - o LIQUID OXYGEN - RP-1
  - o 1985 - FIRST FOLLOW-ON CONTRACT, PREBURNER MODEL TESTING
    - o LIQUID OXYGEN - LIQUID METHANE/LIQUID PROPANE
- o EXISTING TEST STAND AND TEST HARDWARE WILL BE USED
  - o HIGH INJECTION DENSITY INJECTOR WILL BE USED
  - o PROPELLANT FEED SYSTEMS UPGRADED

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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

PROGRAM OBJECTIVE

- QUANTIFY CARBON DEPOSITION AT FLOW RATES REPRESENTATIVE OF FULL-SCALE HARDWARE
  - 15 TESTS
  - $0.25 \leq MR \leq 0.6$
  - $1000 \text{ PSIA} \leq PC \leq 2000 \text{ PSIA}$
  - GAS SAMPLING

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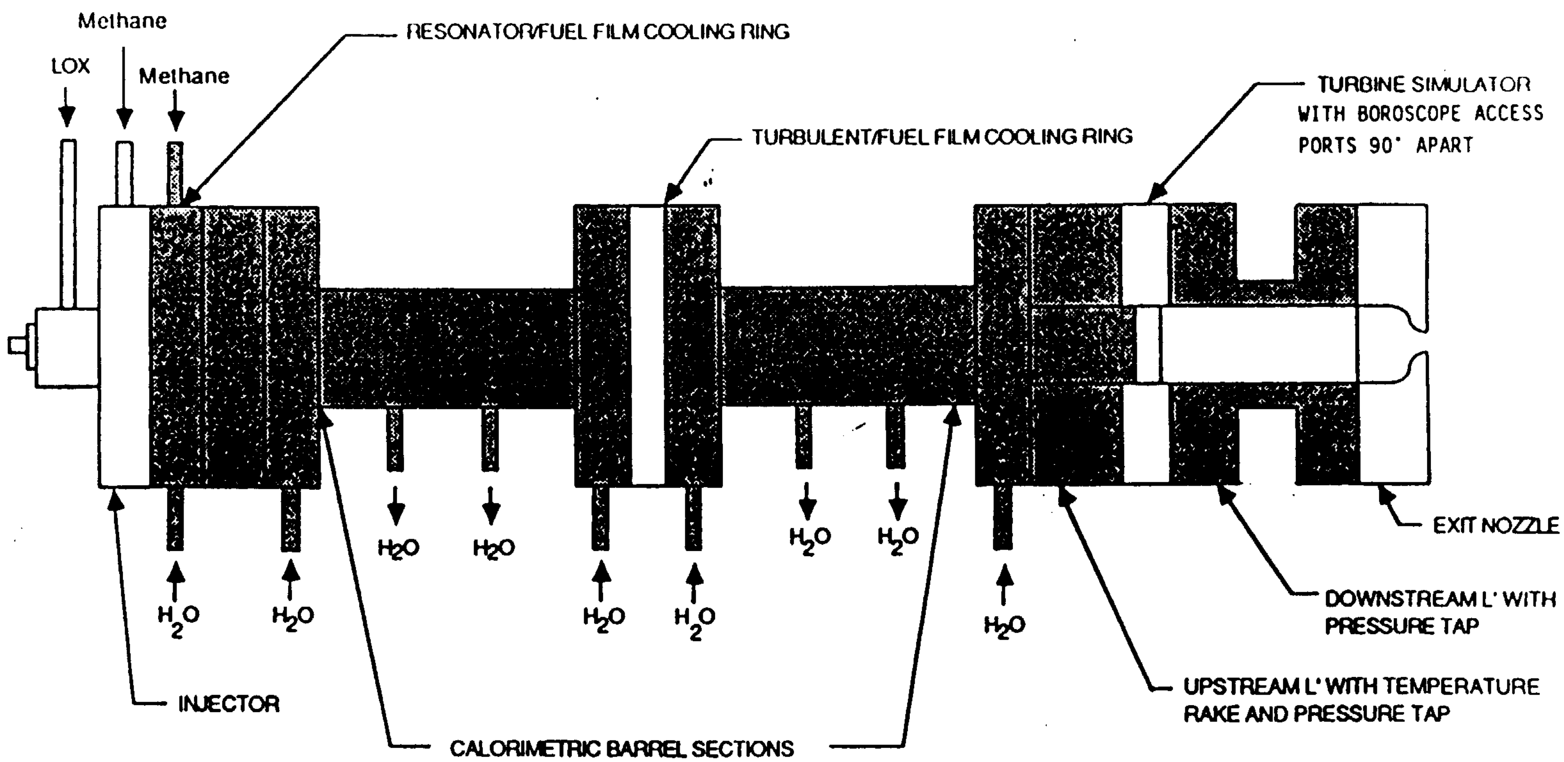
CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

ASSEMBLY SCHEMATIC



NOTE: SKETCH NOT TO SCALE
SHADE PARTS ARE EXISTING HARDWARE

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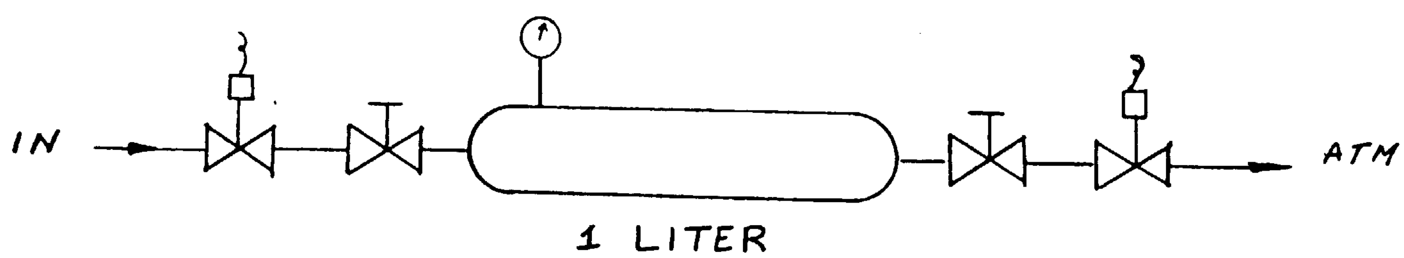
CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

GAS SAMPLING SYSTEM



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① Go over CER action items from previous LNG testing

CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST PLAN

TEST TYPE	TEST NUMBER	TEST OBJECTIVES	P_T OXID ESTIMATE (PSIA)	P_T FUEL ESTIMATE (PSIA)	NOMINAL P_C (PSIA)	NOMINAL MR	DURATION SECONDS	$\dot{W}$ OXID LB/SEC	LOX GALLON	$\dot{W}$ METHANE LB/SEC	METHANE GALLON
CHECKOUT	001	IGNITER COLD FLOW AND VALVE SEQUENCING									
	002	IGNITER COLD FLOW AND VALVE SEQUENCING									
	101	IGNITER CHECKOUT HOT FIRING	1200 GOX	1250 GH_2							
CHECKOUT	003	INJECTOR COLD FLOW AND VALVE SEQUENCING - OXID									
CHECKOUT	004	INJECTOR COLD FLOW AND VALVE SEQUENCING - FUEL									
	102	INJECTOR CHECKOUT FIRING	1066	1346	1000	0.20	1	1.37		6.86	
	103	INJECTOR CHECKOUT FIRING	1066	1346	1000	0.20	10	1.37		6.86	
	104	1000 P_C TESTS	1066	1346	1000	0.20	60	1.37	9	6.86	140
	105	1000 P_C TESTS	1123	1187	1000	0.37		1.87		5.04	
	106	1000 P_C TESTS	1688	1109	1000	0.60		2.31		3.85	
	107	1500 P_C TESTS	1648	2276	1500	0.20		2.05		10.28	
	108	1500 P_C TESTS	1775	1918	1500	0.37		2.79		7.54	
	109	1500 P_C TESTS	1843	1823	1500	0.47		3.12		6.63	
	110	1500 P_C TESTS	1891	1770	1500	0.55		3.33		6.06	
	111	1500 P_C TESTS	1920	1744	1500	0.60		3.45		5.76	
	112	1500 P_C TESTS	1975	1502	1500	0.70		3.67		5.24	

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AEROJET TechSystems COMPANY

CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST PLAN (CONT)

TEST TYPE	TEST NUMBER	TEST OBJECTIVES	P_T OXID ESTIMATE (PSIA)	P_T FUEL ESTIMATE (PSIA)	NOMINAL P_C (PSIA)	NOMINAL MR	DURATION SECONDS	$\dot{W}$ OXID LB/SEC	LOX GALLON	$\dot{W}$ METHANE LB/SEC	METHANE GALLON
	113	2000 P_C TESTS	2265	3376	2000	0.2		2.74		13.69	
	114	2000 P_C TESTS	2486	2740	2000	0.37		3.71		10.04	
	115	2000 P_C TESTS	2608	2571	2000	0.47		4.15		8.82	
	116	2000 P_C TESTS	2692	2476	2000	0.55		4.43		8.05	
	117	2000 P_C TESTS	2743	2430	2000	0.60		4.59		7.65	
	118	2000 P_C TESTS	2840	2357	2000	0.70		4.88		6.97	

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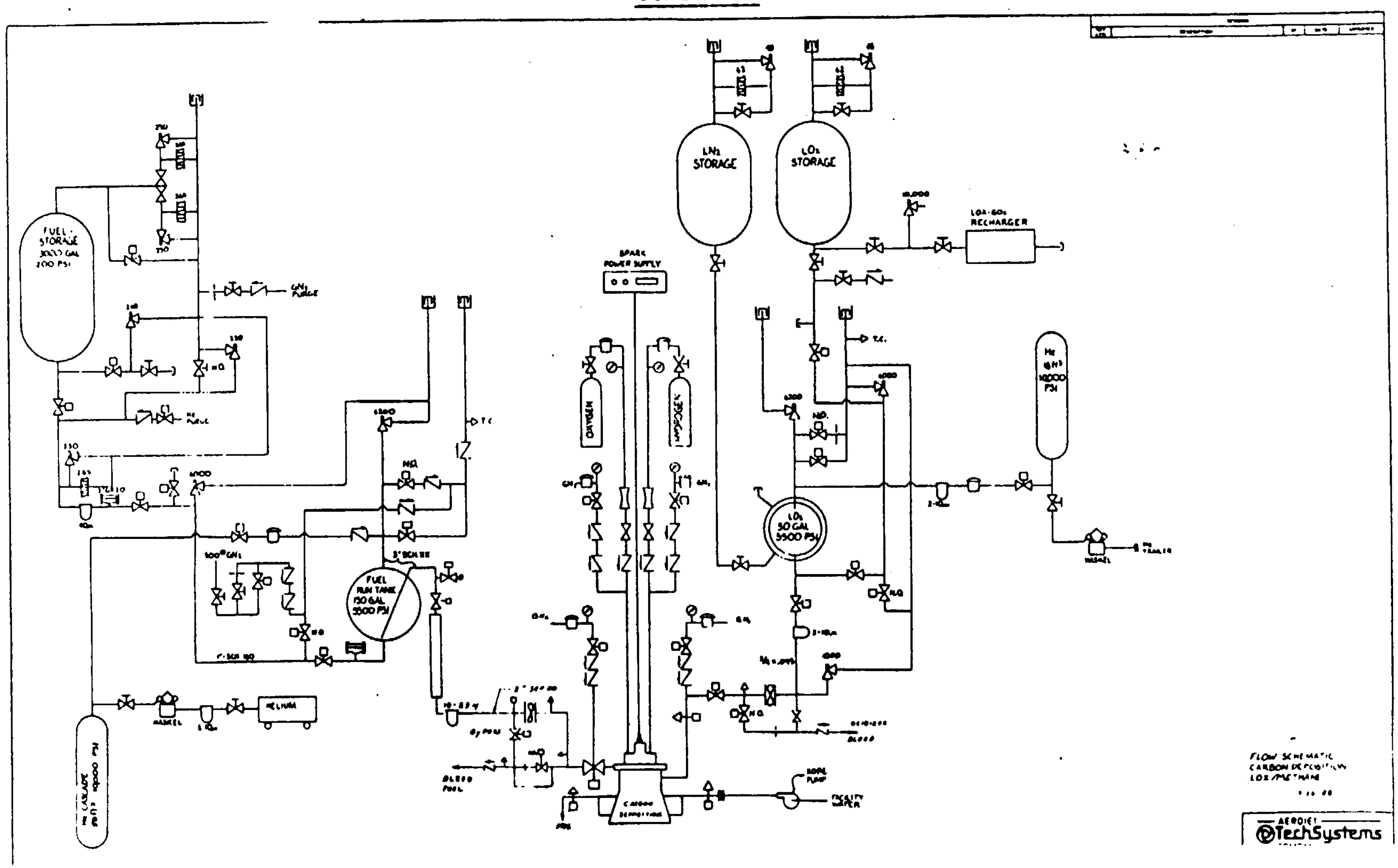
AEROJET TechSystems COMPANY

CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

SCHEMATIC



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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST STAND DETAIL

- LIQUID OXYGEN SYSTEM DESIGN REQUIREMENTS
  - SUPPLY LOX TO GAS GENERATOR INLET
    - 2800 PSIA, 200°R, 5.0 POUNDS/SECOND MAXIMUM
  - SAFETY PROCEDURE 13 "PRESSURIZED EQUIPMENT" APPLIES
  - ALL COMPONENTS LOX COMPATIBLE
  - LINE VELOCITY 50 FT/SECOND MAXIMUM
  - PRECLUDE CRYOGENIC LOCKUP

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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST STAND DETAIL (CONT)

- LIQUID OXYGEN SYSTEM COMPONENT REVIEW
  - LIQUID OXYGEN STORAGE TANK
    - HERRICK JOHNSTON 1800 GALLON, VACUUM JACKETED TANK
    - 50 PSI WORKING PRESSURE, RUPTURE DISK RELIEVED
    - EXISTING FACILITY INSTALLED IN 1985
  - LOX LINE FILL VALVE - ISOLATES STORAGE TANK
    - 1 INCH CCI RSOV, 6000 PSI WORKING PRESSURE
    - STAINLESS STEEL BODY SEAT AND PINTEL, TEFLON SOFT GOODS
    - CCI RSOVS USED WITHOUT INCIDENT FOR YEARS

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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST STAND DETAIL (CONT)

- LIQUID OXYGEN SYSTEM COMPONENT REVIEW (CONT)
  - LIQUID OXYGEN RUN TANK
    - SOUTHWEST WELDING, 50 GALLON, VACUUM JACKETED
    - 5500 PSI WORKING PRESSURE, PRESSURE RELIEF VALVE
    - VACUUM JACKET, RUPTURE DISK RELIEVED
    - LOX TANK SAFETY VALVE
    - 1 INCH CCI RSOV, 6000 PSI WORKING PRESSURE
    - STAINLESS STEEL BODY SEAT AND PINTEL, TEFLON SOFT GOODS
    - CCI RSOVS USED WITHOUT INCIDENT FOR YEARS
    - STAINLESS STEEL WELDS PICKLED AND BRUSHED
    - LINE PROOF PRESSURE TESTED TO 5500 PSI
  - LOX SUPPLY LINE FILTER - 10 MICRON
    - 1 INCH MICROPORUS, 6000 PSI WORKING PRESSURE
    - STAINLESS STEEL BODY AND FILTER

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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST STAND DETAIL (CONT)

- o LIQUID OXYGEN SYSTEM COMPONENT REVIEW (CONT)
  - o LOX LINE BLEED - CHILL DOWN AND RUN SYSTEM
    - o 1/2 INCH CCI RSOV, 6000 PSI WORKING PRESSURE BLEED VALVE
    - o 1 INCH CCI RSOV, 6000 PSI WORKING PRESSURE OTCV
    - o STAINLESS STEEL BODY PINTEL AND SEAT, TEFLON SOFT GOODS
    - o CCI RSOVS USED WITHOUT INCIDENT FOR YEARS
  - o FLOW MEASURING
    - o 3/4 INCH TURBINE FLOWMETER
  - o OXIDIZER THRUST CHAMBER VALVE
    - o 1 INCH CCI RSOV, 6000 PSI WORKING PRESSURE
    - o STAINLESS STEEL BODY PINTEL AND SEAT, TEFLON SOFT GOODS

VWG:AA0798

CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST STAND DETAIL (CONT)

- LIQUID OXYGEN SYSTEM COMPONENT REVIEW (CONT)
  - RUN LINE - TANK SAFETY
    - 3/4 INCH STAINLESS STEEL TUBING, 0.065 WALL, 3500 PSI WORKING PRESSURE
    - AN 37° FLARED FITTINGS
  - LOX FLOWMETER BYPASS - PREVENTS FLOWMETER OVERSPEED DURING CHILL IN
    - 1/2 INCH CCI RSOV, 6000 PSI VALVE
    - VALVE PREVIOUSLY USED IN LOX SERVICE
  - RUN LINE RELIEF VALVE - PREVENTS OVERPRESSURE DUE TO CRYOGENIC LOCKUP
    - SET TO RETURN AT 4500 PSI

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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST STAND DETAIL (CONT)

o LIQUID OXYGEN SYSTEM FAILURE ANALYSIS

FAILURE MODE	INDICATOR	EFFECT
LOX TANK SAFETY DOES NOT OPEN OR CLOSE PREMATURELY	LOW POJ, P_C,	LOW P_C KILL
LOX TANK REGULATOR FAILS OPEN	HIGH POJ, P_C	HIGH PC KILL, HIGH TCR-1, 5 KILL POSSIBLE HARDWARE DAMAGE
LOX TANK REGULATOR FAILS CLOSED	LOW POJ, P_C	LOW P_C KILL
LOX FLOWMETER BYPASS DOES NOT OPEN	NO TEMPERATURE DROP	CHILL IN DOES NOT BEGIN
LOX FLOWMETER BYPASS DOES NOT CLOSE	LOW OXIDIZER FLOW	INACCURATE FUEL FLOW MEASUREMENT. ALL OTHER PARAMETERS LOOK GOOD, SLIGHTLY HIGH OXIDIZER FLOW POSSIBLE

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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST STAND DETAIL (CONT)

o LIQUID OXYGEN SYSTEM FAILURE ANALYSIS (CONT)

FAILURE MODE	INDICATOR	EFFECT
LOX LINE BLEED DOES NOT CLOSE	VISUAL VENTING PRIOR TO FS_1	NO EFFECT ON TEST HARDWARE, RESULTS IN FUEL RICH MR LOW P_C KILL
LOX LINE BLEED DOES NOT OPEN	T_{OX} DOES NOT REACH TARGET TEMPERATURE	TEST TERMINATED
OTCV FAILS TO OPEN OR CLOSES PREMATURELY	OLVDT, LOW P_C	NO IGNITION, LOW P_C KILL

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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST STAND DETAIL (CONT)

o LIQUID OXYGEN SYSTEM FAILURE ANALYSIS (CONT)

FAILURE MODE	INDICATOR	EFFECT
OTCV FAILS TO CLOSE AT FS_2	OLVDT, P_C CONTINUES,	OX RICH SHUTDOWN, POSSIBLE HARDWARE DAMAGE. HAZARDOUS CONDITION MINIMIZED BY RAPID GN_2 PURGE OF ENGINE, BOTH OXIDIZER AND FUEL CIRCUITS SEQUENCED ON BY COMPUTER. SINGLE POINT SAFETY BACKUP BY SEQUENCED OF POT SAFETY CLOSED AT FS_2. LOX FLOW CAN BE TERMINATED BY CLOSURE OF OXIDIZER TANK SAFETY.

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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST STAND DETAIL (CONT)

- o LIQUID METHANE SYSTEM DESIGN REQUIREMENTS
  - o SUPPLY LIQUID METHANE TO GAS GENERATOR INLET
  - o SAFETY PROCEDURE 13 "PRESSURIZED EQUIPMENT" APPLIES
  - o EXISTING RUN TANK, STORAGE TANK AND FILL SYSTEM USED AS IS

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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST STAND DETAIL (CONT)

- LIQUID METHANE SYSTEM COMPONENT REVIEW
  - FUEL RUN TANK SAFETY - ISOLATES RUN TANK FROM RUN LINE
    - 2 INCH CALMEC RSOV, 7000 PSI VALVE
    - VALVE PREVIOUSLY USED IN LNG SERVICE
  - FUEL FLOWMETER BYPASS - PREVENTS FLOWMETER OVERSPEED DURING CHILL IN
    - 1 INCH CCI RSOV, 6000 PSI VALVE
    - VALVE PREVIOUSLY USED IN LNG SERVICE
  - FLOW MEASUREMENT SECTION
    - 2 INCH SCH 80 PIPE, 3500 PSI WORKING PRESSURE, 5500 PROOF PRESSURE
    - TURBINE TYPE FLOWMETER 2 INCH A.N.
  - RUN LINE RELIEF VALVE - PREVENTS OVERPRESSURE DUE TO CRYOGENIC LOCKUP
    - SET TO RELIEVE AT 4500
  - VACUUM JACKETED RUN LINE
    - STAINLESS STEEL 5500 PSI WORKING PRESSURE
    - BURST DISK PREVENTS JACKET RUPTURE

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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST STAND DETAIL (CONT)

- LIQUID METHANE SYSTEM COMPONENT REVIEW (CONT)
  - INLINE FILTER - 25 MICRON
    - STAINLESS STEEL, 3600 PSI WORKING PRESSURE
  - FUEL LINE BLEED VALVE, NORMALLY OPEN - LINE CHILL IN AND VENT
    - 1/2 INCH CCI RSOV, 6000 PSI WORKING PRESSURE
    - OUTLET PLUMBED TO BLEED EXTENSION LINE
  - FUEL THRUST CHABMER VALVE
    - DUAL 1 INCH CCI RSOV, 6000 PSI WORKING PRESSURE
    - LINEAR POSITION INDICATOR INSTALLED
  - INSULATION FROM TANK TO FTCV
    - VACUUM JACKETED RUN LINE TO FLOWMETER SECTION
    - MECHANICAL INSULATION FLOW SECTION TO FTCV

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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST STAND DETAILS (CONT)

- o LIQUID METHANE SYSTEM FAILURE ANALYSIS

FAILURE MODE	INDICATOR	EFFECT
TANK PRESSURE REGULATOR FAILS OPEN	PFT/CASCADE PRESSURE	TANK PRESSURE APPROACHES CASCADE PRESSURE OF 6600 PSI MAXIMUM. LINE PRESSURE RELIEF VALVE WILL OPEN,. HIGH P_C KILL
TANK VENT FAILS OPEN	AUDIBLE VENTING, LOW PFT	EXCESSIVE GH_2 USE. CAN'T ACHIEVE RUN PRESSURE
FUEL FLOWMETER BYPASS DOES NOT OPEN	NO TEMPERATURE DROP	CHILL IN DOES NOT BEGIN
FUEL FLOWMETER BYPASS DOES NOT CLOSE	LOW FMF	INACCURATE FUEL FLOW MEASUREMENT. ALL OTHER PARAMETERS LOOK GOOD, SLIGHTLY HIGH FUEL FLOW POSSIBLE

CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST STAND DETAIL (CONT)

o LIQUID METHANE SYSTEM FAILURE ANALYSIS (CONT)

FAILURE MODE	INDICATOR	EFFECT
FUEL RUN TANK SAFETY DOES NOT OPEN OR CLOSES PREMATURELY	PFFM	NO IGNITION - TEST TERMINATION OX RICH SHUTDOWN AS FUEL FLOW DECAYS POSSIBLE HARDWARE DAMAGE, LINE CHILL IN DOES NOT BEGIN
FUEL RUN TANK SAFETY DOES NOT CLOSE	PRESSURE IN RUN LINE	METHANE FLOWS OUT OF FUEL LINE BLEED TO ATMOSPHERE AFTER TANK VENTS TO AMBIENT
FUEL BLEED VALVE DOES NOT OPEN	NO VISABLE INDICATION OF FUEL BLEED. T BLEED READING ABOVE DESIRED TEMPERATURE	SEQUENCE TERMINATION
FUEL BLEED VALVE DOES NOT CLOSE	EXCESSIVE FMF READING, LOW PFJ, HIGH TCR-1	PROBABLE HIGH MR CONDITION, POSSIBLE TCR-1 > 1900°R KILL

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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST STAND DETAIL (CONT)

- LIQUID METHANE SYSTEM FAILURE ANALYSIS (CONT)

FAILURE MODE	INDICATOR	EFFECT
FUEL TCV DOES NOT OPEN OR CLOSES PREMATURELY	FLVDT, FMF, HIGH TCR-1, LOW PC	LOW P_C KILL - NO IGNITION OX RICH SHUTDOWN, POSSIBLE HARDWARE DAMAGE, OX RICH CONDITION IN ENGINE SYSTEM AUTOMATIC GN_2 PURGE OF OXIDIZER AND FUEL CIRCUITS
FUEL TCV DOES NOT CLOSE	FMF, PFJ, LOW TCR-1	RAPIDLY COOL GAS GENERATOR CHAMBER, OVERSPEED FMF, FUEL RICH SHUTDOWN, NO HARDWARE DAMAGE, CLOSE RUN TANK SAFETY, AUTOMATIC GN_2 PURGE OF ENGINE SYSTEM, BOTH OXIDIZER AND FUEL CIRCUITS

VWG:AA0798

CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST STAND DETAIL (CONT)

- LIQUID METHANE SYSTEM CLEANLINESS
  - ALL WELDED AREAS PICKLED
  - SYSTEM COMPONENTS UPSTREAM OF FILTER FIELD CLEANED
  - FILTER AND DOWNSTREAM COMPONENTS CLEANED TO LVL 400 PER ATC-STD-4940
  - PROPELLANT BLEED LINE EXITS SEPARATED BY 50 FEET
  - PROPELLANT LINE BETWEEN TANK SAFETIES AND ENGINE TCV'S ARE PROTECTED BY PRESSURE RELIEF VALVES
  - FLOWMETERS HAVE BYPASS BLEED VALVES TO PROTECT FROM OVERSPEED
  - SAFETY OF THE HARWARE IS PROTECTED BY KILL PARAMETERS

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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST STAND DETAIL (CONT)

- GO_2/GH_2 IGNITER FAILURE ANALYSIS

FAILURE MODE	INDICATOR	EFFECT
OXIDIZER OR FUEL VALVES FAIL TO OPEN	NO POJ/PFJ OR P_C IGNITER INCLINATION	NO IGNITION IGNITERS, TEST TERMINATION BY SEQUENCE, NO HARDWARE DAMAGE

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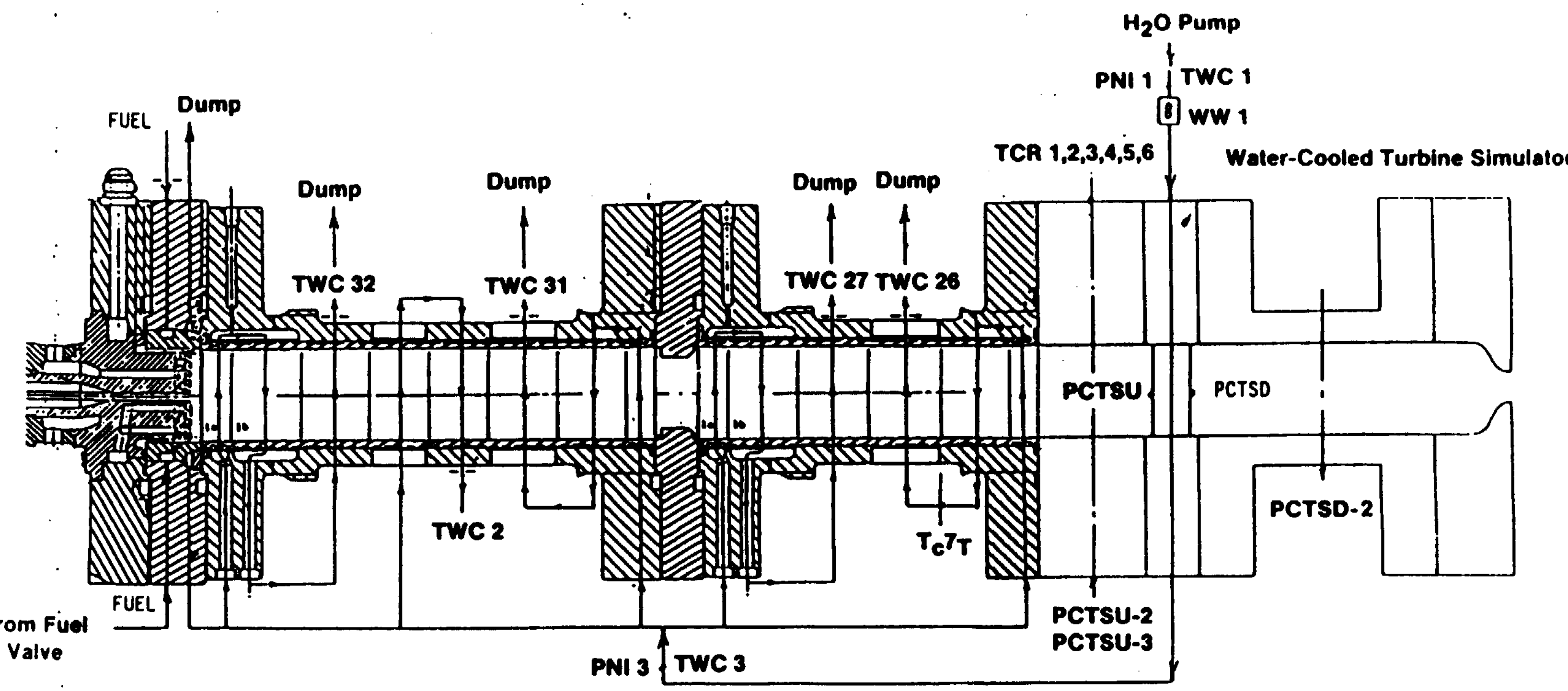
CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

① E Outboard Ignition & Plume?

HARDWARE INSTRUMENTATION



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Aerojet TechSystems Company

CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

INSTRUMENTATION

Parameter	Symbol	Transducer Type	Range	Accuracy + % Reading	Recording Device FM	Recording Device O-Graph	Recording Device Digital
Igniter Ox Injection Pressure	POJI	Strain Gauge	0-3000 psi	0.45		X	X
Igniter Fuel Injection Pressure	PFJI	Strain Gauge	0-3000 psi	0.45		X	X
Igniter Ox Purge Pressure	POPI	Gauge	0-500 psi	0.45			
Igniter Fuel Purge Pressure	PFPI	Gauge	0-500 psi	0.45			
Injector Fuel Purge Pressure	PPOJ	Gauge	0-500 psi	0.45		X	X
Injector Fuel Purge Pressure	PPFJ	Gauge	0-500 psi	0.45		X	X
Ox Tank Pressure	POT	Strain Gauge	0-3000 psi	0.45		X	X
Fuel Tank Pressure	PFT	Strain Gauge	0-3000 psi	0.45		X	X
Ox Injection Pressure	POJ	Strain Gauge	0-3000 psi	0.45		X	X
Fuel Injection Pressure	PFJ	Strain Gauge	0-3000 psi	0.45		X	X
Chamber Pressure (Injector)	PC-1	Strain Gauge	0-3000 psi	0.45		X	X
Tur Sim Upstream Pressure (water-cooled)	PCTSU	Strain Gauge	0-2000 psi	0.45			X
Tur Sim Downstream Pressure (water-cooled)	PCTSD	Strain Gauge	0-2000 psi	0.45			
Tur Sim Upstream Pressure (uncooled)	PCTSU-2,-3	Strain Gauge	0-3000 psi	0.25			
Tur Sim Downstream Pressure (uncooled)	PCTSD-2	Strain Gauge	0-3000 psi	0.25			
Water Inlet Pressure	PW I-1, -3	Strain Gauge	0-3000 psi	0.45		X	X
Tur Sim Pressure Drop (uncooled)	PDCDP	Strain Gauge	0-500 psi	Class 5			X
Water Flow 2 each	WW-1, -2	Turbine	0-20 lb/sec	0.5			X
Ox Flowmeter Temperature	TOFM	Thermocouple	-300 to -200 F	0.5			X
Fuel Flowmeter Temperature	TFFM	Thermocouple	50 to 100 F	0.5			
Water Inlet Temperature	TWC-1	Thermocouple	50 to 100 F	0.5			
Water Outlet Temperature	TWC-2, -3,	Thermocouple	50 to 300 F	0.5			
Chamber Wall Temperature	TC-7	Thermocouple	0 to 2000 F	0.5			
Chamber Wall Rake Temperature	TCR-1 -6'	Thermocouple	0 to 2000 F	0.5			
*High Frequency Ox Injection	KOJ	Piezioelectric	0 to 3000	5.0	X		
*High Frequency Fuel Injection	KFJ	Piezioelectric	0 to 3000	5.0	X		
[illegible] Control Valve Trace	LTOCV	Potentiometer	0 to 100%	1.0		X	X

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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

INSTRUMENTATION (CONT)

Parameter	Symbol	Transducer Type	Range	Accuracy + % Reading	Recording Device FM	Recording Device O-Graph	Recording Device Digital
Fuel Control Valve Trace	LTFCV	Potentiometer	0 to 100%	1.0		X	X
Ox Control Valve Signal	VOCV	Voltage	0 to 100%	-		X	
Fuel Control Valve Signal	VFCV	Voltage	0 to 100%	-		X	
Ox Igniter Valve Current	COIV	Amperage	0 to 100%	-		X	
Fuel Igniter Valve Current	CFIV	Amperage	0 to 100%	-		X	
Ox Igniter Valve Signal	VOIV	Voltage	0 to 100%	-		X	
Fuel Igniter Valve Signal	VFIV	Voltage	0 to 100%	-		X	
Instrumentation for High Injection Density Testing							
Ox Flow Rate	WO-1	Turbine	0-10 lb/sec	0.5		X	X
Fuel Flow Rate	WF-1	Turbine	0-20 lb/sec	0.5		X	X

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AEROJET TechSystems COMPANY

CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

INJECTOR FLOW REQUIREMENTS

PC (PSIA)	MR	CSTAR (FPS)	THROAT AREA SQ. INCH	WT (LBM/S)	WOX (LBM/S)	WF (LBM/S)	DPO (PSID)	DPF (PSID)	POT (PSIA)	PFT (PSIA)
1000	0.20	3068	.785	8.23	1.37	6.86	66.2	346	1066	1346
1000	0.37	3654	.785	6.91	1.87	5.04	123.4	187	1123	1187
1000	0.60	4097	.785	6.16	2.31	3.85	188	109	1188	1109
1500	0.20	3072	.785	12.33	2.05	10.28	148	776	1648	2276
1500	0.37	3666	.785	10.33	2.79	7.54	275	418	1775	1918
1500	0.47	3889	.785	9.75	3.12	6.63	343	323	1843	1823
1500	0.55	4035	.785	9.39	3.33	6.06	391	270	1891	1770
1500	0.60	4114	.785	9.21	3.45	5.75	420	244	1920	1744
1500	0.70	4250	.785	8.91	3.67	5.24	475	202	1975	1702
2000	0.20	3075	.785	16.43	2.74	13.69	265	1376	2265	3376
2000	0.37	3675	.785	13.75	3.71	10.04	486	740	2486	2740
2000	0.47	3899	.785	12.97	4.15	8.82	608	571	2608	2571
2000	0.55	4046	.785	12.48	4.43	8.05	692	476	2692	2476
2000	0.60	4125	.785	12.24	4.59	7.65	743	430	2743	2430
2000	0.70	4263	.785	11.85	4.88	6.97	840	357	2840	2357

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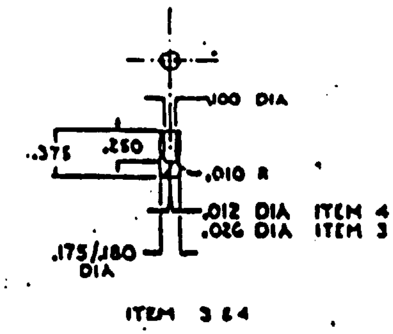
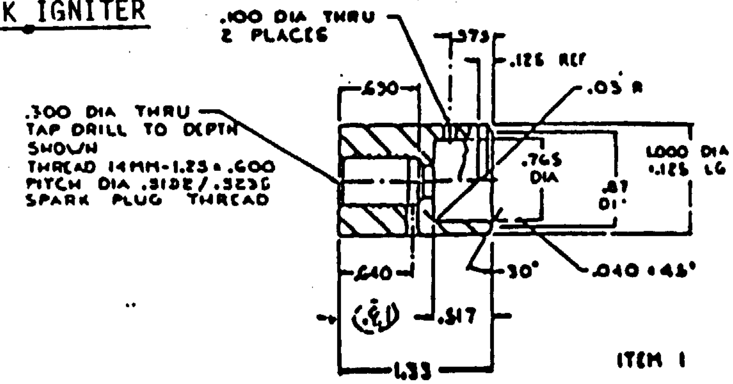
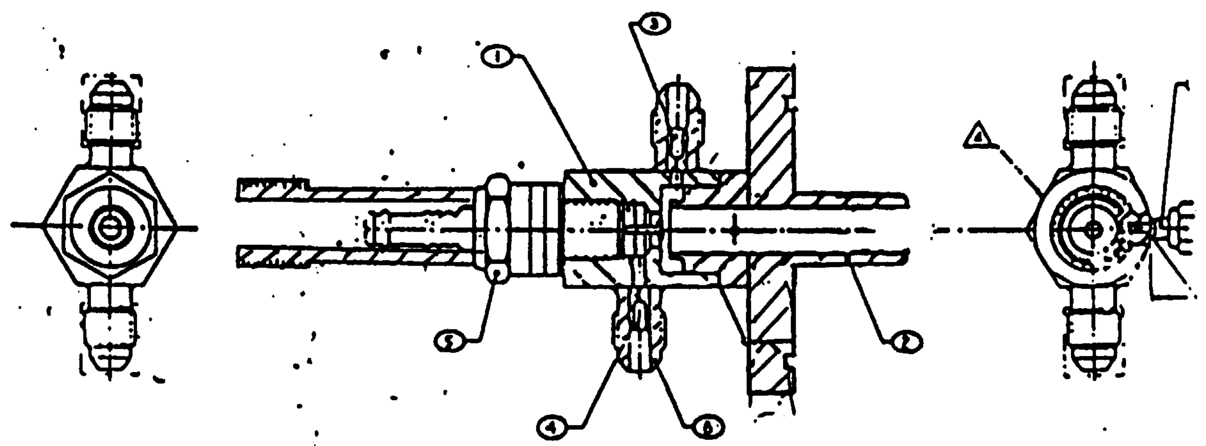
CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

SPARK IGNITER







SPARK PLUG - CHAMPION OR GLA

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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

GO_2/H_2 IGNITER OPERATING CONDITIONS

- FUEL ORIFICE INLET PRESSURE 1250 PSIA
- OXIDIZER ORIFICE INLET PRESSURE 1200 PSIA
- SPARK ENERGY = 30 MILLIJOULES
- SPARK RATE = 500 SPARKS/SECOND
- SPARK VOLTAGE = 6,000 VOLTS, BLACK BOX
- MAXIMUM FIRING DURATION = 0.400 SECONDS MAXIMUM TIME FOR IGNITER

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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

GO_2/H_2 IGNITER OPERATING CONDITIONS CONT

P_C (PSIA)	500	
MR	45:1	
C* (FT/SEC)	3,300	
$\dot{W}_F$ (LBM/SEC)	0.0040	
$\dot{W}_{OX}$ (LBM/SEC)	0.181	
$\dot{W}_{TOTAL}$ (LBM/SEC)	0.185	
ORIFICE $DIAMETER_F$ (INCHES) (AT 1700 PSIA)	0.0225	(.0250)
ORIFICE $DIAMTER_{OX}$ (INCHES) (AT 1700 PSIA)	0.0750	(.085)

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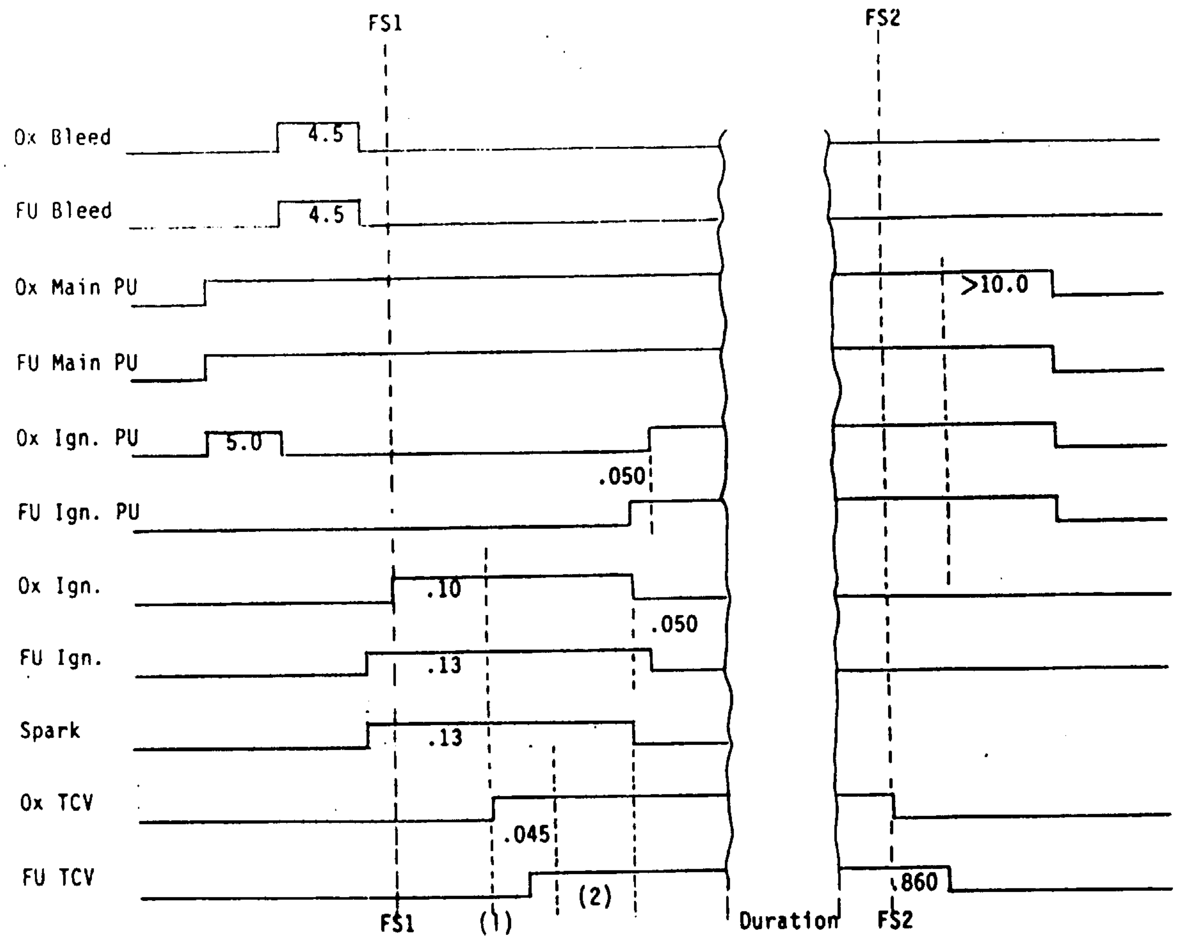
AEROJET TechSystems COMPANY

CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

OPERATING SEQUENCE



J5Q93
Carbon Dep.
as of 8-19-86
Last electrical
duration 201.055
camera on at FS1 +
31.015 for 1.5 Secs
CSM enabled from
FS1 + 1.015 to FS2
-.04

(1) Igniter Gate Limit Check - .1 Sec. or less, PFJI must reach >140 psig or terminate
(2) Main Ignition Gate Limit Check - .65 Sec. or less, PC-1 must reach >350 psig or terminate

(1) worst case for stress analyses ΔP pressure

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AEROJET TechSystems COMPANY

CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

JSQ93 LIMITS FOR HOT FIRE TESTING

- 1ST 10 SECONDS
  - FMW-1 4 TO 12 POUNDS/SECOND COOLANT H_2O FLOW RATE
  - PWI 500 TO 1500 PSIG COOLANT H_2O PRESSURE
  - P_C-1 300 TO 2000 PSIG
- AFTER 10 SECONDS UNTIL FS_2
  - FMW-1 4 TO 12 POUNDS/SECOND COOLANT H_2O FLOWRATE
  - PWI 500 TO 1500 PSIG COOLANT H_2O PRESSURE
  - TCR-2 < 2000°F
  - TCR-5 < 2000°F

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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

LOX/METHANE TEST SERIES KILL PARAMETERS

POTENTIAL FAILURE MODE	MEASUREMENT	KILL VALUE
INSTABILITY	KOJ	> 200 PSI PK - PK
LOW P_C	P_CTSU-1	< 80% NOMINAL
HIGH P_C	P_CTSU-1	> 120% NOMINAL
LACK OF IGNITION	PFJ1	< 140 PSI
HOT GAS TEMPERATURE (PROTECT UNCOOLED HARDWARD)	TCR-1 TCR-5	> 1900°F
LOW WATER FLOW (PLUGGED LINE)	WW1	< 4 LBM/SECOND
HIGH WATER FLOW (BURST LINE, CHAMBER HOLE, TURBINE SIMULATOR HOLE, LOOSE FITTING)	WW1	> 12 LBM/SECOND
LOW WATER PRESSURE	PWI 1	< 500 PSI
HIGH WATER PRESSURE	PWI 1	> 2500 PSI
HOT WALL TEMPERATURE	TC 12	< 1600°F
FUEL EXPENDED	WF-1	LIMIT TEST DURATION

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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

CRITICAL PARAMETERS

- THIS TABLE IDENTIFIES THE CRITICAL PARAMETERS REQUIRED FOR THE LOX/PROPANE TEST SERIES ON THE CARBON DEPOSITION PROGRAM. THE PARAMETERS ARE LISTED IN DESCENDING ORDER OF IMPORTANCE

W_F	-	FUEL FLOW RATE
W_{OX}	-	OXIDIZER FLOW RATE
T_{OX}	-	OXIDIZER TEMPERATURE
T_F	-	FUEL TEMPERATURE
PCTSD	-	CHAMBER PRESSURE DOWNSTREAM OF THE TURBINE SIMULATOR. PREFER PCTSD BUT WILL ACCEPT PCTSD-2
PCTSU	-	CHAMBER PRESSURE UPSTREAM OF THE TURBINE SIMULATOR. PREFER PCTSU BUT WILL ACCEPT PCTSU-2 FOLLOWED BY PCTSU-3
TCR	-	GAS TEMPERATURE; MUST HAVE AT LEAST TWO. PREFER TWO FROM TCR-2, TCR-3 OR TCR-4, BUT WILL ACCEPT ONE FROM TCR-1 OR TCR-5.
P_C-1	-	USE PCTSU. CHECK START UP SEQUENCE FOR TIME KILL PARAMETER.

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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

MACHINE DATA PLOT PARAMETERS

- INJECTOR PRESSURE VERSUS TIME
  - P_C-1, POJI, PFJI, POJ, PFJ, POT, PFT
- INJECTOR FLOW VERSUS TIME
  - WF, WO, WTOT, MR
- INJECTOR CALCULATIONS VERSUS TIME
  - DPOJ, DPFJ, KWOJ, KWFJ, CSTRPB
- GAS-SIDE WALL TEMPERATURES VERSUS TIME
  - TC-10, TC-12
- COOLANT OUTLET TEMEPRATURES VERSUS TIME
  - TWC-2, TWC-26, TWC-27, TWC-31, TWC-32, TWC-33

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AEROJET TechSystems COMPANY

CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

MACHINE DATA PLOT PARAMETERS CONT

- TURBINE BUILDUP DATA VERSUS TIME
  - PLOT NUMBER
    - CHAMBER PRESSURE RATIOS AND DIFFERENCES
      - PRTR, PRTS, PRTS CORR, DPTR, DPTS-C, DPTS
    - NOZZLE AREA CHANGE
      - NA1, NA2, CDA, DTD
    - TURBINE SIMULATOR PRESSURE MEASUREMENTS
      - PCTSU, PCTSU-2, PCTSU-3, PCTSD, PCTSD-2
- GAS TEMPERATURES VERSUS TIME
  - TCR-1, TCR-2, TCR-3, TCR-4, TCR-5, TCR-6 (AVAILABLE THERMOCOUPLES)

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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST SERIES

CARBON BUILD-UP AND INJECTOR CALCULATION REQUIREMENTS

Carbon Build-up

1. Turbine Simulator Pressure Rates

   PR_{TS} = PCTSD/PCTSU

   DPTS-C = DPTS measured or (PCTSU-PCTSD) if DPTS measure invalid.

   DP CORR = [(DPTS-C) - (PCTSU - PCTSD)] /2

   PR_{TS} CORR =(PCTSD - DP CORR)/(PCTSU + DP CORR)

2. Turbine Simulator Pressure Drop

   DP_{TS} = PCTSU - PCTSD

3. Turbulence Ring Pressure Ratio

   PR_{TR} = (PCTSU/PC-1)

4. Turbulence Ring Pressure Drop

   DP_{TR} = (PC-1) - PCTSU

5. Nozzle Area

   NA1 = WTOT * C/(PC-1)/gc

   NA2 - WTOT * C/PCTSD/gc

6. Turbine Simulator Area

$$C_DA = A_t\left[\frac{(\gamma-1)}{2\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{\gamma-1}}\left[(PR_{TSC})^{2/\gamma} - (PR_{BC})^{\frac{\gamma+1}{\gamma}}\right]}\right]^{1/2}$$

Calculate C_DA for γ = 1.1
γ = 1.2
γ = 1.3

A_t will be provided by the Project Engineer

VWG:AA0798

CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST SERIES (CONT)

7. New Turbine Simulator Pressure Ratio

PRTS-2 = (PCTSD-2)/(PCTSU-2)

DPTS2-C = (PCTSU-2) - (PCTSD-2)

DP-2 CORR = [(DPTS-2) - (DPT2-C)] /2

DPTS-2 is measured

PRTS2 CORR = [(PCTSD-2) - (DP-2 CORR)] / [(PCTSU-2) + (DP-2 CORR)]

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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

INJECTOR

1. $C_{P.B.} = PCTSO \times A_t \times gc/WTOT$
2. $WTOT = WOX + WF$
3. $MR = WOX/WF$
4. $DPOJ = POJ - (PC-1)$
5. $DPFJ = PFJ - (PC-1)$
6. $WFC = KWFC * \sqrt{DPFJ * S.G._F}$ $KWFC = 0.0655$ (P.B.)
7. $MRC = WOX/WFC$
8. $MPB = 1/MRC * \sqrt{DPFJ/DPOJ} * \sqrt{S.G._{ox}/S.G._F}$ (Momentum outer/inner)
9. $MMC = MR * \sqrt{DPOJ/DPFJ} * \sqrt{S.G._F/S.G._{ox}}$
10. $KWOJ = WOX/\sqrt{DPOJ * S.G._{ox}}$ $S.G._{ox} = f$ (TOTCV,POJ)
11. $KWFJ = WF/\sqrt{DPFJ * S.G._F}$ $S.G._f = f$ (TFFM)

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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

PHOTOGRAPHIC COVERAGE REQUIREMENTS

- FACILITY AND TEST STAND SETUP
- ALL HARDWARE PRIOR TO THE HIGH FLOW RATE TEST SERIES
- PHOTOGRAPHIC STILLS OF THE EXHAUST PLUME AT P = 1000 PSI FOR MR = .20, .37, AND .60, P = 1500 PSI FOR MR = .20, .37, .47, .55, .60 AND .70, P = 2000 PSI FOR MR = .20, .37, .47, .55, .60 AND .70 AS A MINIMUM.
- PHOTOGRAPH OF THE THERMOCOUPLE RAKE AFTER COMPLETION OF THE GAS TEMPERATURE CHARACTERIZATION TESTING IF THE TEST SCHEDULE IS NOT DELAYED
- PHOTOGRAPH OF THE THERMOCOUPLE RAKE DURING THE NOZZLE CHANGE ~~IF~~ without TIME PERMITS
- PHOTOGRAPH OF ALL HARDWARE AT THE COMPLETION OF THE LOX/~~LNG~~ TEST SERIES
- VIDEOTAPE OF TURBINE SIMULATOR THROUGH BOROSCOPE ACCESS PORT AT P = 1000, 1500 AND 2000 PSI FOR ALL MR

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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

ENVIRONMENTAL

- EMMISSIONS ARE WITHIN PERMIT LIMITS
- FLUSH OF LOX CIRCUIT. ALL EFFLUENT WILL BE CONTAINED.
- FLUSH FLUID AND DEGREASE PROCEDURE

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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

AEROJET TECHSYSTEMS COMPANY
Interoffice Memorandum

18 February 1988
9510:3493:ARK:jcm

TO: T. C. Trafzer

FROM: A. R. Keller

SUBJECT: Carbon Deposition Propellants

DISTRIBUTION: E.M. VanderWall

Here is the information you requested for the upcoming testing in A Area. The propellants are liquid natural gas, and liquid oxygen. The testing is scheduled for mid March to April.

If there is a problem with the exhaust product release permit, please let us know.

A R Keller
A. R. Keller
Test Engineer
A Zone
Test Operations

Approved: EM VanderWall
E. M. VanderWall, Manager
A Zone
Test Operations

2-25-88

A review of the data submitted in support of the A-Zone air Pollution Permit and the emission Data for this program show this program to be within your permit limitations
TC Trafzer

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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

EMMISSIONS

TOTAL PROJECTED EMISSIONS AND SPECIES FOR THE LOX/CH_4 HIGH DENSITY INJECTOR TEST SERIES

TOTAL 02 PROJECTED = 11996 POUNDS

TOTAL CH_4 PROJECTED = 28320 POUNDS

TOTAL TEST TIME = 3008 SECONDS

SPECIES	TOTAL POUNDS	% MASS	
CH_4	19702	0.49	
CO	4137	0.10	below 550 lbs/day
CO_2	3354	0.08	
H_2	1150	0.03	
H_2O	8206	0.21	
C (GRAPHITE)	3767	0.09	
	40316	1.00	

VWG:AA0798

CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

OPERATIONAL PROCEDURES

- VISITOR INFORMATION
  - SIGN IN AND OUT OF TEST ZONE
    - LOG LOCATED IN BUILDING 30003
  - BUILDING 30003 IS EMERGENCY CONTROL CENTER
    - REPORT TO LOBBY IMMEDIATELY DURING GAS EMERGENCY
      - ALL AREA WARBLER SIREN AND PAGE WILL ALERT PERSONNEL
  - HARD HATS REQUIRED IN TEST BAYS
  - OBSERVE WARNINGLIGHTS
    - GREEN - NO RESTRICTIONS
    - YELLOW - RESTRICTED TO ALL BUT THOSE AUTHORIZED BY TEST CONDUCTOR
    - RED - RESTRICTED TO ALL PERSONNEL
  - CONTROL ROOM ACTIVITES
    - FOLLOWING 10 MINUTE WARNING - LIMIT CONVERSATIONS TO THAT REQUIRED TO PERFORM THE TESTING
    - POST TEST HARDWARE INSPECTION AFTER TEST BAY IS CLEARED TO ALL PERSONNEL

VWG:AA0798

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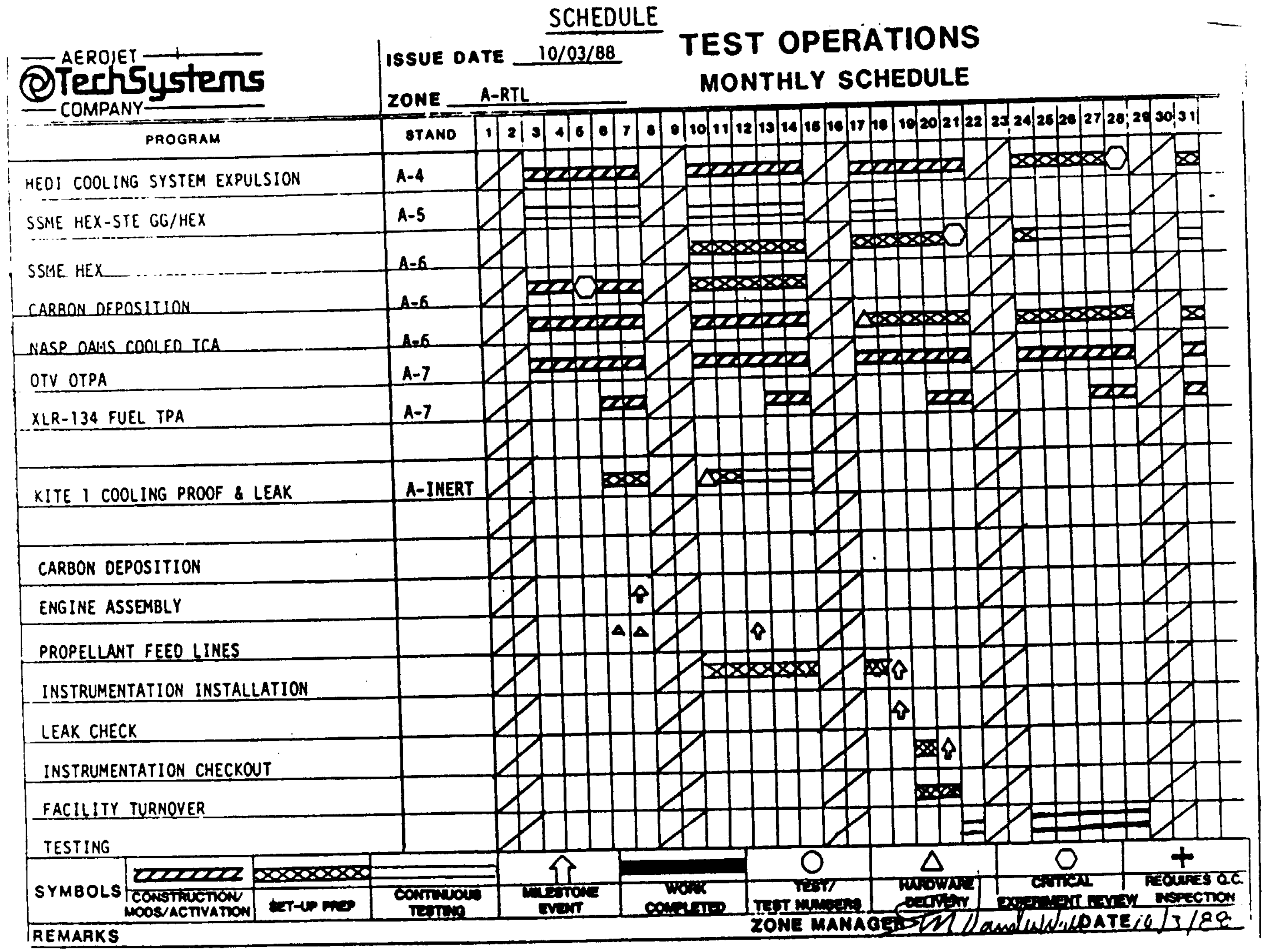
CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE



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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

ACTION ITEMS

		Person(s) Assigned
1.	Duration limits; fuel exhaustion	Keller Werling Bossard
2.	Max allowable ΔP	Bossard
3.	Boroscope checkout	Keller Bossard
4.	Caron monoxide emissions less than 550 lbm/day	Werling
5.	Methane lead time	Werling

APPENDIX B

LIQUID-LIQUID COAX INJECTOR
CONCEPT REVIEW

CARBON DEPOSITION PROGRAM
LIQUID-LIQUID COAX INJECTOR
DESIGN CONCEPT REVIEW

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30 SEPTEMBER 1988

CARBON DEPOSITION LIQUID-LIQUID COAX INJECTOR
CONCEPT REVIEW AGENDA

• INTRODUCTION	J. BOSSARD
• ANALYSIS	K. NIIYA
• DESIGN	B. CAROTHERS
• SUMMARY	
• ACTION ITEMS	

CARBON DEPOSITION LIQUID-LIQUID COAX INJECTOR DESIGN REVIEW BOARD MEMBERS

CHAIRMAN	J. L. PIEPER
PERFORMANCE ANALYSIS	R. E. WALKER
THERMAL ANALYSIS	F. F. CHEN
STRESS ANALYSIS	J. E. JELLISON
MATERIALS	R. M. HORN
PRODUCIBILITY	J. A. PHIPPS
DESIGN	L. C. FEMLING

INTRODUCTION

JOHN BOSSARD

PROGRAM OBJECTIVES

- PERFORM LNG TESTS AND COMPARE WITH PREVIOUS METHANE RESULTS
- VERIFY LACK OF CARBON BUILD-UP FOR LOX/METHANE PROPELLANTS ON TURBINE SIMULATOR AT FULL SCALE INJECTION RATES WITH STBE GG TYPE INJECTOR
- ~~UPDATE FUEL RICH COMBUSTION MODEL (FRCM) TO INCLUDE METHANE~~
- DESIGN, FABRICATE, AND BUILD A LIQUID-LIQUID COAX INJECTOR TO OPERATE AT FULL SCALE INJECTION RATES

COAX INJECTOR OBJECTIVES

- RUN LOX/METHANE IN A LIQ-LIQ COAX INJECTOR
- OPERATE AT SIMILIAR FLOW RATES AND Pc 'S AS IN THE PREVIOUS LOX/METHANE TESTING
- COMPARE CARBON DEPOSTION EFFECTS OF THE COAX INJECTOR TO THE IMPINGING TRIPLET INJECTOR
- COMPATIBILITY WITH ALS TECHNOLOGY WHERE POSSIBLE

INJECTOR REQUIREMENTS

PARAMETER	REQUIREMENT	SOURCE
PROPELLANT	LOX/METHANE	CONTRACT MOD.
INJECTOR ELEMENT	LIQ/LIQ COAX	CONTRACT MOD.
$\dot{M}_{TOTAL}$	13 - 16 lbm/sec	PREVIOUS TESTING
Pc	2000 psi	PREVIOUS TESTING
MR	.20 - .60	PREVIOUS TESTING
FUEL AND OX SUPPLY LINE PRESSURE	< 3000 psi	TEST EQUIPMENT LIMITATION
INJECTOR DIAMETER	2.38 in	HARDWARE INTERFACE
IGNITER	GOX/GH_2	PREVIOUS TESTING
CHAMBER LENGTH	20 in max.	HARDWARE
THRUST LEVEL	2 - 3 k lbf.	PREVIOUS TESTING

ANALYSIS

KAREN NIIYA

SWIRL COAX INJECTOR ELEMENT DESIGN CRITERIA

ELEMENT TYPE: DOUBLE SWIRL COAX

OXIDIZER: LO_2

FUEL: LCH_4

OXIDIZER FLOWRATE = 3.85 lbm/s

FUEL FLOWRATE = 10.39 lbm/s

MIXTURE RATIO = 0.37

P_c = 2000 psia

ΔP_{ox} = 300 psid

ΔP_f = 600 psid

INJECTOR FACE DIAMETER = 2.175"

NUMBER OF ELEMENTS = 18

CONE ANGLE PARAMETRIC STUDY:

- OXIDIZER HALF CONE ANGLE RANGE = 15° TO 60°
- FUEL HALF CONE ANGLE RANGE = 15° TO 60°

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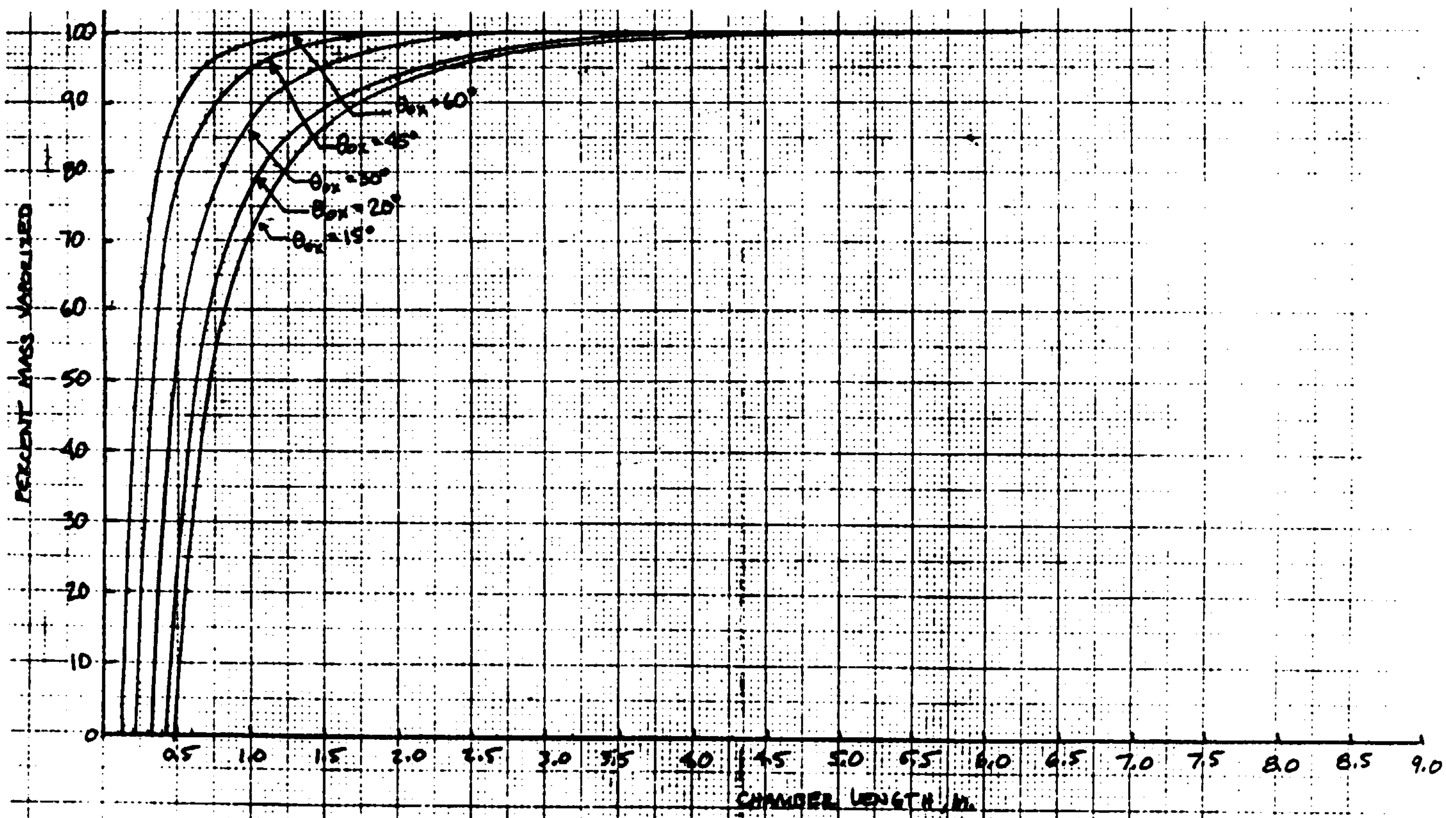
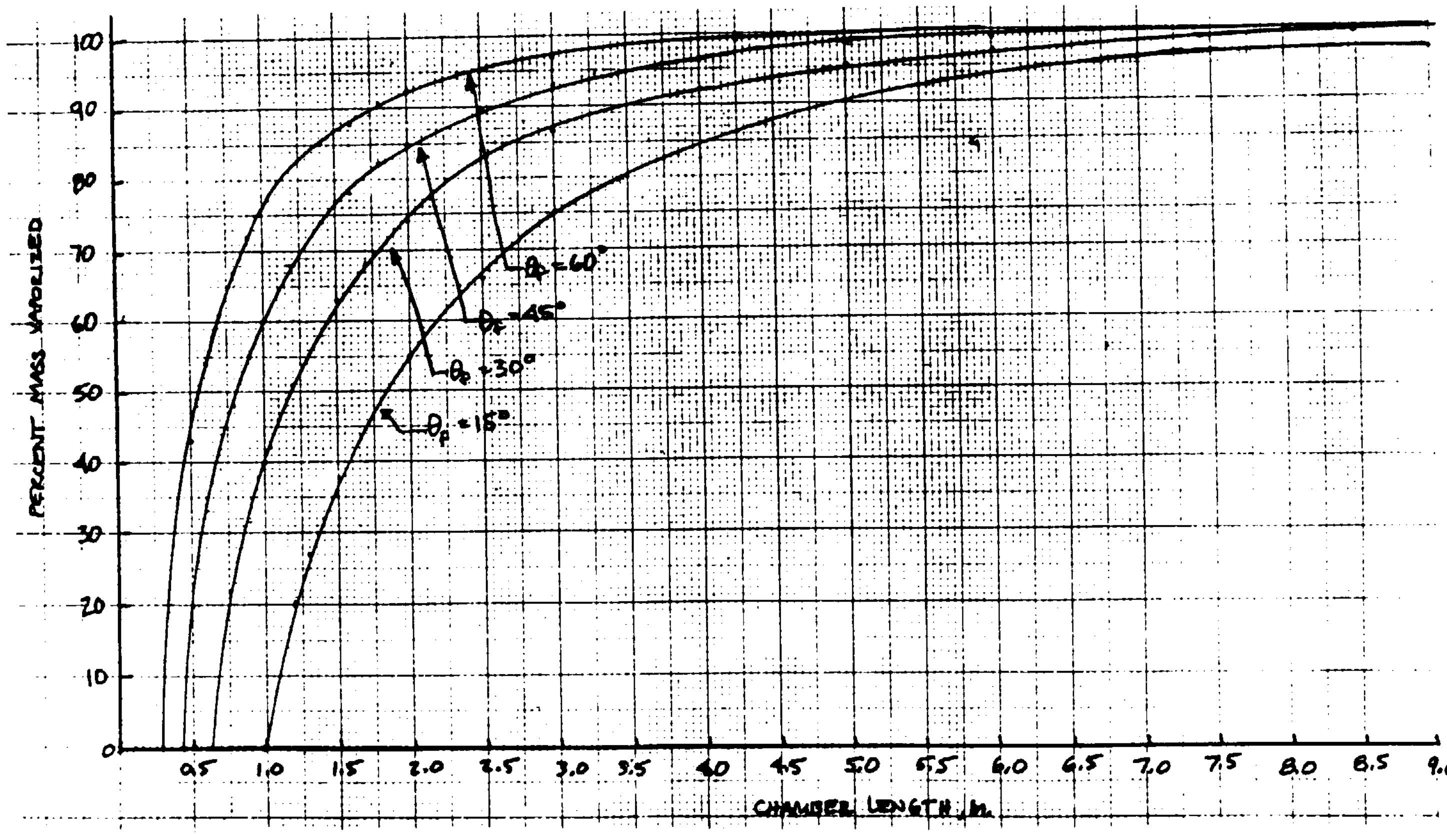
LO2 VAPORIZATION PROFILE IS A FUNCTION OF CONE ANGLE

- Vaporization rate increases with cone angle
- Atomization distance decreases with cone angle



METHANE VAPORIZATION PROFILE IS A FUNCTION OF CONE ANGLE

- For a given cone angle, the ox vaporization rate is higher than the fuel vaporization rate



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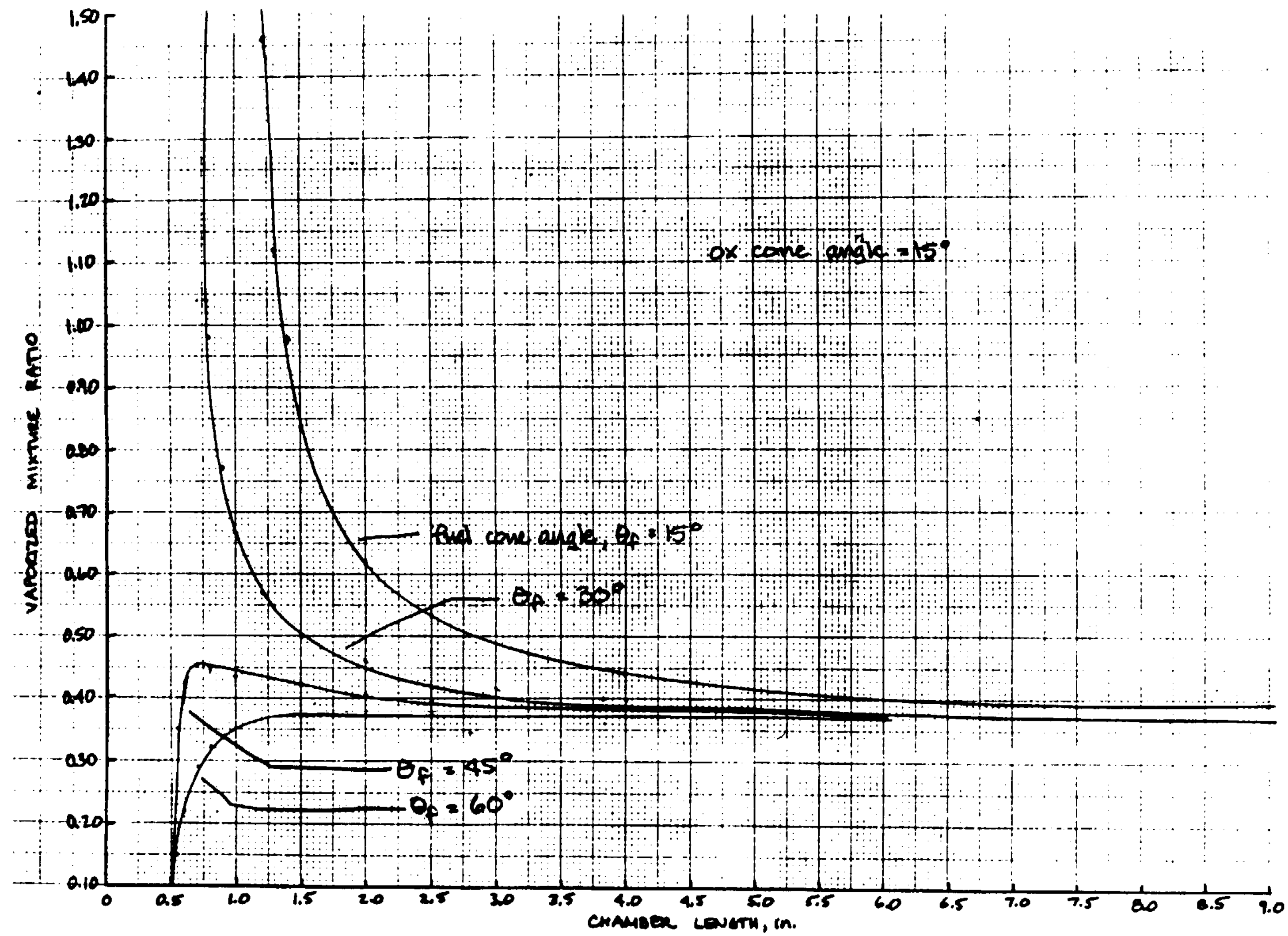
FOR $\Theta_{OX} = 15^{o}$, PREFERRED FUEL CONE ANGLE RANGE FOR INJECTOR FACE THERMAL COMPATIBILITY IS 45^{o} TO 60^{o}



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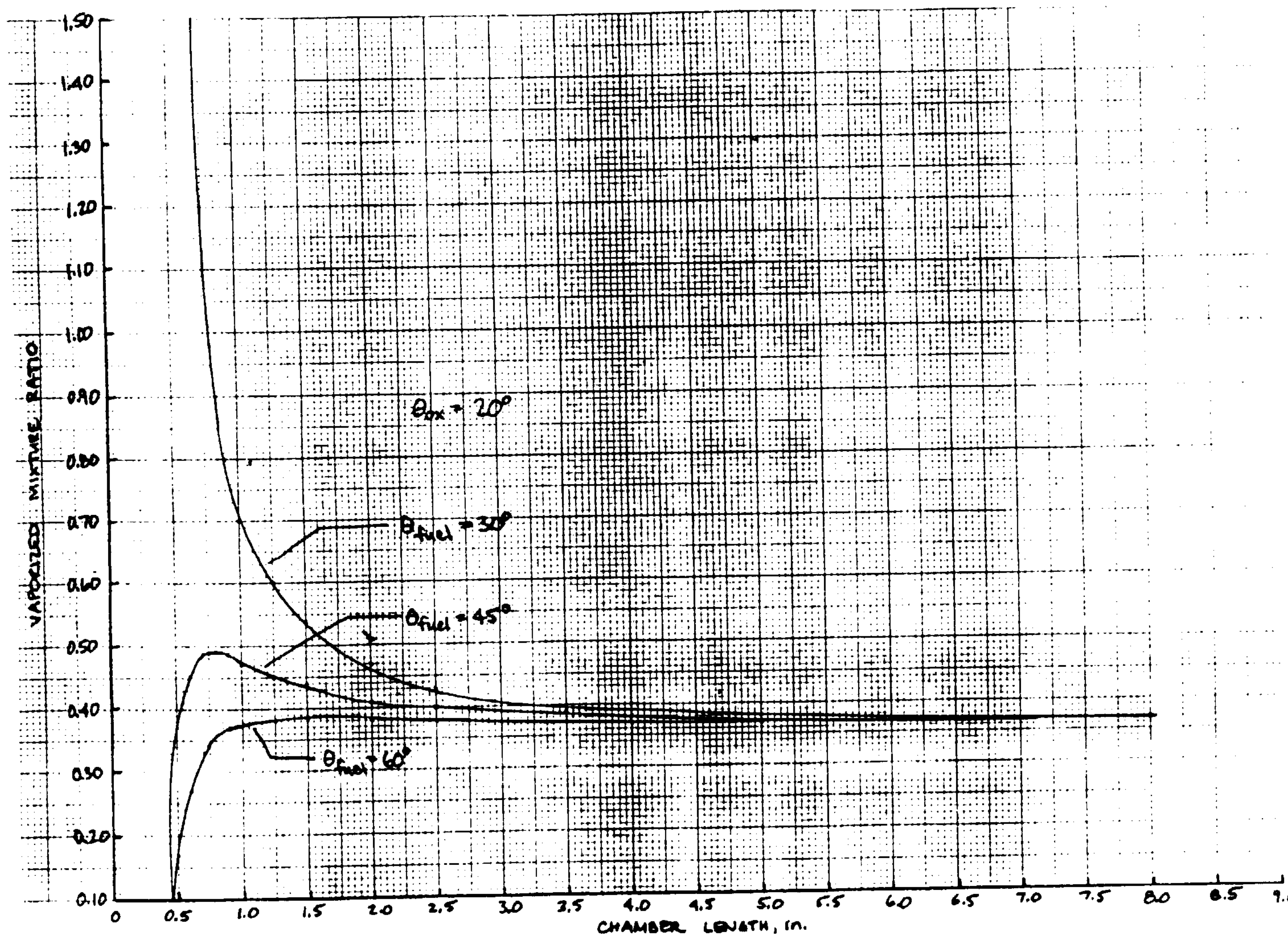
FOR Θ_{OX} = 20°, PREFERRED FUEL CONE ANGLE RANGE FOR INJECTOR FACE THERMAL COMPATIBILITY IS 45° TO 60°



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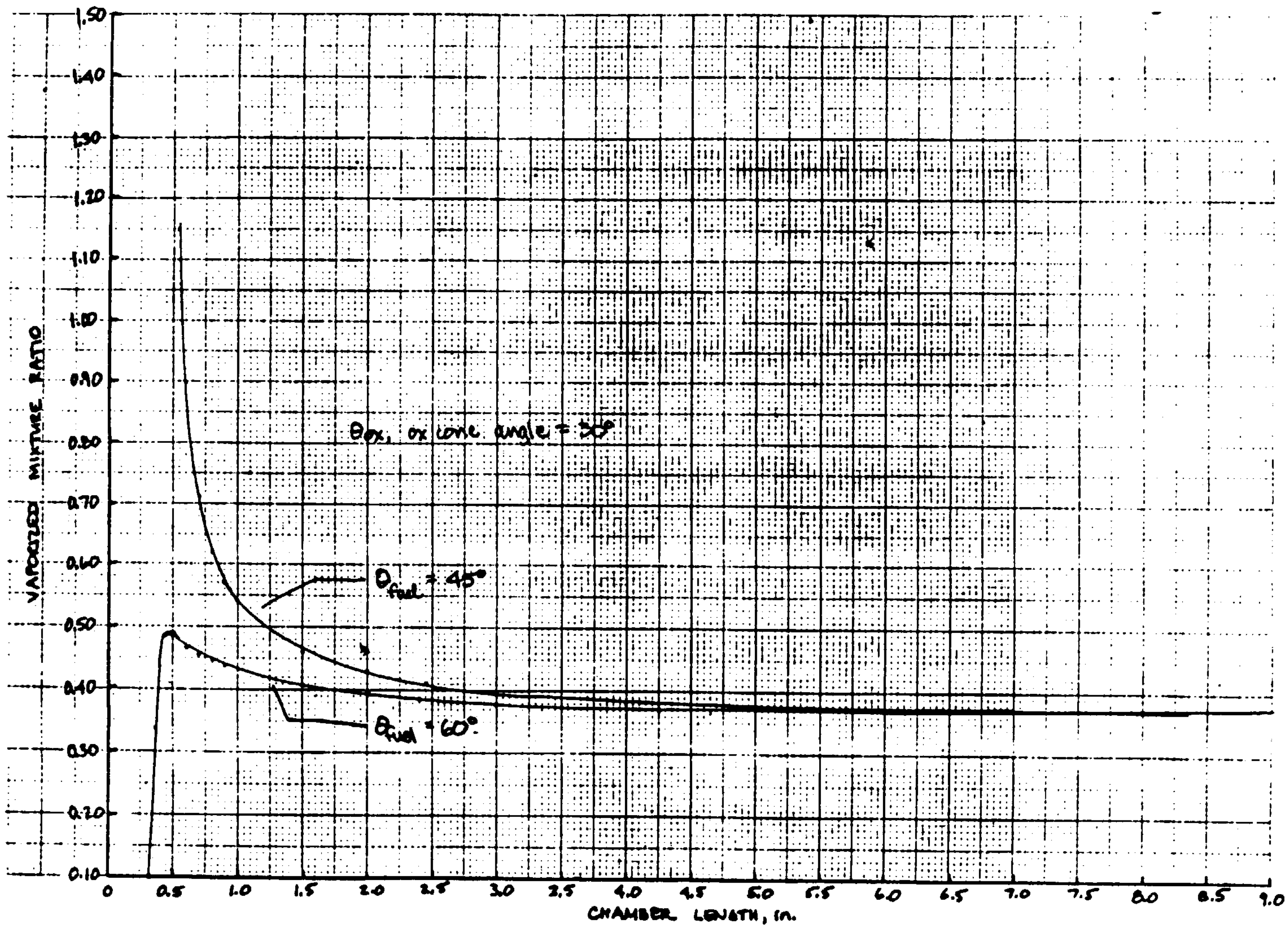
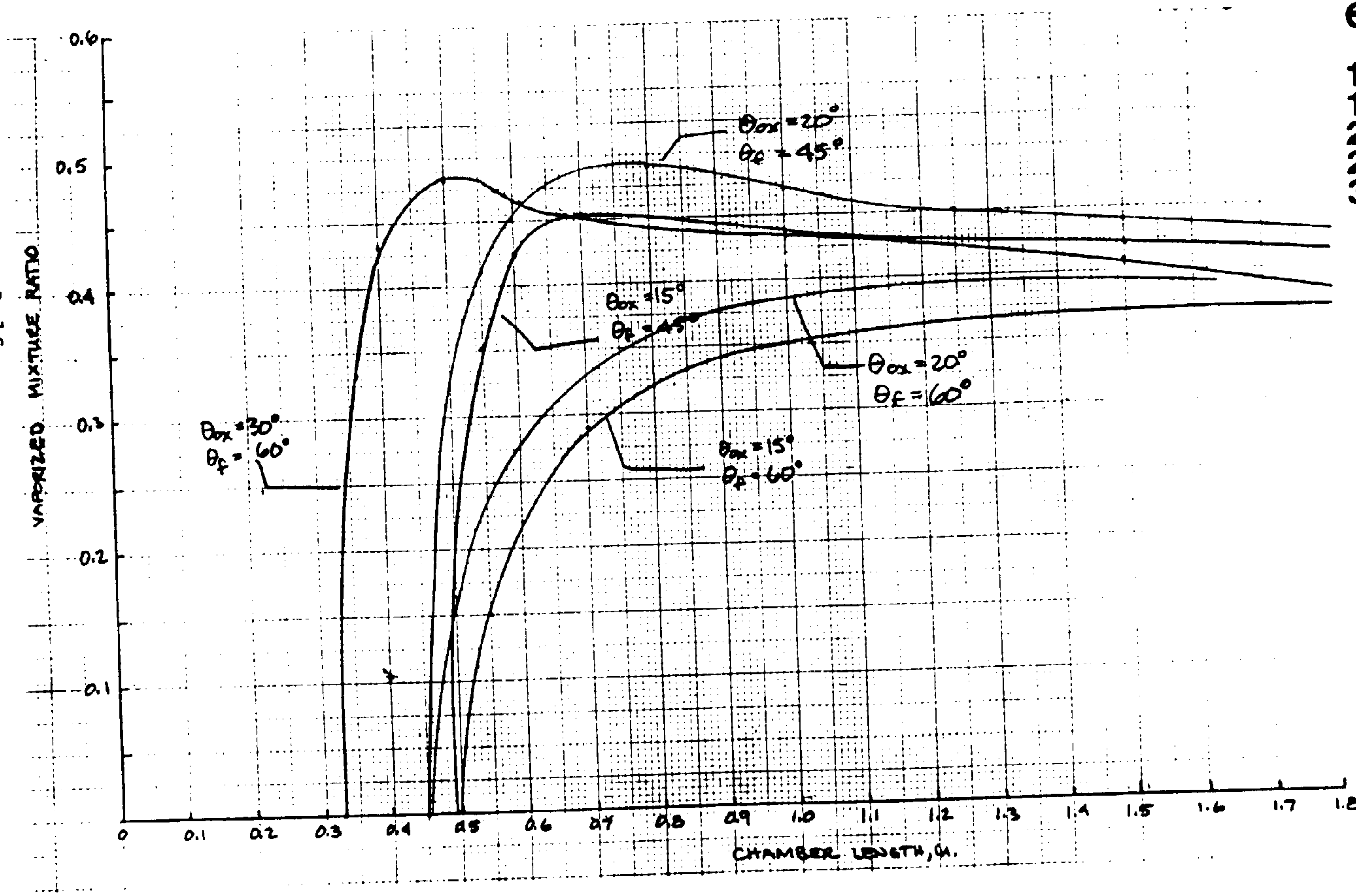
FOR Θ_{OX} = 30°, PREFERRED FUEL CONE ANGLE RANGE FOR INJECTOR FACE THERMAL COMPATIBILITY IS 60°



PARAMETRIC STUDY CONCLUSIONS

Based on thermal compatibility, the possible cone half angle combinations are:

θ_{ox}	θ_f
15°	45°
15°	60°
20°	45°
20°	60°
30°	60°



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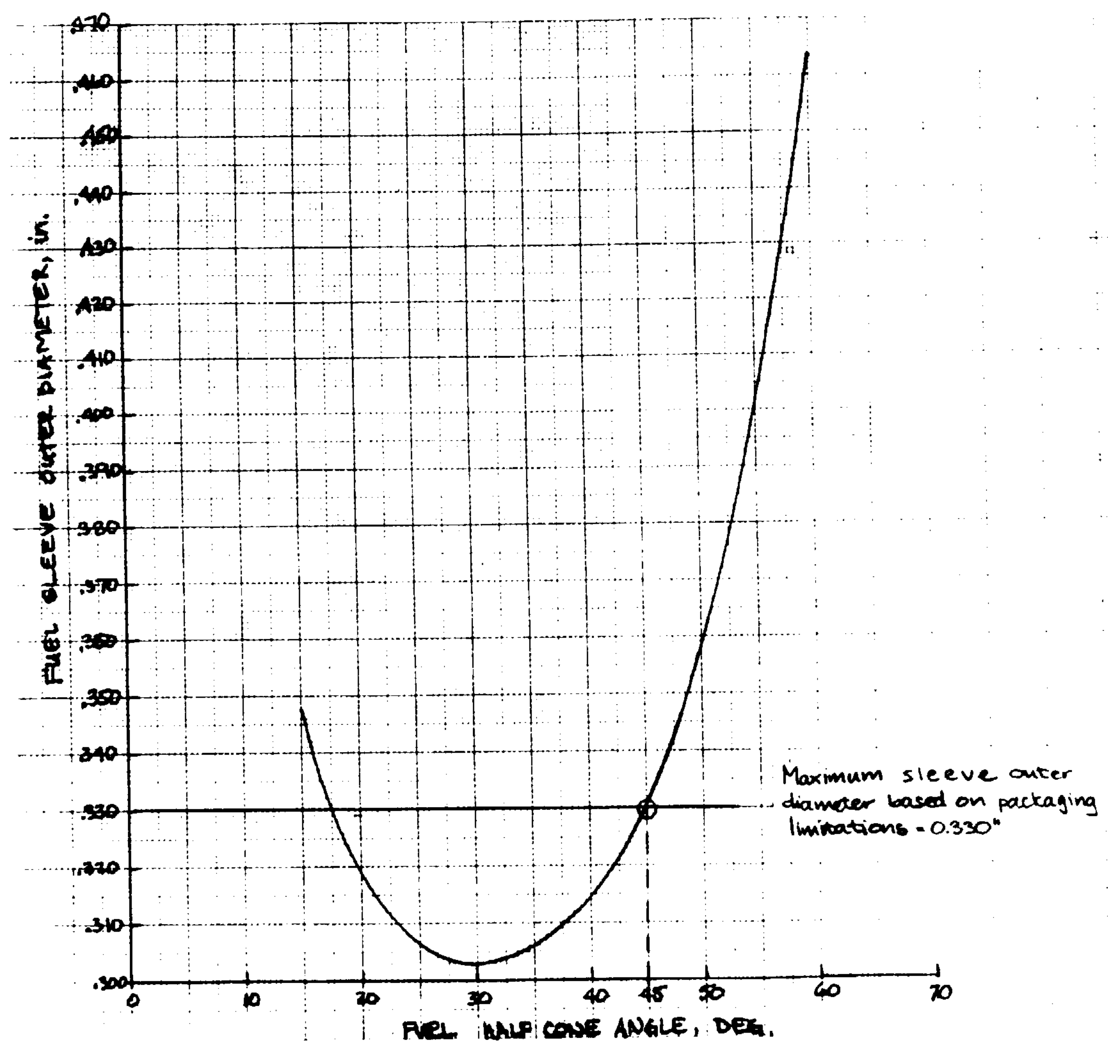
HYDRAULIC AND MECHANICAL DESIGN ANALYSES INDICATE MAXIMUM ALLOWABLE FUEL HALF CONE ANGLE = 45°



- Due to tight fit between elements, the fuel sleeve outer diameter is restricted to less than or equal to 0.330".

- Fuel sleeve O.D. is dependent on desired fuel cone angle.

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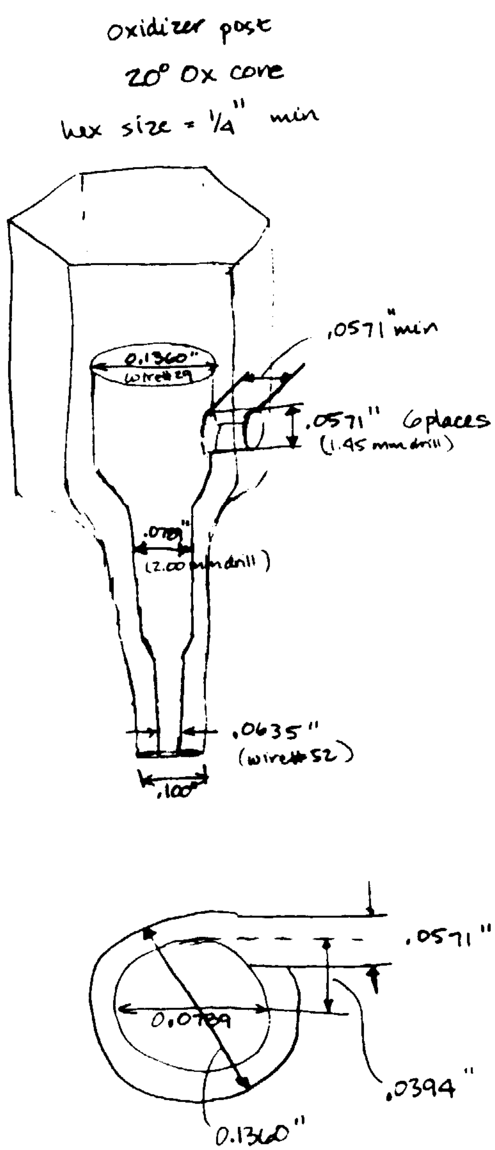
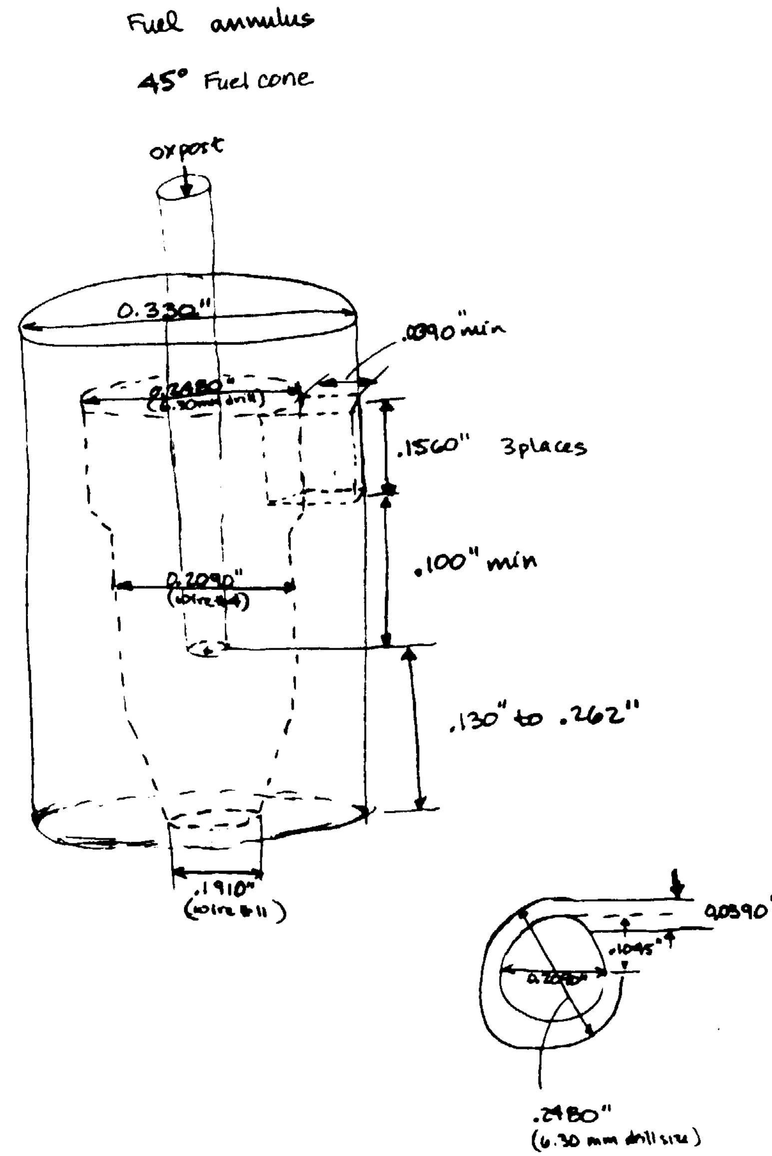
ROUGH SKETCH OF OX POST AND FUEL ANNULUS GEOMETRIES (NOT TO SCALE)





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CARBON DEPOSITION SWIRL COAX INJECTOR CURRENT DESIGN POINT

P_c = 2000 psia

OX FLOWRATE = 3.85 lbm/s

FUEL FLOWRATE = 10.39 lbm/s

MIXTURE RATIO = 0.37

ΔP_{ox} = 300 psi

ΔP_f = 600 psi

NO. OF ELEMENTS = 18

OX CONE HALF ANGLE = 20^o

FUEL CONE HALF ANGLE = 45^o

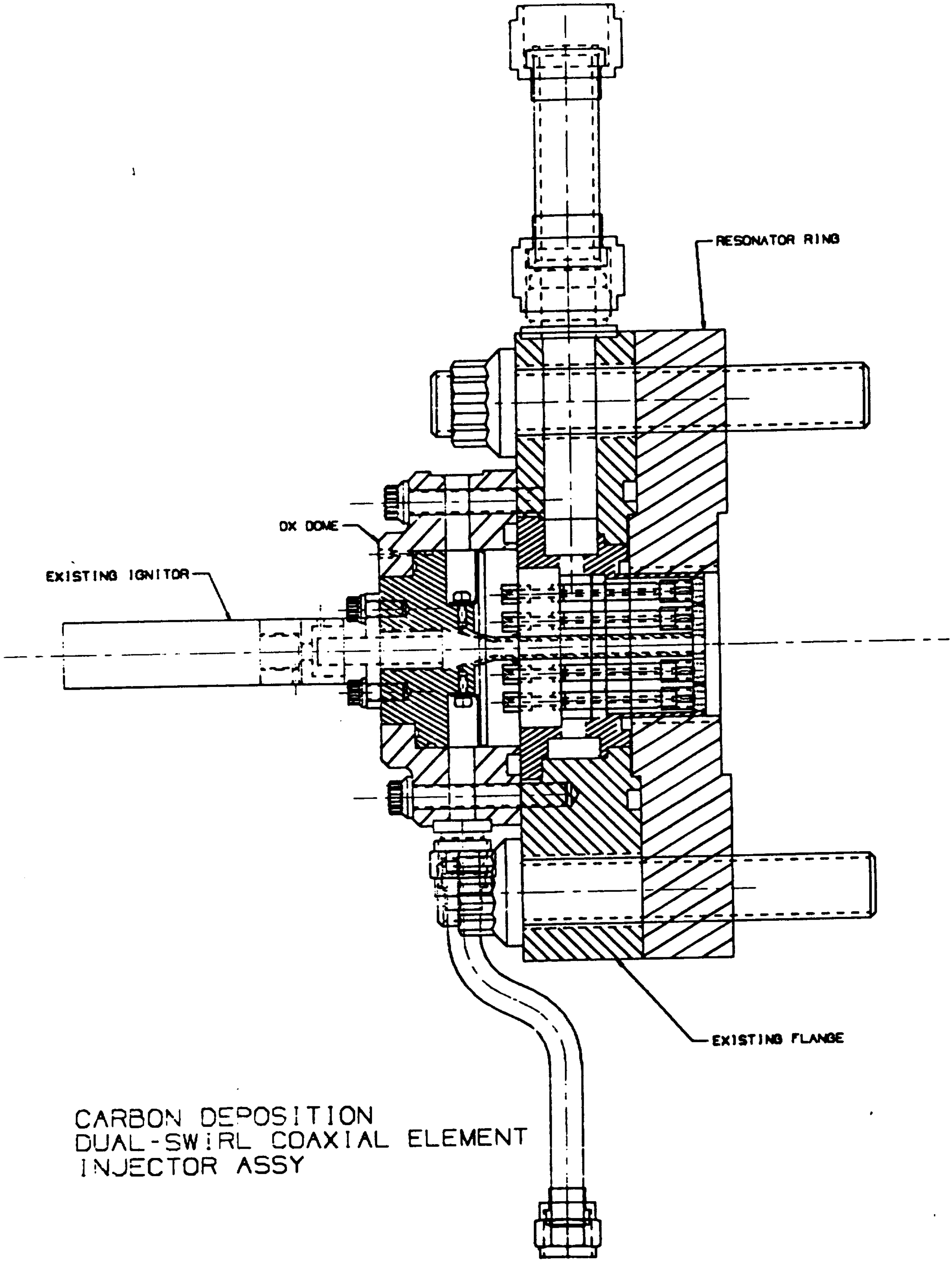
D_{ox} ORIFICE = 0.0635 in.

D_{ox} POST = 0.100 in.

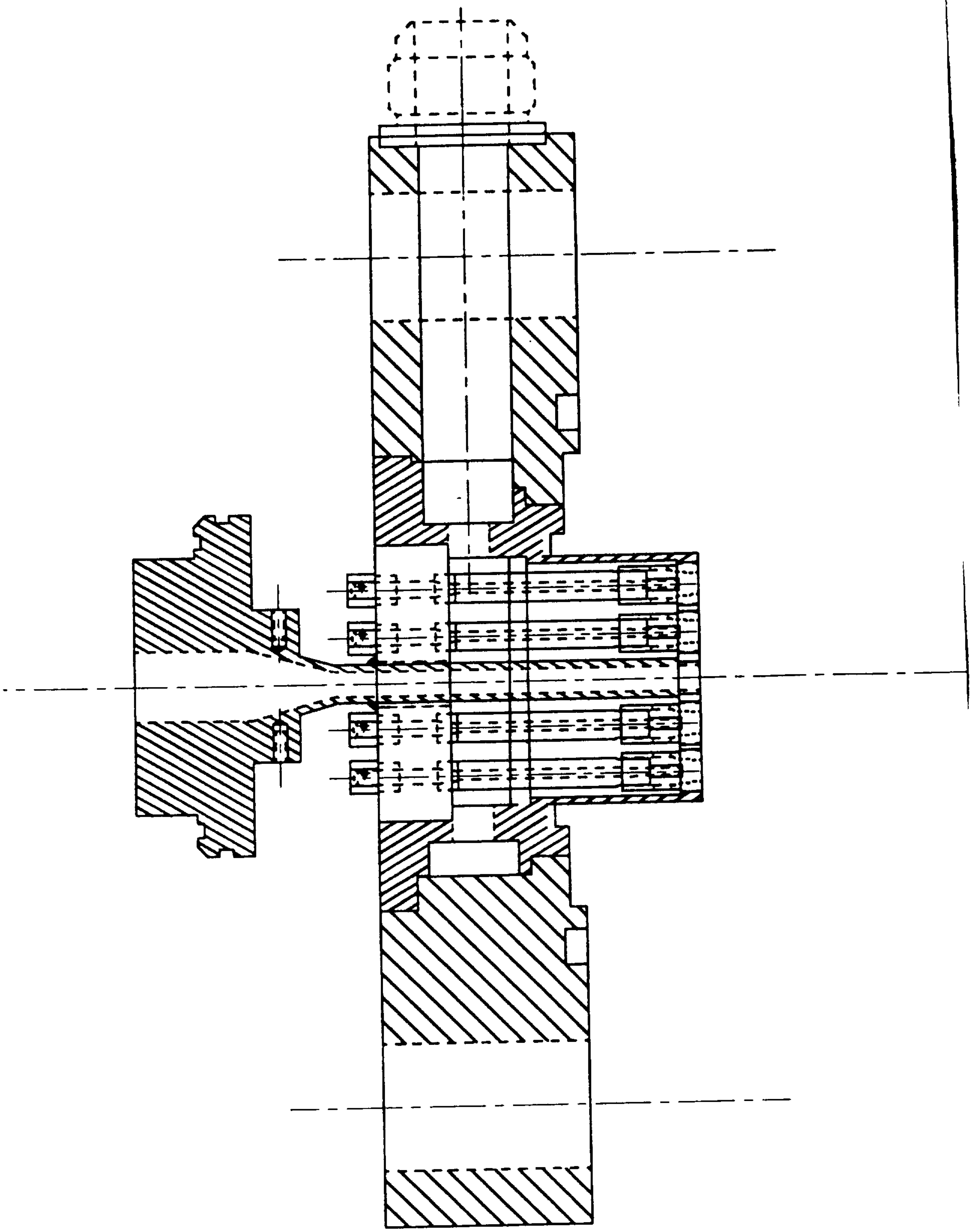
OD FUEL ANNULUS = 0.1910 in.

DESIGN

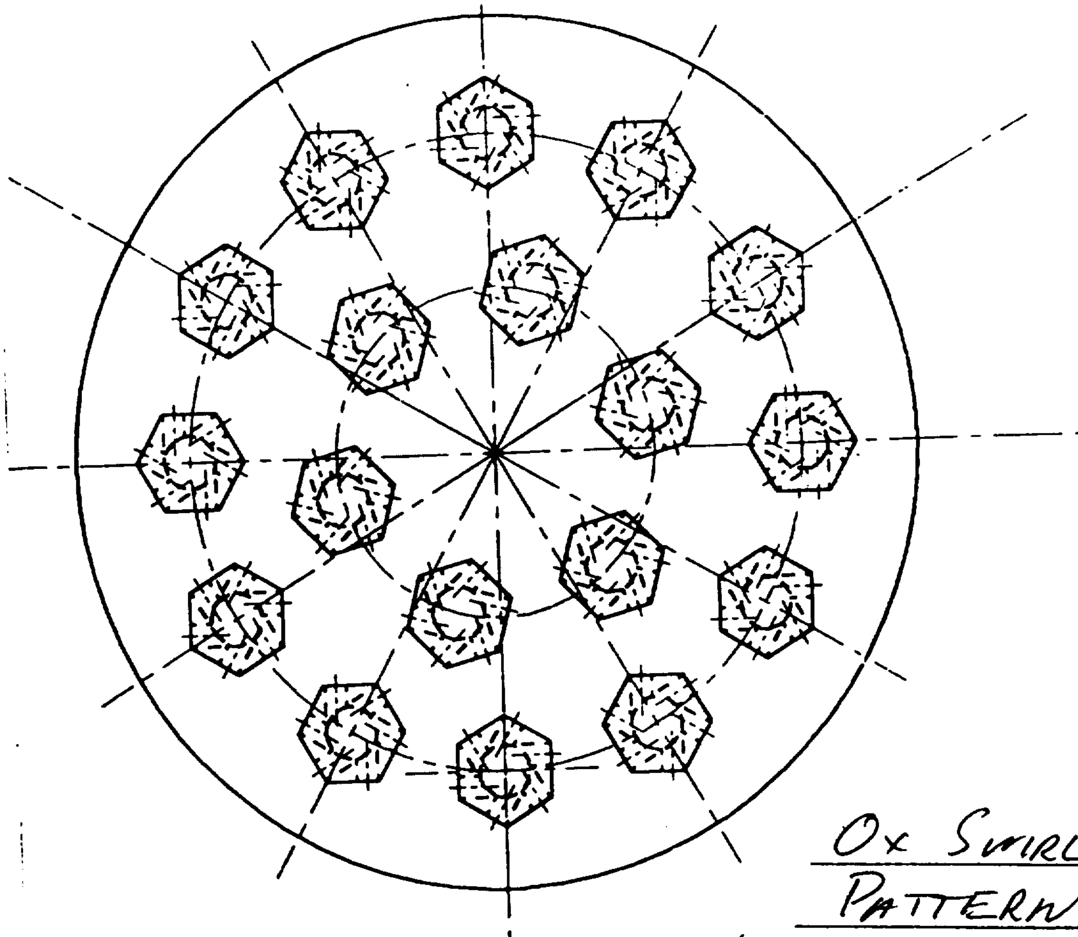
BRIAN CAROTHERS



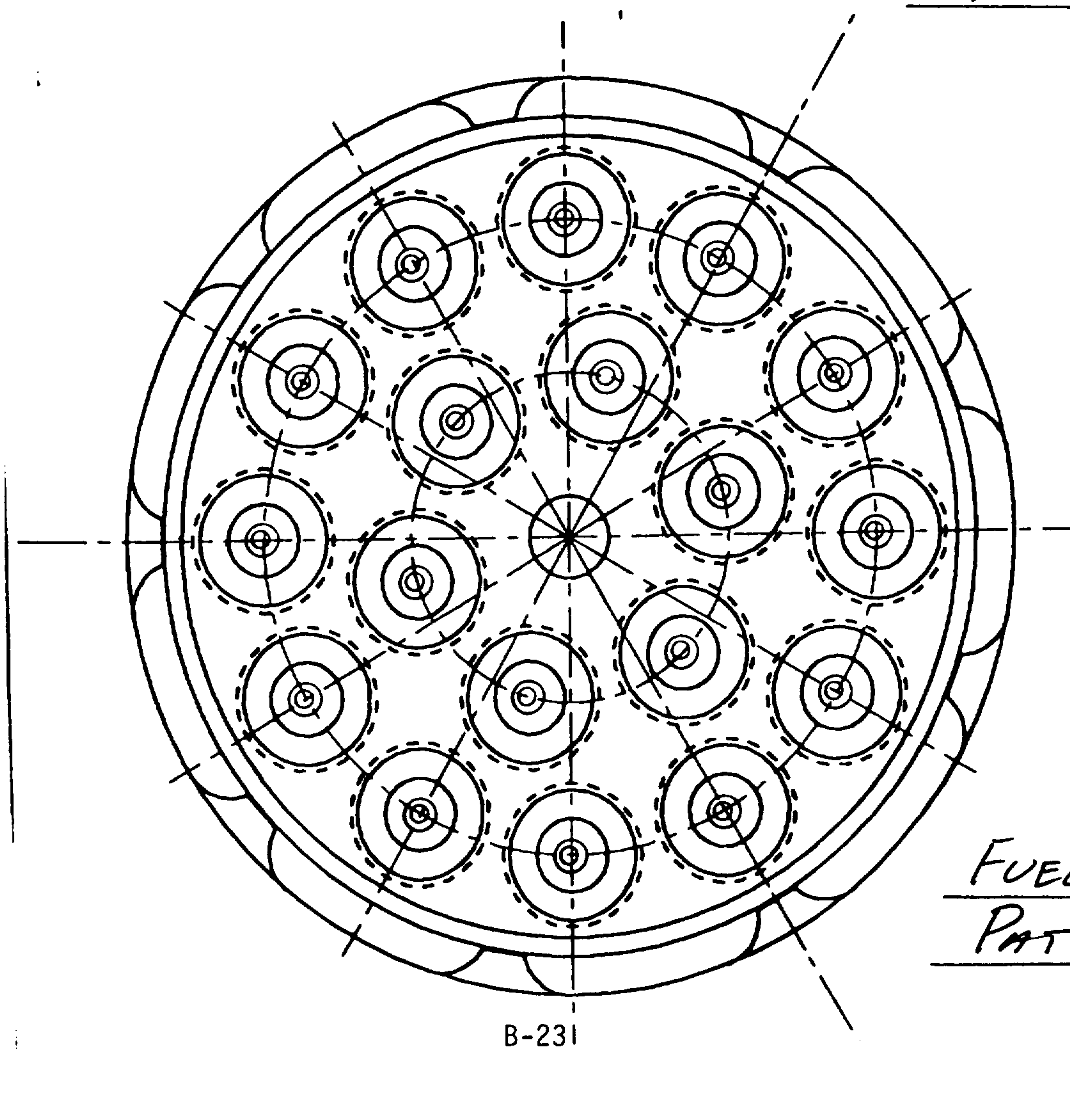
CARBON DEPOSITION
DUAL-SWIRL COAXIAL ELEMENT
INJECTOR ASSY



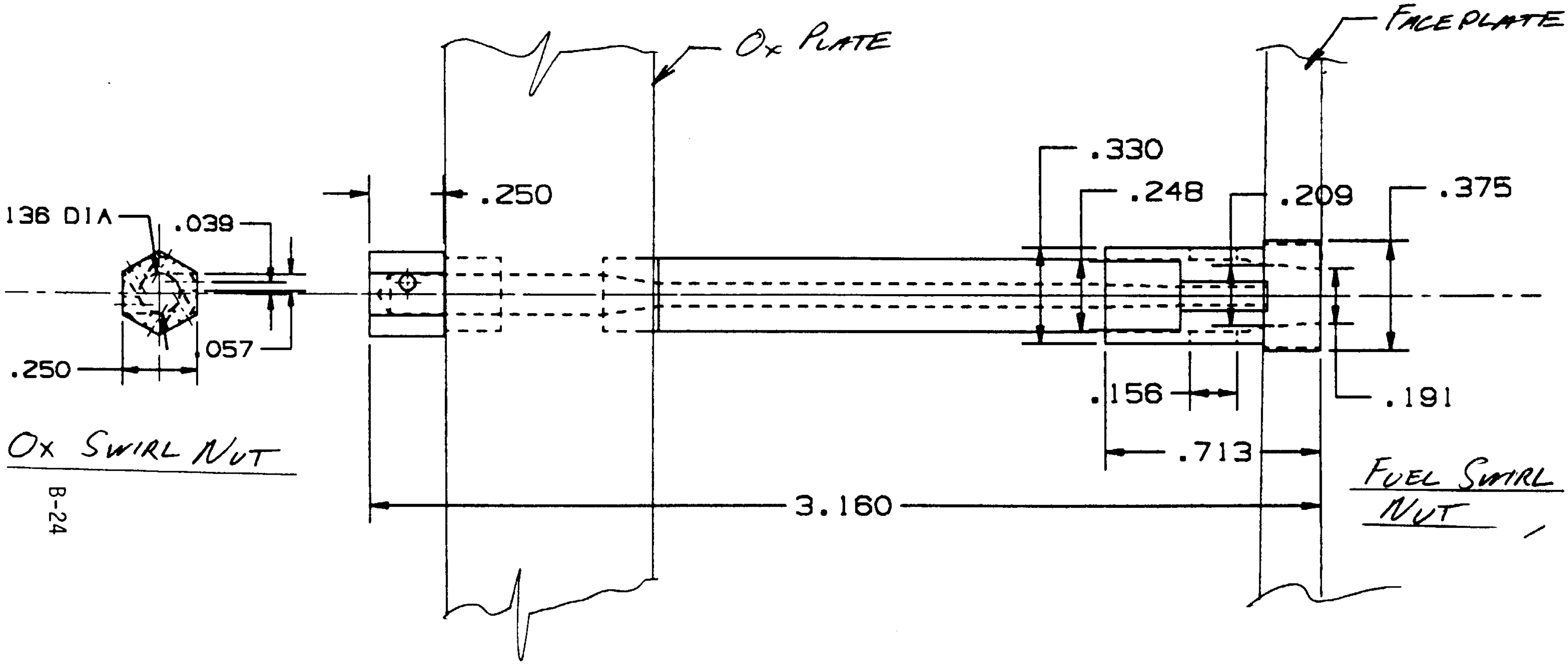
SWIRL ELEMENT ACCESSIBILITY



Ox Swirl Nut Pattern



Fuel Swirl Nu Pattern



Ox Plate
Faceplate
.250
.330
.248
.209
.375
136 DIA
.039
.057
.250
.156
.191
.713
3.160
Ox Swirl Nut
Fuel Swirl Nut

RISK ASSESSMENT

PERFORMANCE ANALYSIS	
1) CONE ANGLES	NO → YES COLD FLOW TESTING
THERMAL ANALYSIS	YES F-O-F TRIPLET EXPERIENCE
STRESS ANALYSIS	NO → YES COMPLETED STRESS ANALYSIS
MATERIALS	YES
PRODUCIBILITY	NO
DESIGN	
1) FACE NUTS	NO
2) CONFINED ENVELOPE	NO
FABRICATION	NO