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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Carbon Deposition Model For Oxygen-Hydrocarbon Combustion

Contract NAS 8-34715

Bimonthly Progress Report

Prepared For
NASA/George C. Marshall Space Flight Center
Huntsville, Alabama 35812

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RPT/AA05703
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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 LO2/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 LO2/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
Introduction (cont.)

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 LO₂/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, LO₂/propane can be operated in the desired temperature range up to a maximum of 1500°F (1088 K), without carbon buildup. Operation with LO₂/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.
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 LO2/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. Task 1 - Requirements

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,
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LEGEND:
- MILESTONE COMPLETE
- SLP
- PROCUREMENT
- MAJOR MILESTONES
- PERCENT COMPLETE
- TIME NOW

Note:
Contract Mod 594 New Scope-Come;
Deleted Scope in Analysis

Figure 1. Program Schedule
D, Detailed Task Descriptions (cont.)

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 LO2/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.
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 LO₂/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**

<table>
<thead>
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<tr>
<td>Turbine Simulator</td>
<td>2</td>
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<tr>
<td>Exit Nozzle</td>
<td>1</td>
</tr>
<tr>
<td>Turbulence Ring</td>
<td>1</td>
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<tr>
<td>Access Port</td>
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</table>
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 CDA 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
D. Detailed Task Descriptions (cont.)

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 GN2 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
Figure 3B. Fuel Circuit
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
Figure 4. Assembly Schematic
Figure 5. Gas Sampling System
E, Current Status (cont.)

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
CRITICAL EXPERIMENT REVIEW

CARBON DEPOSITION OF LOX/METHANE

NUMBER 10006

05 OCTOBER 1988
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

VWG: AA0798
CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

INTRODUCTION

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

ASSEMBLY SCHEMATIC

NOTE: SKETCH NOT TO SCALE
SHADE PARTS ARE EXISTING HARDWARE

VWG: AA0798
CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

GAS SAMPLING SYSTEM

IN 1 LITER  ATN
# CRITICAL EXPERIMENT REVIEW
## CARBON DEPOSITION OF LOX/METHANE

## TEST PLAN

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## CRITICAL EXPERIMENT REVIEW
### CARBON DEPOSITION OF LOX/METHANE

### TEST PLAN (CONT)

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<tr>
<th>TEST TYPE</th>
<th>TEST NUMBER</th>
<th>TEST OBJECTIVES</th>
<th>$P_T$ OXID ESTIMATE (PSIA)</th>
<th>$P_T$ FUEL ESTIMATE (PSIA)</th>
<th>NOMINAL $P_C$ (PSIA)</th>
<th>NOMINAL MR</th>
<th>DURATION SECONDS</th>
<th>$\dot{\dot{W}}$ OXID LB/SEC</th>
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<th>$\dot{\dot{W}}$ METHANE LB/SEC</th>
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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°F, 5.0 POUNDS/SECOND MAXIMUM
  - SAFETY PROCEDURE 13 "PRESSURIZED EQUIPMENT" APPLIES
  - ALL COMPONENTS LOX COMPATIBLE
  - LINE VELOCITY 50 FT/SECOND MAXIMUM
  - PRECLUDE CRYOGENIC LOCKUP
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, TEFILON SOFT GOODS
    - CCI RSOVS USED WITHOUT INCIDENT FOR YEARS
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, TEFLOWN 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
CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST STAND DETAIL (CONT)

LIQUID OXYGEN SYSTEM COMPONENT REVIEW (CONT)

- LOX LINE BLEED - CHILL DOWN AND RUN SYSTEM
  - 1/2 INCH CCI RSOV, 6000 PSI WORKING PRESSURE BLEED VALVE
  - 1 INCH CCI RSOV, 6000 PSI WORKING PRESSURE OTCV
  - STAINLESS STEEL BODY PINTEL AND SEAT, TEFLOMN SOFT GOODS
  - CCI RSOVS USED WITHOUT INCIDENT FOR YEARS

- FLOW MEASURING
  - 3/4 INCH TURBINE FLOWMETER

- OXIDIZER THRUST CHAMBER VALVE
  - 1 INCH CCI RSOV, 6000 PSI WORKING PRESSURE
  - STAINLESS STEEL BODY PINTEL AND SEAT, TEFLOMN SOFT GOODS
CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST STAND DETAIL (CONT)

0 LIQUID OXYGEN SYSTEM COMPONENT REVIEW (CONT)

0 RUN LINE - TANK SAFETY
   0 3/4 INCH STAINLESS STEEL TUBING, 0.065 WALL, 3500 PSI WORKING PRESSURE
   0 AN 37° FLARED FITTINGS

0 LOX FLOWMETER BYPASS - PREVENTS FLOWMETER OVERSPEED DURING CHILL IN
   0 1/2 INCH CCI RSOV, 6000 PSI VALVE
   0 VALVE PREVIOUSLY USED IN LOX SERVICE

0 RUN LINE RELIEF VALVE - PREVENTS OVERPRESSURE DUE TO CRYOGENIC LOCKUP
   0 SET TO RETURN AT 4500 PSI
CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST STAND DETAIL (CONT)

0. LIQUID OXYGEN SYSTEM FAILURE ANALYSIS

<table>
<thead>
<tr>
<th>FAILURE MODE</th>
<th>INDICATOR</th>
<th>EFFECT</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOX TANK SAFETY DOES NOT OPEN OR CLOSE PREMATURELY</td>
<td>LOW POJ, P_C</td>
<td>LOW P_C KILL</td>
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<tr>
<td>LOX TANK REGULATOR FAILS OPEN</td>
<td>HIGH POJ, P_C</td>
<td>HIGH P_C KILL, HIGH TCR-1, 5 KILL POSSIBLE HARDWARE DAMAGE</td>
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<tr>
<td>LOX TANK REGULATOR FAILS CLOSED</td>
<td>LOW POJ, P_C</td>
<td>LOW P_C KILL</td>
</tr>
<tr>
<td>LOX FLOWMETER BYPASS DOES NOT OPEN</td>
<td>NO TEMPERATURE DROP</td>
<td>CHILL IN DOES NOT BEGIN</td>
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<tr>
<td>LOX FLOWMETER BYPASS DOES NOT CLOSE</td>
<td>LOW OXIDIZER FLOW</td>
<td>INACCURATE FUEL FLOW MEASUREMENT. ALL OTHER PARAMETERS LOOK GOOD, SLIGHTLY HIGH OXIDIZER FLOW POSSIBLE</td>
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TEST STAND DETAIL (CONT)

LIQUID OXYGEN SYSTEM FAILURE ANALYSIS (CONT)

<table>
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<tr>
<th>FAILURE MODE</th>
<th>INDICATOR</th>
<th>EFFECT</th>
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<tbody>
<tr>
<td>LOX LINE BLEED DOES NOT CLOSE</td>
<td>VISUAL VENTING PRIOR TO FS₁</td>
<td>NO EFFECT ON TEST HARDWARE, RESULTS IN FUEL RICH MR LOW ( P_c ) KILL</td>
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<tr>
<td>LOX LINE BLEED DOES NOT OPEN</td>
<td>TOX DOES NOT REACH TARGET TEMPERATURE</td>
<td>TEST TERMINATED</td>
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<tr>
<td>OTCV FAILS TO OPEN OR CLOSES PREMATURELY</td>
<td>OLVDT, LOW ( P_c )</td>
<td>NO IGNITION, LOW ( P_c ) KILL</td>
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<tr>
<td>FAILURE MODE</td>
<td>INDICATOR</td>
<td>EFFECT</td>
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<tr>
<td>OTCV fails to close at FS₂</td>
<td>OLVDT, PC continues</td>
<td>Ox rich shutdown, possible hardware damage. Hazardous condition minimized by rapid GN₂ purge of engine, both oxidizer and fuel circuits sequenced on by computer. Single point safety backup by sequenced of POT safety closed at FS₂. LOX flow can be terminated by closure of oxidizer tank safety.</td>
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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST STAND DETAIL (CONT)

- LIQUID METHANE SYSTEM DESIGN REQUIREMENTS
  - SUPPLY LIQUID METHANE TO GAS GENERATOR INLET
  - SAFETY PROCEDURE 13 "PRESSURIZED EQUIPMENT" APPLIES
  - EXISTING RUN TANK, STORAGE TANK AND FILL SYSTEM USED AS IS
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
CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST STAND DETAIL (CONT)

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

TEST STAND DETAILS (CONT)

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<td>TANK PRESSURE REGULATOR FAILS OPEN</td>
<td>PFT/CASCADE PRESSURE</td>
<td>TANK PRESSURE APPROACHES CASCADE PRESSURE OF 6600 PSI MAXIMUM. LINE PRESSURE RELIEF VALVE WILL OPEN. HIGH P_c KILL</td>
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<tr>
<td>TANK VENT FAILS OPEN</td>
<td>AUDIBLE VENTING, LOW PFT</td>
<td>EXCESSIVE GH_2 USE. CAN'T ACHIEVE RUN PRESSURE</td>
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<tr>
<td>FUEL FLOWMETER BYPASS DOES NOT OPEN</td>
<td>NO TEMPERATURE DROP</td>
<td>CHILL IN DOES NOT BEGIN</td>
</tr>
<tr>
<td>FUEL FLOWMETER BYPASS DOES NOT CLOSE</td>
<td>LOW FMF</td>
<td>INACCURATE FUEL FLOW MEASUREMENT. ALL OTHER PARAMETERS LOOK GOOD, SLIGHTLY HIGH FUEL FLOW POSSIBLE</td>
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<th>FAILURE MODE</th>
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<tr>
<td>FUEL RUN TANK SAFETY DOES NOT OPEN OR CLOSE</td>
<td>PFFM</td>
<td>NO IGNITION - TEST TERMINATION OX</td>
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<tr>
<td>PREMATURELY</td>
<td>PFFM</td>
<td>RICH SHUTDOWN AS FUEL FLOW DECAYS</td>
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<tr>
<td>FUEL RUN TANK SAFETY DOES NOT CLOSE</td>
<td>PRESSURE IN RUN LINE</td>
<td>POSSIBLE HARDWARE DAMAGE, LINE CHILL IN DOES NOT BEGIN</td>
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<td>FUEL BLEED VALVE DOES NOT OPEN</td>
<td>NO VISABLE INDICATION OF FUEL BLEED</td>
<td>METHANE FLOWS OUT OF FUEL LINE BLEED TO ATMOSPHERE AFTER TANK VENTS TO AMBIENT</td>
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<tr>
<td>FUEL BLEED VALVE DOES NOT CLOSE</td>
<td>EXCESSIVE FMF READING, LOW PFI, HIGH TCR-1</td>
<td>SEQUENCE TERMINATION</td>
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<td>PROBABLE HIGH MR CONDITION, POSSIBLE TCR-1 &gt; 1900° R KILL</td>
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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST STAND DETAIL (CONT)

0 LIQUID METHANE SYSTEM FAILURE ANALYSIS (CONT)

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<td>FUEL TCV DOES NOT OPEN OR CLOSES PREMATURELY</td>
<td>FLVDT, FMF, HIGH TCR-1, LOW PC</td>
<td>LOW PC KILL - NO IGNITION OX RICH SHUTDOWN, POSSIBLE HARDWARE DAMAGE, OX RICH CONDITION IN ENGINE SYSTEM AUTOMATIC GN₂ PURGE OF OXIDIZER AND FUEL CIRCUITS</td>
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<tr>
<td>FUEL TCV DOES NOT CLOSE</td>
<td>FMF, PFJ, LOW TCR-1</td>
<td>RAPIDLY COOL GAS GENERATOR CHAMBER, OVERSPEED FMF, FUEL RICH SHUTDOWN, NO HARDWARE DAMAGE, CLOSE RUN TANK SAFETY, AUTOMATIC GN₂ PURGE OF ENGINE SYSTEM, BOTH OXIDIZER AND FUEL CIRCUITS</td>
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CRITICAL EXPERIMENT REVIEW  
CARBON DEPOSITION OF LOX/METHANE

TEST STAND DETAIL (CONT)

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

TEST STAND DETAIL (CONT)

0. O$_2$/GH$_2$ IGNITER FAILURE ANALYSIS

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<th>INDICATOR</th>
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<td>OXIDIZER OR FUEL VALVES FAIL TO OPEN</td>
<td>NO POJ/PFJ OR P$_C$ IGNITER INCLINATION</td>
<td>NO IGNITION IGNITERS, TEST TERMINATION BY SEQUENCE, NO HARDWARE DAMAGE</td>
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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

HARDWARE INSTRUMENTATION

Water-Cooled Turbine Simulator

PCTBU
PCTSD
PCTSD-2
TcT

TCR 1,2,3,4,5,6

H₂O Pump
PNI 1 TWC 1 WW 1

From Fuel Valve

Fuel Dump

TWC 32 TWC 31 TWC 27 TWC 26

Dump Dump

PNI 3 TWC 3

PCTSU-2 PCTSU-3

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### CRITICAL EXPERIMENT REVIEW

**CARBON DEPOSITION OF LOX/METHANE**

#### INSTRUMENTATION

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<th>Accuracy + % Reading</th>
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<td>Strain Gauge</td>
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<td>Igniter Fuel Injection Pressure</td>
<td>PFJI</td>
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<td>Igniter Ox Purge Pressure</td>
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<td>Gauge</td>
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<tr>
<td>Igniter Fuel Purge Pressure</td>
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<td>Gauge</td>
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<tr>
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<td>Ox Tank Pressure</td>
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<tr>
<td>Ox Injection Pressure</td>
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<tr>
<td>Fuel Injection Pressure</td>
<td>POJ</td>
<td>Strain Gauge</td>
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<td>Chamber Pressure (Injector)</td>
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<td>Tur Sim Upstream Pressure (water-cooled)</td>
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<td>0-2000 psi</td>
<td>0.45</td>
<td>X</td>
</tr>
<tr>
<td>Tur Sim Upstream Pressure (uncooled)</td>
<td>PCTSU-2,-3</td>
<td>Strain Gauge</td>
<td>0-3000 psi</td>
<td>0.25</td>
<td>X</td>
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<tr>
<td>Tur Sim Downstream Pressure (uncooled)</td>
<td>PCTSD-2</td>
<td>Strain Gauge</td>
<td>0-3000 psi</td>
<td>0.25</td>
<td>X</td>
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<tr>
<td>Water Inlet Pressure</td>
<td>PW I-1,-3</td>
<td>Strain Gauge</td>
<td>0-3000 psi</td>
<td>0.45</td>
<td>X</td>
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<tr>
<td>Tur Sim Pressure Drop (uncooled)</td>
<td>PDCDP</td>
<td>Strain Gauge</td>
<td>0-500 psi</td>
<td>Class 5</td>
<td>X</td>
</tr>
<tr>
<td>Water Flow 2 each</td>
<td>WW-1,-2</td>
<td>Turbine</td>
<td>0-20 lb/sec</td>
<td>0.5</td>
<td>X</td>
</tr>
<tr>
<td>Ox Flowmeter Temperature</td>
<td>TOFM</td>
<td>Thermocouple</td>
<td>-300 to -200 F</td>
<td>0.5</td>
<td>X</td>
</tr>
<tr>
<td>Fuel Flowmeter Temperature</td>
<td>TFFM</td>
<td>Thermocouple</td>
<td>50 to 100 F</td>
<td>0.5</td>
<td>X</td>
</tr>
<tr>
<td>Water Inlet Temperature</td>
<td>TWC-1</td>
<td>Thermocouple</td>
<td>50 to 100 F</td>
<td>0.5</td>
<td>X</td>
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<tr>
<td>Water Outlet Temperature</td>
<td>TWC-2,-3</td>
<td>Thermocouple</td>
<td>50 to 300 F</td>
<td>0.5</td>
<td>X</td>
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<tr>
<td>Chamber Wall Temperature</td>
<td>TC-7</td>
<td>Thermocouple</td>
<td>0 to 2000 F</td>
<td>0.5</td>
<td>X</td>
</tr>
<tr>
<td>Chamber Wall Rake Temperature</td>
<td>TCR-1 -6</td>
<td>Thermocouple</td>
<td>0 to 2000 F</td>
<td>0.5</td>
<td>X</td>
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<tr>
<td>High Frequency Ox Injection Control Valve Trace</td>
<td>KDOJ</td>
<td>Piezoelectric</td>
<td>0 to 3000</td>
<td>5.0</td>
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<td>High Frequency Fuel Injection Control Valve Trace</td>
<td>KFJ</td>
<td>Piezoelectric</td>
<td>0 to 3000</td>
<td>5.0</td>
<td>X</td>
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<tr>
<td>LTOCV</td>
<td></td>
<td>Potentiometer</td>
<td>0 to 100%</td>
<td>1.0</td>
<td>X</td>
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### CRITICAL EXPERIMENT REVIEW
#### CARBON DEPOSITION OF LOX/METHANE

#### INSTRUMENTATION (CONT)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Transducer Type</th>
<th>Range</th>
<th>Accuracy + % Reading</th>
<th>Recording Device</th>
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<tr>
<td>Fuel Control Valve Trace</td>
<td>LTFCV</td>
<td>Potentiometer</td>
<td>0 to 100%</td>
<td>1.0</td>
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<td>Ox Control Valve Signal</td>
<td>V0CV</td>
<td>Voltage</td>
<td>0 to 100%</td>
<td>-</td>
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<td>Fuel Control Valve Signal</td>
<td>VF0V</td>
<td>Voltage</td>
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<td>-</td>
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<tr>
<td>Ox Igniter Valve Current</td>
<td>COIV</td>
<td>Amperage</td>
<td>0 to 100%</td>
<td>-</td>
<td>x</td>
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<td>Fuel Igniter Valve Current</td>
<td>CFIV</td>
<td>Amperage</td>
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<td>x</td>
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<td>Voltage</td>
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<td>-</td>
<td>x</td>
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<td>Fuel Igniter Valve Signal</td>
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**Instrumentation for High Injection Density Testing**

<table>
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<th>Parameter</th>
<th>Symbol</th>
<th>Transducer Type</th>
<th>Range</th>
<th>Accuracy + % Reading</th>
<th>Recording Device</th>
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<td>Ox Flow Rate</td>
<td>W0-1</td>
<td>Turbine</td>
<td>0-10 lb/sec</td>
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<td>Fuel Flow Rate</td>
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<td>Turbine</td>
<td>0-20 lb/sec</td>
<td>0.5</td>
<td>x</td>
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**CRITICAL EXPERIMENT REVIEW**  
**CARBON DEPOSITION OF LOX/METHANE**

**INJECTOR FLOW REQUIREMENTS**

<table>
<thead>
<tr>
<th>PC (PSIA)</th>
<th>MR</th>
<th>CSTAR (FPS)</th>
<th>THROAT AREA (SQ. INCH)</th>
<th>WT (LBM/S)</th>
<th>WOX (LBM/S)</th>
<th>WF (LBM/S)</th>
<th>DPO (PSID)</th>
<th>DPF (PSID)</th>
<th>POT (PSIA)</th>
<th>PFT (PSIA)</th>
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<td>3068</td>
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</tbody>
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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

SPARK IGNITER

SPARK PLUG - CHAMPION OR GLA
CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

GO₂/H₂ 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
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_c ) (psia)</td>
<td>500</td>
</tr>
<tr>
<td>( M_R )</td>
<td>45:1</td>
</tr>
<tr>
<td>( C^* ) (ft/sec)</td>
<td>3,300</td>
</tr>
<tr>
<td>( \dot{W}_f ) (lbm/sec)</td>
<td>0.0040</td>
</tr>
<tr>
<td>( \dot{W}_{ox} ) (lbm/sec)</td>
<td>0.181</td>
</tr>
<tr>
<td>( \dot{W}_{total} ) (lbm/sec)</td>
<td>0.185</td>
</tr>
<tr>
<td>Orifice Diameter_F (inches) (at 1700 psia)</td>
<td>0.0225 (.0250)</td>
</tr>
<tr>
<td>Orifice Diameter_OX (inches) (at 1700 psia)</td>
<td>0.0750 (.085)</td>
</tr>
</tbody>
</table>
CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

OPERATING SEQUENCE

Ox Bleed
4.5

FU Bleed
4.5

Ox Main PU

FU Main PU

Ox Ign. PU
5.0

FU Ign. PU

Ox Ign.

FU Ign.

Spark

Ox TCV

FU TCV

FS1 (1) (2) Duration FS2

(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

J5093
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

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Note: worst case for system analysis ΔP pressure.
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 H₂O FLOW RATE
  - PWI 500 TO 1500 PSIG COOLANT H₂O PRESSURE
  - PC-1 300 TO 2000 PSIG

- AFTER 10 SECONDS UNTIL FS₂
  - FMW-1 4 TO 12 POUNDS/SECOND COOLANT H₂O FLOWRATE
  - PWI 500 TO 1500 PSIG COOLANT H₂O PRESSURE
  - TCR-2 < 2000°F
  - TCR-5 < 2000°F
CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

LOX/METHANE TEST SERIES KILL PARAMETERS

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

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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.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W_F )</td>
<td>Fuel flow rate</td>
</tr>
<tr>
<td>( W_{OX} )</td>
<td>Oxidizer flow rate</td>
</tr>
<tr>
<td>( T_{OX} )</td>
<td>Oxidizer temperature</td>
</tr>
<tr>
<td>( T_F )</td>
<td>Fuel temperature</td>
</tr>
<tr>
<td>( P_{CTSD} )</td>
<td>Chamber pressure downstream of the turbine simulator. Prefer ( P_{CTSD} ) but will accept ( P_{CTSD}-2 )</td>
</tr>
<tr>
<td>( P_{CTSU} )</td>
<td>Chamber pressure upstream of the turbine simulator. Prefer ( P_{CTSU} ) but will accept ( P_{CTSU}-2 ) followed by ( P_{CTSU}-3 )</td>
</tr>
<tr>
<td>( TCR )</td>
<td>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 ).</td>
</tr>
<tr>
<td>( P_{C-1} )</td>
<td>Use ( P_{CTSU} ). Check start up sequence for time kill parameter.</td>
</tr>
</tbody>
</table>

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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

MACHINE DATA PLOT PARAMETERS

- INJECTOR PRESSURE VERSUS TIME
  - PC-1, POJI, PFJ1, 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 TEMPERATURES VERSUS TIME
  - TWC-2, TWC-26, TWC-27, TWC-31, TWC-32, TWC-33
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)
CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST SERIES
CARBON BUILD-UP AND INJECTION CALCULATION REQUIREMENTS

Carbon Build-up

1. Turbine Simulator Pressure Rates

\[ P_{TS} = \frac{P_{CTSU}}{P_{CTSD}} \]

\[ DPTS-C = \text{DPTS measured or \((PCTSU-PCTSD)\) if DPTS measured invalid.} \]

\[ DP \text{CORR} = \left[ (DPTS-C) - (PCTSU - PCTSD) \right] / Z \]

\[ P_{TS \text{CORR}} = \frac{(PCTSU - DP \text{CORR})/(PCTSU + DP \text{CORR})} \]

2. Turbine Simulator Pressure Drop

\[ DP_{TS} = P_{CTSU} - P_{CTSD} \]

3. Turbulence Ring Pressure Ratio

\[ PR_{TR} = \frac{(PCTSU/PC-1)}{1} \]

4. Turbulence Ring Pressure Drop

\[ DP_{TR} = (PC-1) - PCTSU \]

5. Nozzle Area

\[ NA1 = WTOT \times \frac{C/(PC-1)/gc}{1} \]

\[ NA2 = WTOT \times \frac{C/PCTSD/gc}{1} \]

6. Turbine Simulator Area

\[ C_{pA} = A_t \left( \frac{y+1}{y-1} \right)^{\left( \frac{y+1}{2} \right)} - \left( \frac{y+1}{y-1} \right)^{\left( \frac{y+1}{2} \right)} \]

Calculate \( C_{pA} \) for

\[ \gamma = 1.1 \]

\[ \gamma = 1.2 \]

\[ \gamma = 1.3 \]

\( A_t \) will be provided by the Project Engineer

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CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

TEST SERIES (CONT)

7. New Turbine Simulator Pressure Ratio

\[ PRTS-2 = \frac{PCTS-2}{PCTSU-2} \]
\[ DPTS2-C = PCTSU-2 - PCTS-2 \]
\[ DP-2\ CORR = \left[ (DPTS-2) - (DPT2-C) \right] / 2 \]

\[ DPTS-2 \] is measured

\[ PRTS2\ CORR = \left[ (PCTS-2) - (DP-2\ CORR) \right] / \left[ (PCTSU-2) + (DP-2\ CORR) \right] \]
CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

injector

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

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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 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 $MR$
CRITICAL EXPERIMENT REVIEW  
CARBON DEPOSITION OF LOX/METHANE

TO: T. C. Trafzer  
FROM: A. R. Keller  
SUBJECT: Carbon Deposition Propellants  
DISTRIBUTION: E.M. VanderWall

In February 1980  
9579: 10:05, ARC: JCM

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  
Test Engineer  
A Zone  
Test Operations

E. M. VanderWall, Manager  
A Zone  
Test Operations

A review of the data submitted in support of the A-Zone air pollutant permit and the emission data for this program show the program to be within your permit limitations.

VWG: AA0798
CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

EMISSIONS

TOTAL PROJECTED EMISSIONS AND SPECIES FOR
THE LOX/CH₄ HIGH DENSITY INJECTOR TEST SERIES

TOTAL O₂ PROJECTED = 11996 POUNDS
TOTAL CH₄ PROJECTED = 28320 POUNDS
TOTAL TEST TIME = 3008 SECONDS

<table>
<thead>
<tr>
<th>SPECIES</th>
<th>TOTAL POUNDS</th>
<th>% MASS</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₄</td>
<td>19702</td>
<td>0.49</td>
</tr>
<tr>
<td>CO</td>
<td>4137</td>
<td>0.10</td>
</tr>
<tr>
<td>CO₂</td>
<td>3354</td>
<td>0.08</td>
</tr>
<tr>
<td>H₂</td>
<td>1150</td>
<td>0.03</td>
</tr>
<tr>
<td>H₂O</td>
<td>8206</td>
<td>0.21</td>
</tr>
<tr>
<td>C (GRAPHITE)</td>
<td>3767</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>40316</td>
<td>1.00</td>
</tr>
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VWG: AA0798
CRITICAL EXPERIMENT REVIEW
CARBON DEPOSITION OF LOX/METHANE

OPERATIONAL PROCEDURES

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

ACTION ITEMS

1. Duration limits; fuel exhaustion
   Person(s) Assigned
   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

30 SEPTEMBER 1988
<table>
<thead>
<tr>
<th>Role</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHAIRMAN</td>
<td>J. L. PIEPER</td>
</tr>
<tr>
<td>PERFORMANCE ANALYSIS</td>
<td>R. E. WALKER</td>
</tr>
<tr>
<td>THERMAL ANALYSIS</td>
<td>F. F. CHEN</td>
</tr>
<tr>
<td>STRESS ANALYSIS</td>
<td>J. E. JELLISON</td>
</tr>
<tr>
<td>MATERIALS</td>
<td>R. M. HORN</td>
</tr>
<tr>
<td>PRODUCIBILITY</td>
<td>J. A. PHIPPS</td>
</tr>
<tr>
<td>DESIGN</td>
<td>L. C. FEMLING</td>
</tr>
</tbody>
</table>
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 similar flow rates and Pc's as in the previous LOX/Methane testing

- Compare carbon deposition effects of the COAX Injector to the impinging triplet injector

- Compatibility with ALS technology where possible
## INJECTOR REQUIREMENTS

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>REQUIREMENT</th>
<th>SOURCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROPELLANT</td>
<td>LOX/METHANE</td>
<td>CONTRACT MOD.</td>
</tr>
<tr>
<td>INJECTOR ELEMENT</td>
<td>LIQ/LIQ COAX</td>
<td>CONTRACT MOD.</td>
</tr>
<tr>
<td>$\dot{m}_{\text{TOTAL}}$</td>
<td>13 - 16 lbm/sec</td>
<td>PREVIOUS TESTING</td>
</tr>
<tr>
<td>Pc</td>
<td>2000 psi</td>
<td>PREVIOUS TESTING</td>
</tr>
<tr>
<td>MR</td>
<td>.20 - .60</td>
<td>PREVIOUS TESTING</td>
</tr>
<tr>
<td>FUEL AND OX SUPPLY LINE PRESSURE</td>
<td>&lt; 3000 psi</td>
<td>TEST EQUIPMENT LIMITATION</td>
</tr>
<tr>
<td>INJECTOR DIAMETER</td>
<td>2.38 in</td>
<td>HARDWARE INTERFACE</td>
</tr>
<tr>
<td>IGNITER</td>
<td>GOX/GH$_2$</td>
<td>PREVIOUS TESTING</td>
</tr>
<tr>
<td>CHAMBER LENGTH</td>
<td>20 in max.</td>
<td>HARDWARE</td>
</tr>
<tr>
<td>THRUST LEVEL</td>
<td>2 - 3 k lbf.</td>
<td>PREVIOUS TESTING</td>
</tr>
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</table>
SWIRL COAX INJECTOR ELEMENT DESIGN CRITERIA

ELEMENT TYPE: DOUBLE SWIRL COAX

OXIDIZER: LO₂
FUEL: LCH₄

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°
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
FOR $\theta_{ox} = 15^\circ$, PREFERRED FUEL CONE ANGLE RANGE FOR INJECTOR FACE THERMAL COMPATIBILITY IS 45$^\circ$ TO 60$^\circ$
FOR $\Theta_{0X} = 20^\circ$, PREFERRED FUEL CONE ANGLE RANGE FOR INJECTOR FACE THERMAL COMPATIBILITY IS $45^\circ$ TO $60^\circ$.
FOR $\theta_{ox} = 30^\circ$, PREFERRED FUEL CONE ANGLE RANGE FOR INJECTOR FACE THERMAL COMPATIBILITY IS $60^\circ$
Based on thermal compatibility, the possible cone half angle combinations are:

<table>
<thead>
<tr>
<th>$\theta_{ox}$</th>
<th>$\theta_f$</th>
</tr>
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<tbody>
<tr>
<td>15°</td>
<td>45°</td>
</tr>
<tr>
<td>15°</td>
<td>60°</td>
</tr>
<tr>
<td>20°</td>
<td>45°</td>
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<tr>
<td>20°</td>
<td>60°</td>
</tr>
<tr>
<td>30°</td>
<td>60°</td>
</tr>
</tbody>
</table>
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.
ROUGH SKETCH OF OX POST AND FUEL ANNULUS GEOMETRIES
(NOT TO SCALE)
CARBON DEPOSITION SWIRL COAX INJECTOR
CURRENT DESIGN POINT

\[ P_C = 2000 \text{ psia} \]
\[ \text{OX FLOWRATE} = 3.85 \text{ lbm/s} \]
\[ \text{FUEL FLOWRATE} = 10.39 \text{ lbm/s} \]
\[ \text{MIXTURE RATIO} = 0.37 \]
\[ \Delta P_{\text{ox}} = 300 \text{ psi} \]
\[ \Delta P_f = 600 \text{ psi} \]
\[ \text{NO. OF ELEMENTS} = 18 \]
\[ \text{OX CONE HALF ANGLE} = 20^\circ \]
\[ \text{FUEL CONE HALF ANGLE} = 45^\circ \]
\[ D_{\text{ox ORIFICE}} = 0.0635 \text{ in.} \]
\[ D_{\text{ox POST}} = 0.100 \text{ in.} \]
\[ \text{OD FUEL ANNULUS} = 0.1910 \text{ in.} \]
CARBON DEPOSITION
DUAL-SWIRL COAXIAL ELEMENT
INJECTOR ASSY

EXISTING IGNITOR

EXISTING FLANGE

RESONATOR RING

DX DOME
## RISK ASSESSMENT

### PERFORMANCE ANALYSIS
1) CONE ANGLES

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<tr>
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### THERMAL ANALYSIS

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<td>F-O-F TRIPLET EXPERIENCE</td>
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### STRESS ANALYSIS

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<td>COMPLETED STRESS ANALYSIS</td>
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### MATERIALS

|   | YES |

### PRODUCIBILITY

|   | NO |

### DESIGN
1) FACE NUTS
2) CONFINED ENVELOPE

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### FABRICATION

|   | NO |