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Development of Advanced Hydrocarbon Fuels at Marshall Space Flight Center

S.D. Bai, P. Dumbacher, and J.W. Cole
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LIST OF ACRONYMS AND SYMBOLS

A1	AFRL–1
AF	advanced fuel
AFRL	Air Force Research Laboratory
amb	ambient
BCP	bicyclopropylidene (B)
CINCH	competitive impulse noncarcinogenic hypergol (C)
CSV	comma separated variables
D2	throat diameter
gN_2	gaseous nitrogen
gox	gaseous oxygen
HEDM	high-energy-density materials
LC	load cell
lox	liquid oxygen
MSDS	material safety data sheets
MSFC	Marshall Space Flight Center
O	1-7 octadiyne
PLC	programmable logic controller
Q	quadricyclane
RP–1	rocket propellant–1
S/N	serial number
sqrt	square root
SS	stainless steel
TP	Technical Publication
TRD	test request document

NOMENCLATURE

A	throat area (in^2)
C^*	characteristic exhaust velocity
C_d	discharge coefficient
D	compressibility factor
g_c	gravitational constant $(lb_m*ft)/(lb_f*s^2)$
H_f	heat of formation
I_{sp}	specific impulse
M	Mach number
N	number of data
P	pressure
P_c	chamber pressure
R	gas constant
r	rank
T	temperature
t	time
$\dot{w}$	mass flow rate (lb_m/s)
γ	specific heat ratio
η	combustion efficiency
μ	standard mean

TECHNICAL PUBLICATION

DEVELOPMENT OF ADVANCED HYDROCARBON FUELS AT MARSHALL SPACE FLIGHT CENTER

1. BACKGROUND

This test series was a small-scale, hot-fire test series to make initial measurements of performance differences of five new liquid fuels relative to rocket propellant–1 (RP–1). The program was part of a high-energy-density materials (HDEMs) development at NASA Marshall Space Flight Center (MSFC). The fuels tested were quadricyclane, 1-7 octadiyne, AFRL–1, biclopropylidene (BCP), and competitive impulse noncarcinogenic hypergol (CINCH) (di-methyl-aminoethyl-azide). All tests were conducted at MSFC. The first four fuels were provided by the U.S. Air Force Research Laboratory (AFRL), Edwards Air Force Base, CA. The U.S. Army, Redstone Arsenal, Huntsville, AL, provided the last fuel, CINCH.

The data recorded in all hot-fire tests were used to calculate specific impulse (I_{sp}) and characteristic exhaust velocity (C^*) for each fuel, then compare them to RP–1 at the same conditions. This was not an exhaustive study, comparing each fuel to RP–1 at an array of mixture ratios, nor did it include important fuel parameters, such as fuel handling or long-term storage. The test hardware was designed for liquid oxygen (lox)/RP–1, then modified for gaseous oxygen (gox)/RP–1 to avoid two-phase lox at very small flow rates. All fuels were tested using the thruster/injector combination designed for RP–1. The results of these tests will be used to determine which fuels will be tested in future programs. The fuels tested and a brief commentary of results are as follows:

(1) Quadricyclane: The density is 17 percent higher than RP–1, and the I_{sp} is ≈2 percent better. This yields a 17-percent fuel tank volume and an approximate 10-percent propellant volume benefit to a launch vehicle (test Nos. 17 and 18). The results of this fuel test warrant scaling to higher thrust levels and additional tests.

(2) 1-7 Octadiyne: The density is 1.8 percent less than RP–1, but the I_{sp} is ≈3 percent better. The fuel volume benefit was negative, but the propellant benefit was slightly better than RP–1. Further study of 1-7 octadiyne, including a launch system evaluation, is required to fully describe 1-7 octadiyne benefits or cost.

(3) AFRL–1: The density is ≈7 percent less than RP–1, but the I_{sp} is ≈4.5 percent higher. The fuel volume benefit was negative. Like 1-7 octadiyne, AFRL–1 requires additional study to determine the launch system benefits or cost of this fuel.

(4) BCP: The density is 1.5 percent greater than RP–1, and the I_{sp} is approximately 2 to 4 percent better. However, the volume benefit is negative. Further launch system analysis is not necessary until resolution of the oxidation problem of BCP is reached.

(5) CINCH: The density is 11 percent higher than RP–1 and the I_{sp} is 3.5 percent better at the test condition. The results of this fuel were inconclusive because of the large difference in the mixture ratio of gox/RP–1 and gox/CINCH. CINCH tests required a mixture ratio of 1.4 compared to RP–1 at a mixture ratio of 2. I_{sp} was better than predicted and initial results indicate an 11-percent volume benefit for this fuel. The propellant volume benefit was ≈9.6 percent due to the difference of the mixture ratio. Additional study is necessary to better determine the performance cost and benefits of CINCH.

2. INTRODUCTION

The necessity to reduce launch costs demands the development of highly energetic propellants that will reduce the size of launch vehicles. The Air Force and NASA initiated the cooperative effort to develop HDEMs. The AFRL conducted theoretical studies, formulated the propellants, and shipped them to MSFC for hot-fire testing. The initial screening (on 10 g samples) is composed of computational chemistry; synthesis routes; preliminary characterization—chemical, physical, and hazard properties; toxicity, if known; and synthesis cost evaluation. The synthesis scale-up (10 lb) consisted of additional characterization—chemical, physical, and hazard properties; formulation; initial aging studies; initial compatibility; initial thermal studies; and initial toxicity studies. The overall development approach of the strained-ring hydrocarbon project consists of a small-scale combustion performance screening test consisting of ≈50-lbf-thrust hot-fire tests, limited by quantity of fuel. C^* and I_{sp} were determined, and material compatibility tests and initial aging studies were completed. The U.S. Army joined this effort at a later date and provided one propellant for testing, known as CINCH.

A simple plan to measure propellant performance was developed. The performance of a rocket propellant combination is generally expressed in terms of I_{sp}, combustion efficiency (η), and C^*. I_{sp} is total thrust per unit mass of propellants. The η is the ratio of actual heat of reaction per unit mass of propellant over the ideal heat of reaction per unit mass. C^* is the characteristic exhaust velocity, which can be determined by chamber pressure times the nozzle throat area per unit mass of propellant and is related to combustion efficiency via chamber pressure. C^* is independent of nozzle characteristics where I_{sp} and η include effects of the injector and nozzle geometry.[1] Generally, a propellant with a higher heat of formation performs better than one with a lower heat of formation, because the heat of reaction is the heat of formation of reactants minus the heat of formation of products. However, I_{sp} is proportional to the inverse of the propellant molecular weight. Therefore, low molecular weight materials with high heats of formation are better propellants. Hydrogen is an excellent example. The heat of formation for a chemical fuel can be predicted by using the bond energy of the molecular structure and the thermochemical equation.[2] For example, C_6H_8, the chemical compound of various molecular structures, is examined. The heat of formation and I_{sp} of the various C_6H_8 structures[3] are tabulated in table 1. This simple plan is incomplete because it does not consider important fuel parameters, such as long-term storage, handling, and material compatibility, in the performance calculations.

Table 1. Heat of formation and I_{sp} of C_6H_8.

Compound Name	Formula	ΔH_f (Kcal/mole)	Oxidizer/ Fuel Ratio	I_{sp} at Sea Level
Cyclopropyl methyl acetylene	C_6H_8	52.0	2.11	307.8
Allene-type isomer of above	C_6H_8	56.2	2.10	308.7
Cyclobutyl acetylene	C_6H_8	56.3	2.10	308.7
Cyclobutyl allene	C_6H_8	54.4	2.11	308.3

The fuels selected for hot-fire tests were chosen by various factors, such as performance, availability, toxicity, safety, stability, and material compatibility. The cost of manufacturing the propellant was not considered. Initially, BCP, spiro-petane, tripropargyl amine, LM–1 (a Lockheed Martin fuel), and 1.5 hexadiyne were considered for hot-fire tests. Spiro-petane, tripropargyl amine, and 1.5 hexadiyne were replaced with quadracyclane and 1-7 octadiyne due to the low vapor pressure, material compatibility, safety, and handling issues of the original fuels. Chemists at AFRL synthesized BCP because it is not commercially available. The physical and chemical properties of the tested fuels are shown in table 2.

The theoretical performance, C^*, and I_{sp}, of these fuels at 175 psia chamber pressure at equilibrium conditions are tabulated in table 3 and shown in figures 1 and 2.

Table 2. Physical and chemical properties of tested fuels.

Name	Quadricyclane	BCP	AFRL–1	CINCH	1-7 Octadiyne
Chemical formula	C_7H_8	C_6H_8	–	$C_4H_{10}N_4$	C_8H_{10}
Molecular weight (g/mole)	–	–	–	114.15	106.17
Density (g/cc)					
10 C	0.9894	–	0.7907	–	–
20 C	0.9787	0.8454	0.7801	0.9307	0.817 (@ 21 C)
30 C	0.9693	–	0.7691	0.9206	–
40 C	0.9592	–	0.7588	0.9102	–
50 C	0.9487	–	0.7500	0.8998	–
Flash point (°C)	11	–6.4	–	30	23
Boiling point (°C)	108	101	–	135	135–136
Melting point (°C)	–40	–12	–97.3	–68.92	–
Vapor pressure	23 mmHg @ amb	85.9 mmHg @ 25 C	34.1 kPa	10–50 mmHg	–
Viscosity (cp)	–	–	–	<10	–
Kin. viscosity 40 C	1.03	0.808	0.449	0.676	1.008
Heat of combustion (Btu/lb)	19,346	19,113	18,315	11,979	19,297
Heat of formation (Kcal/mole)	72.2	63.1	–	66.9	79.9
Appearance	–	Clear liquid, strong odor	Clear, water-white liquid, strong odor	Clear mobil liquid, strong amine-type odor	Flammable liquid, will emit toxic fumes of CO and CO_2

Table 3. Theoretical C^* and I_{sp} of fuels.

C^* (ft/s)											
Mixture Ratio	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**2**	**2.1**	**2.2**	**2.3**
RP–175	5,150	5,361	5,531	5,665	5,766	5,839	5,887	5,914	5,924	5,920	5,906
Q–175	5,936	6,009	6,052	6,071	6,070	6,055	6,030	5,998	5,962	5,925	5,888
B–175	5,996	6,071	6,117	6,139	6,143	6,131	6,108	6,079	6,044	6,007	5,970
O–175	5,947	6,025	6,072	6,096	6,099	6,087	6,064	6,034	6,000	5,964	5,926
C–175	5,953	5,906	5,856	5,805	5,754	–	–	–	–	–	–
A1–175	6,075	6,130	6,160	6,169	6,160	6,139	6,109	6,074	6,036	5,996	5,957
I_{sp}											
Mixture Ratio	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**2**	**2.1**	**2.2**	**2.3**
RP–175	225.09	234.42	241.58	247.21	251.47	254.50	256.46	257.39	257.53	257.05	256.13
Q–175	259.34	262.3	263.86	264.31	263.91	262.89	261.49	259.90	258.23	256.53	254.84
B–175	261.99	265.07	266.78	267.4	267.17	266.32	265.03	263.49	261.83	260.12	258.41
O–175	259.84	263.04	264.82	265.47	265.25	264.38	263.08	261.54	259.90	258.21	256.52
C–175	257.93	255.69	253.41	251.14	248.91	–	–	–	–	–	–
A1–175	265.43	267.56	268.48	268.45	267.71	266.45	264.89	263.18	261.40	259.62	257.84

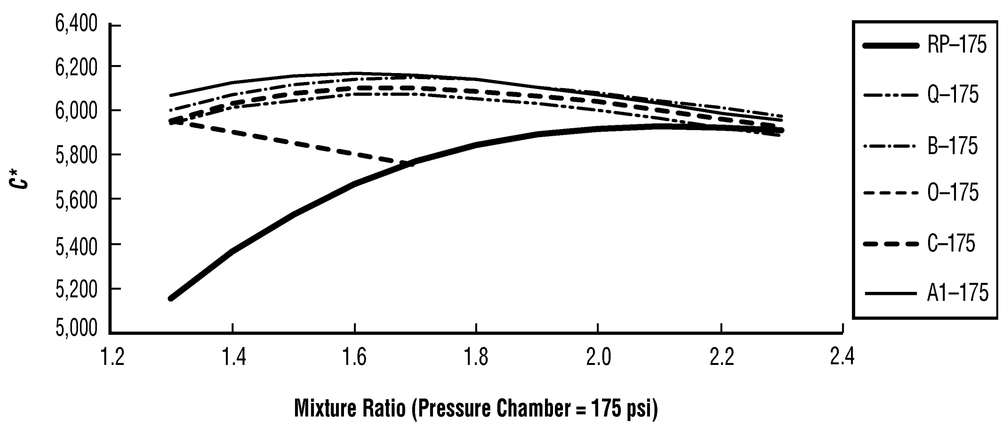

Figure 1. I_{sp} of fuels at various mixture ratios.

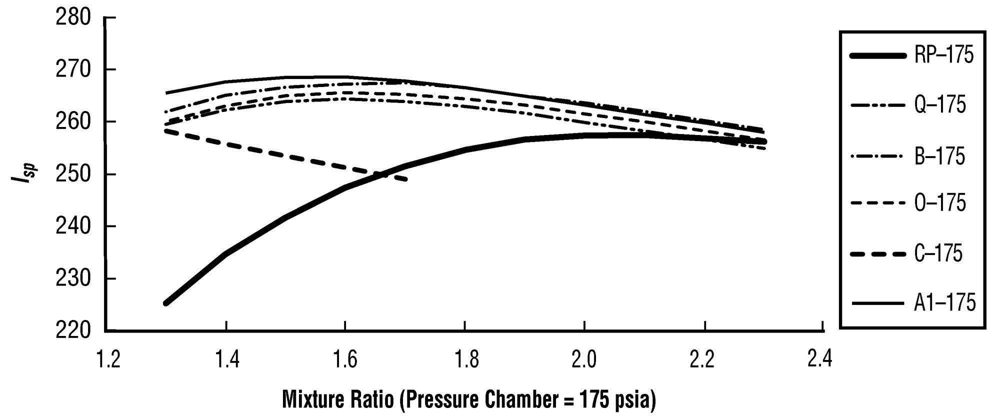

Figure 2. *C** of fuels at various mixture ratios.

Theoretical analysis can identify high-performance fuels, but many other concerns and issues exist, such as chemistry, logistics, safety, and performance. Chemistry concerns are whether the synthesis route is known and understood; whether the compound can be produced in large quantities at a reasonable cost; and whether the thermal, physical, chemical, and hazard properties meet desirable constraints. Logistics issues include long-term storability, storage vessel material compatibility, and transport concerns. Safety issues include resistance to adiabatic compression, auto ignition, liquid toxicity, vapor inhalation concerns, etc. Performance issues include combustor design, combustion characteristics, and accuracy of instrumentation measurements.

The maximum performance of an advanced hydrocarbon fuel may not be realized if tested in a combustor not optimized for the new fuel. Atomization, mixing, and calculated combustion efficiencies are dependent on both the combustor design and fuel properties. If the experimentally determined performance of an advanced fuel is better than RP–1 using an RP–1 combustor, then it is assumed that the performance may be enhanced if tested in a specifically designed advanced fuel thruster. On the contrary, if the performance of an advanced fuel is less than that of RP–1, it is not conclusive that the performance would actually be less in an optimal combustor. In this test series, a single combustor/injector design was employed for all fuel tests. In future detailed studies of one or two selected fuels, combustion characteristics, plume analysis, and specifically designed and fabricated combustor/injectors will be considered.

The primary goal of the MSFC task was the measurement of thrust to calculate I_{sp} performance using a 50-lbf thruster. The thruster size was determined by the available quantity of the new advanced fuels. Dynamic response tests of the assembled thrust measurement system were completed to demonstrate how the structural responses influenced thrust data. Accelerometers were placed in two locations of the thrust measurement system to correlate with the dynamic response data. The dynamic data consisted of transfer functions of measured input force rms versus measured output force in the frequency domain. The dynamic test is described in section 3.6 and the data are included in appendix E. The test team has a high degree of confidence in the ΔI_{sp} calculations of the advanced fuels relative to RP–1, but much lower confidence in the absolute I_{sp} calculations. Future testing will be completed using an improved thrust measurement system with much better absolute accuracy for enhanced I_{sp} calculations.

The second challenge of this task was the handling and material compatibility issues of testing new fuels. Most of these fuels had never been hot-fire tested. Instrumentation assembly materials, valve soft goods, fuel storage, fuel transport, fuel tanking, quantity distances, explosive limits, inhalation concerns, and personnel protective equipment were issues addressed prior to the first hot-fire test. The MSFC Materials Laboratory analyzed heat of formation and material compatibility for each fuel. Analysis included long-term bath compatibility tests for ≈1 wk. Short-term test durations were <24 hr.

The original test fixture and combustor were designed and fabricated for lox/RP–1 by Mason-Holodyne and G.G. Industries, respectively. The test fixture included two fuel systems, a water-cooled combustor, and a thrust measurement system. The test fixture was extensively modified to meet MSFC test safety requirements. Prior to testing, the oxidizer system was changed from lox to gox to eliminate the concern of two-phase lox flow at the injector. The system included a mainstage propellant feed system and a startup system of 25 percent of mainstage flow rate to initiate combustion and minimize chamber overpressure due to start pressure transients.

All tests were initiated at 25 percent of mainstage gox and RP–1 flow rates. At t+5 s, the bypass propellant valves were closed and the mainstage gox and RP–1 valves opened to achieve 100 percent of propellant flow rate. At approximately t+12 s, fuel switch was initiated from RP–1 to the advanced fuel at 100-percent flow rate. At t+≈20 s, test cutoff was commanded. Every test followed this sequence to eliminate possible start problems with untested fuels. Each test measured the variables for calculating C^* and I_{sp} for RP–1 and the advanced fuel. A successful test involved the accurate measurement of fuel flow rate, oxidizer flow rate, propellant temperatures, chamber pressure, and thrust.

3. TEST DESCRIPTION

3.1 System Description

The test fixture included two fuel tanks, a fuel tank pressurant system, fuel and gox startup and mainstage flow systems, purge systems, instrumentation, a thrust measurement system, and combustor. The schematic diagram of the test article is shown in figure 3.

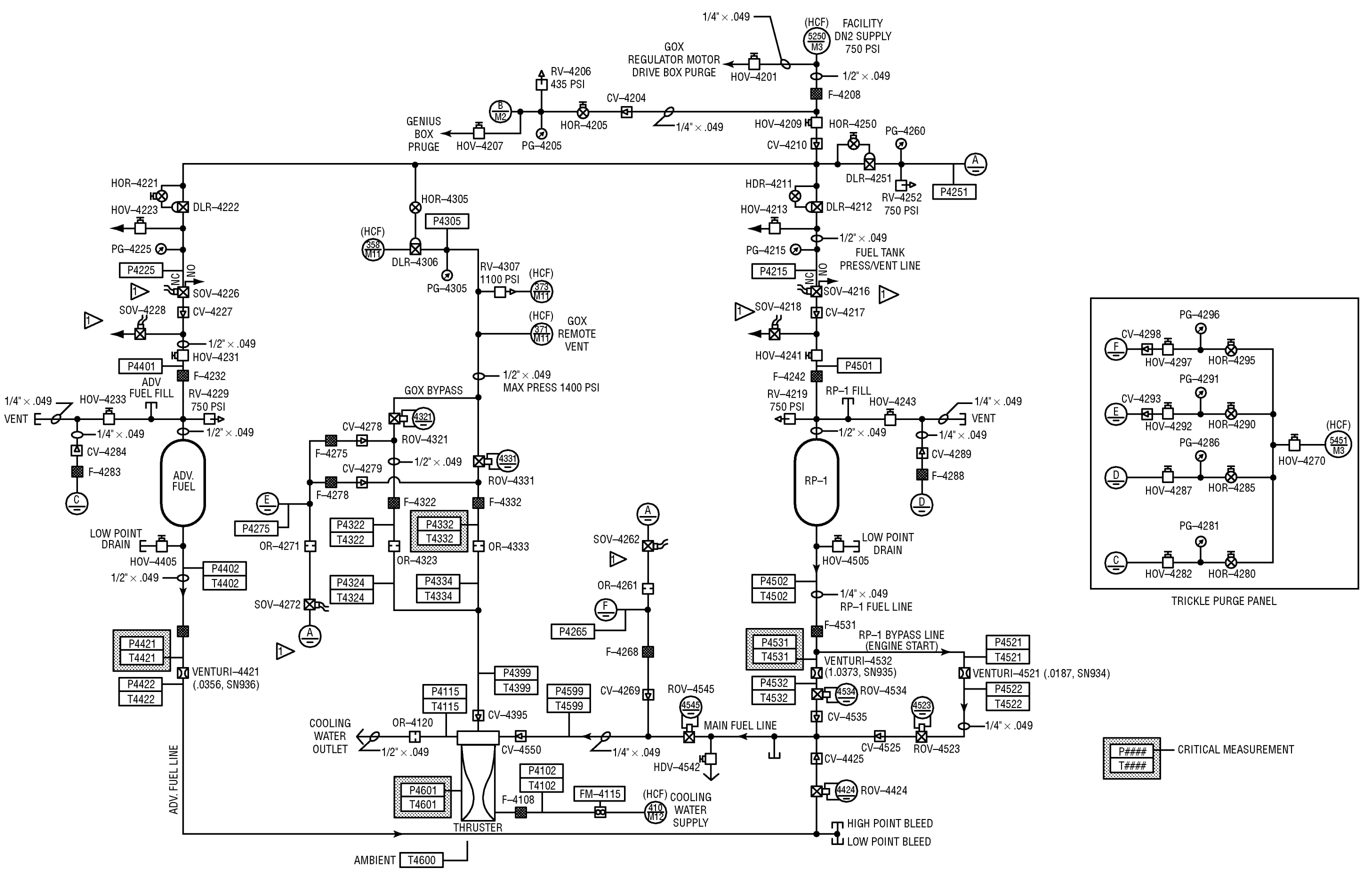

Figure 3. Test fixture schematic.

The fuel tanks have volumes of 4.5 gal and are rated at 1,800 psi. Tank A, shown on the right-hand side in figure 3, was for RP–1, and tank B, shown on the left-hand side, was for the advanced fuel(s). Fuel tank set pressures for testing were ≈400 psig using gaseous nitrogen (gN_2) as the pressurant. The designed mainstage fuel flow rate for both fuels was 0.08 lb_m/s. The gox flow rate was 0.160 lb_m/s. The cooling water flow rate was 0.65 lb_m/s. The startup propellant systems were called the “fuel bypass” or “gox bypass” and sized to deliver 25 percent of mainstage propellant mass flow rates; i.e., 0.04 lbm/s gox and

0.02 lb_m/s RP–1. Gox was supplied to the test fixture from a pressurized tube trailer. GN_2 was supplied to the test article via the test facility gN_2 system. The deionized water was provided from a tank trailer via a 300-psi water pump.

The multifuel system design had several advantages over a single-fuel system design for this type of testing. The first advantage was consistent ignition. The system was always ignited with gox and RP–1. This eliminated the variation of ignition characteristics of the different advanced fuels. Another advantage was that if there is an ignition problem or programmable logic controller (PLC) cut command issued prior to tank switch, no advanced fuel was exhausted. The ignition system was a simple spark wire inserted into the nozzle and positioned near the injector face. Audible igniter checks were performed prior to each test. The test fixture is shown in figure 4.

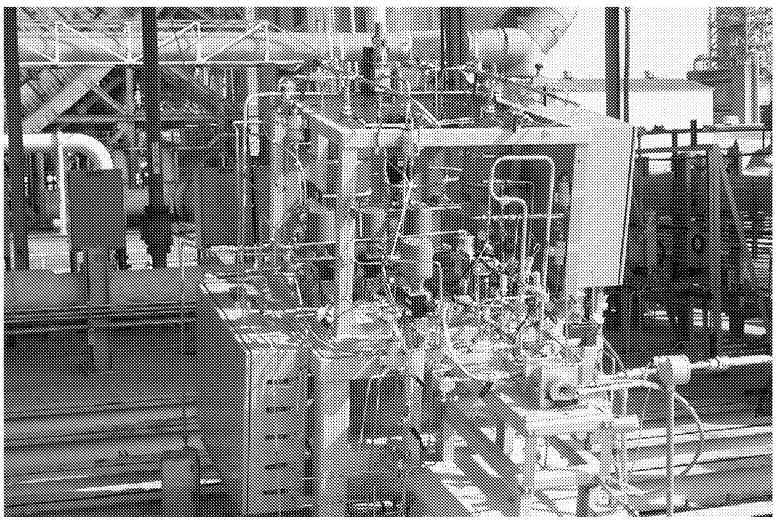

Figure 4. Test fixture.

A successful test was defined as full duration, with accurate measurements of fuel pressure and temperature, oxidizer pressure and temperature, chamber pressure, thrust, and calculated fuel and oxidizer flow rates. Data ranges were established for each critical measurement to define test cut parameters. Test cuts were armed and disarmed as the test sequence progressed. If at anytime in the sequence a cut was armed and the measurement value out of range, a cut command was issued and the test terminated. One test that cut before full duration, due to an advanced fuel low pressure cut, was considered successful because sufficient data were recorded to meet the successful test definition above. All other tests that cut were considered unsuccessful tests.

The test fire sequence had five specific stages:

(1) Pretest purge with gN_2
(2) Startup (gox/RP–1)
(3) Mainstage (gox/RP–1)
(4) Mainstage (gox/advanced fuel)
(5) Posttest purge with gN_2.

Pretest purge began after all fuel tank set pressures and oxidizer regulator pressures were set. Gox and fuel system purges were remotely commanded via the PLC at the test conductor's request. Once tank set pressures were within tolerance and the PLC is not displaying any warning, the auto sequence start command was requested by the test conductor and initiated by the test control technician. This PLC command assumed control from the control panel operator and issued valve and igniter commands as programmed and verified prior to test.

The startup phase began at auto sequence start (t+0). Thruster purges were commanded off and the main fuel shutoff and gox bypass valves commanded open to initiate propellant flow at 25 percent of mainstage mass flow rate. At t+0.1 s, the igniter-on command was issued and ignition attempted. At t+2.1 s, the igniter was commanded off, and if chamber pressure was within range at t+5 s, transition to gox/RP–1 mainstage occurred.

Mainstage began at t+5 s when the gox main and RP–1 main valves were opened. At t+5.8 s, the gox bypass valve was commanded closed; at t+5.9 s, the RP–1 bypass valve commanded closed. This overlap of valve open/close times accounted for ramp times of both the opening and closing valves to ensure continued combustion and ensure that the mixture ratio was kept within allowable limits. Ramp times were determined during test article checkouts. Gox/RP–1 mainstage continued until t+11.4 s when the transition to advanced fuel mainstage occurred.

Advanced fuel mainstage began when the advanced fuel shutoff valve was opened at t+11.4 s. At t+11.7 s, the RP–1 main valve was commanded closed. This overlap provided ≈1.75 s of an RP–1/advanced fuel mixture as the fuel. This was evident in several data plots. After ≈2 s, the RP–1 depleted from the mixture and the measured performance was strictly due to the advanced fuel.

At t+19.2 s, the PLC issued the duration cut command. The duration cut command, or any cut command, closed down the test article by transferring to a cut sequence. In this sequence, the gox valves were commanded closed at the cut command, but the fuel valves were delayed 100 ms. The gox system purge was opened at the cut command, and fuel purged started at cut command plus 0.1 s. This procedure was to protect the thruster, injector, and test article from an undesired gox fire by forcing the mixture ratio fuel rich, then purging with gN_2. Additional combustion after the cut command was caused by consuming the gox in the thruster and then consuming air oxygen outside of the thruster as the burning fuel was pushed from the chamber by system purges. Evidence of this was recorded on several tests. Flameout shutdown was not consistent except that a gox fire never occurred.

Duration of the advanced fuel tests was dictated by the quantities of fuels available for the tests. The maximum total duration for an advanced fuel test was ≈19 s; ≈7 of the 19 s was the advanced fuel burn. The shortest test duration was ≈17 s with 5 s of advanced fuel burn.

After each advanced fuel test, the advanced fuel system was drained and then flushed with RP–1, flushed with pentane, then purged with dry gN_2 at least overnight and often until the next test. Residual fuel was captured, contained, and stored for possible additional tests.

The specific test conditions and sequence for each test were requested on the test request document, shown in appendix B. This test quality record was controlled by the MSFC test area document coordinator.

An example of the autosequence of each test, as recorded by the serial event recorder during the test, is also provided in appendix B. This plot and the tabular data with it are used to verify that the test sequence operated as requested in the test request sheet. The entire test operations procedure/checklist is shown in appendix C.

3.2 Combustion Chamber

The water-cooled combustor assembly consisted of two major components—an injector and a combustion chamber, shown in figure 5. The injector was bolted to the combustion chamber with ten 1/4-in 28 UNF stainless steel (SS) bolts. The injector to chamber seal was a 225 butyl rubber O-ring. The injector had four ports fabricated in it. Gox was introduced axially through the port on the back of the injector while fuel was introduced radially through one side port. The other side port opposite the fuel port was the chamber pressure port. The fourth port was an angled 1/8-in tube for triethyl aluminum/triethyl borane. This port was originally included for ignition; however, it was sealed at the injector face and used to measure injector face temperature.

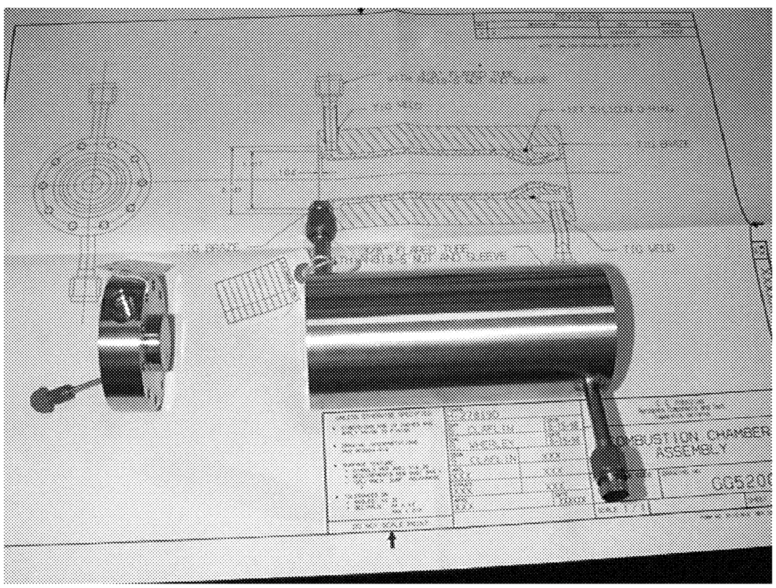

Figure 5. Combustion chamber.

The injector spray pattern consisted of six "split triplet" elements. These elements were configured such that two angled fuel streams impinged on one axially flowing oxidizer stream, allowing the fuel and oxidizer orifice diameters to be sized for optimum mixing.

The combustion chamber was a five-piece assembly consisting of an SS housing, a copper liner, a Delrin filler block, and two radial 3/8-in tubes. Water was introduced at the nozzle combustion chamber radial tube. The water circulated around the liner to the injector end of the chamber where it was discharged through the second radial tube. The combustion chamber design and analysis parameters are shown in table 4. The chamber length was chosen to give a characteristic combustion length of 30 in with a throat diameter of 0.537 in. Predicted mainstage chamber pressure was ≈175 psig.

Table 4. Combustion chamber design and analysis parameters.

Chamber Design	Chamber	Throat	Nozzle
Water flow rate (lb/s)	0.65	0.65	0.65
Water temperature (°F)	197	197	197
Water velocity (ft/s)	32	34	32
Assumed heat flux (Btu/in^2-s)	2	3	0.25
Coolant water temperature (°F)	242	294	88
Hot gas wall temperature (°F)	268	333	91
Water pressure (psia)	250	280	288
Hot gas wall stress (psi)	4,213	6,273	6,093
Nucleate Boiling Analysis			
Water saturation temperature (°F)	401	411	413
Burnout heat flux (Btu/in^2-s)	18	19.7	20.5

3.3 Measurement System

3.3.1 Flow Calibration

Cavitating venturis or orifices were used in the fuel and oxidizer lines to measure and control mass flow rate. Venturis were in the fuel lines and orifices in the oxidizer lines. Pressure and temperature measurements were upstream and downstream of each venturi and orifice. The oxidizer orifices were calibrated in a separate orifice calibration assembly using a known mass flow rate of gN_2 and calculating the actual discharge coefficient (C_d). The fuel venturies were purchased already calibrated with vendor-provided equations for calculating mass flow rate per venturi.

3.3.1.1 Gaseous Oxygen Orifice Sizing. Orifice sizes for the oxidizer lines were estimated using equation (1) and assuming a C_d of 0.6, a specific heat ratio (γ) of 1.4, and sonic velocity at the orifice throat:

$$\dot{w}_{\text{gas}} = C_d PAD\sqrt{\frac{\gamma g_c}{RT}} \tag{1}$$

$$D = M\left[1 + \frac{\gamma - 1}{2}M^2\right]^{\frac{-(\gamma+1)}{2(\gamma-1)}} \; . \tag{1A}$$

If $M = 1$ and $\gamma = 1.4$, then $D = 0.5787$.

A range of orifice sizes was fabricated above and below the predicted size to account for variations in actual C_d. The estimated and actual orifice sizes for the gox lines are shown in table 5.

Table 5. Gox orifice flowmeter sizing estimates and actuals.

Gox Main Throat Diameter (in)	Inlet Pressure (psi)			
	450 (lb_m)	455 (lb_m)	460 (lb_m)	470 (lb_m)
0.175	0.1643	–	0.1716	0.1752
0.170	0.1585	0.1602	0.1619	0.1652
Gox Bypass Throat Diameter (in)	**450 (lb_m)**	**455 (lb_m)**	**460 (lb_m)**	**470 (lb_m)**
0.087	0.0414	0.0419	0.0423	–
0.085	0.0395	0.0400	0.0404	–

Actual Gox Orifices	Diameter (in)	C_d
Bypass	0.0720	0.88
Mainstage	0.1735	0.83

Note that both the main and bypass orifice actual diameters were smaller than estimated, because the calibrated C_d of the orifices was greater than the assumed value of 0.6. The difference in C_d is due to orifice fabrication. The orifices were not sharp-edged orifices, but more like square-edged orifices. The orifices were fabricated by either center drilling a blank 1/2-in AN union fitting or by press fitting a center-drilled brass plug into one end of an open 1/2-in AN union fitting. Calibration of the gox main orifice was verified after test fixture assembly by venting a known quantity of gox through the test fixture in a known period of time.

3.3.1.2 Fuel Venturi Sizing. For the liquid fuel-flow measurement, cavitating venturi sizes were estimated using equation (2):

$$\dot{w}_{\text{liquid}} = 0.668\ C_d A_{\text{throat}} \sqrt{\rho P}\ . \tag{2}$$

This equation assumes sonic flow at the venturi throat and has a C_d of 0.98. If cavitation is the assumption, then the absolute upstream fuel pressure is the only measurement required to calculate the fuel mass flow rate. Three 1/4-in calibrated venturies were purchased from Fox Valve Development Corporation. The throat diameter and vendor flow equations are shown in table 6. For fuels other than quadricyclane, the flow rate calculation was corrected by the advanced fuel specific gravity ratio and achieved by appropriately adjusting the fuel tank pressure.

Table 6. Fuel venturi flowmeter sizing.

	Upstream Pressure (psi)	Main		Bypass	
		D2 (in)	Mass Flow	D2 (in)	Mass Flow
RP–1	200	0.0393	0.7974	0.0198	0.0202
		0.0394	0.0802	0.0197	0.0200
	250	0.0372	0.0799	0.0187	0.0201
		0.0373	0.0803	0.0186	0.0199
Quadricyclane	200	0.0374	0.0798		
		0.0375	0.0802		
	250	0.0354	0.0799		
		0.0356	0.0803		

Venturi	Usage	Throat Diameter (in)	Vendor-Provided Flow Equation (No./s)
S/N 934	RP bypass	0.0187	No./s of RP–1 = 0.0196* sqrt (*P*/314.7)
S/N 935	RP main	0.0373	No./s of RP–1 = 0.0758* sqrt (*P*/314.7)
S/N 936	Quadricyclane	0.0356	No./s of Quad. = 0.0356* sqrt (*P*/314.7)

3.3.2 Critical Measurements

Critical measurements were data measurements required for calculating propellant flow rates and mixture ratios. They were recorded on the standard data system as well as the high-speed data system. The critical measurements were fuel temperature and pressure, oxidizer temperature and pressure, chamber pressure, and thrust.

3.3.3 Control System Measurements

Control system measurements were monitored by the PLC to define test system limits. The control system measurements were the critical measurements plus coolant water pressure, coolant pump power, fuel tank pressures, oxidizer system pressure, and data system malfunction. If any of these measurements violated the preprogrammed limits, the control system issued a cut to terminate the test. Control system measurement ranges were calculated, programmed, and all simulated cuts verified prior to each test.

The additional control system measurements included the mixture ratios, low pressure at the propellant venturi or orifice inlet, loss of coolant flow, loss of fuel tank pressure, or malfunction of the data collection system. Any one of these error conditions terminated the test via a test cut command through the PLC. The control system measurements, measurement range, and arm/disarm times were specified in the test request document (TRD). An example TRD is shown in appendix B, including an example control sequence referred to by the TRD.

3.3.4 Measurement Sample Rate Frequency

All measurements were recorded with a 100-Hz sample rate through 10-Hz, low-pass filters. The critical measurements were also recorded with a high-speed data system using a 40-kHz sample rate through 10-kHz, low-pass filters. The allowable experimental error tolerance for the critical measurements was 0.1 ± 0.05 percent.

3.3.5 Test Data Display Characteristics

All measurements were displayed in the test control room at one sample per second during the test preparation and test. The delay time between measurement and display was less than ≈1.5 s for all measurements. The data system control room display update rate was independent of the data recording sample rate and fixed at approximately one sample per second for this test series.

3.4 Instrumentation List

Static pressures and temperatures were measured at various locations of the propellant and coolant systems. Measurement locations are shown in figure 3. Appendix D is a list of instrumentation identification numbers, descriptions, ranges, units, and device manufacturers.

3.5 Pretest Activities

Three of the advanced fuels had never been test fired and concerns were raised regarding the material compatibility and detonation stability. The detonation tests were conducted by the AFRL by circulating a small quantity of the advanced fuels through a Marotta MV74 solenoid valve. The objective was to test the detonation nature of the fuel under pressure while actuating the solenoid valve. The fuels tested were BCP, cyclopropylacetylene, and 1-7 octadiyne. The conclusion of the test was that the hydrocarbon fuels did not have any explosive reactions while flowing through the cycling solenoid valve. The Marotta solenoid valve was a representative valve of common solenoid valves used in the MSFC test area for fluid control.

Fuel material compatibility tests were completed by the MSFC Materials and Processes Laboratory. The tests were to observe if any materials on the test fixture that might come in contact with the fuel would show signs of reaction after various durations of fuel exposure. The materials below represent assembly materials for temperature probes, the temperature probe junction materials, and tubing fitting lubricant. A small quantity of Alumel ribbon, Chromel ribbon, magnesium oxide core, DuPont's Krytox® 2400 AC, Sauerisen cement, and E Constantan were placed in beakers with quadricyclane, BCP, 1-7 octadiyne, CINCH, AFRL–1, and RP–1. The results of the tests are tabulated in table 7.

Table 7. Results of material compatibility test.

Advanced Hydrocarbon Fuels (1-wk Observations at Room Temperature)						
	Quadricyclane Lot No. 1001	Bicycloproplidene (aged)	1-7 Octadiyne 99%	Dimethyl-2-Azido Ethylamine	AFRL–1	RP–1
Alumel ribbon	Strong odor, no visible reaction	Very strong odor, no visible reaction, formed residue	Some odor, no visible reaction	Not a very strong odor, no visible reaction	Very strong odor, no visible reaction	Some odor, no visible reaction
Chromel ribbon	Strong odor, no visible reaction	Very strong odor, no visible reaction, formed residue	Some odor, no visible reaction	Not a very strong odor, no visible reaction	Very strong odor, no visible reaction	Some odor, no visible reaction
Magnesium oxide core	Strong odor, no visible reaction	Very strong odor, no visible reaction, formed residue	Some odor, no visible reaction	Not a very strong odor, no visible reaction	–	Some odor, no visible reaction
Krytox 240AC	Strong odor, no visible reaction	Very strong odor, no visible reaction, formed residue	Some odor, no visible reaction	Not a very strong odor, no visible reaction	–	Some odor, no visible reaction
Sauerisen cement	Strong odor, no visible reaction	Very strong odor, no visible reaction, formed residue	Some odor, no visible reaction	Not a very strong odor, no visible reaction	Very strong odor, no visible reaction	Some odor, no visible reaction
E Constantan	Strong odor, no visible reaction	Very strong odor, no visible reaction, formed residue	Some odor, no visible reaction	Not a very strong odor, no visible reaction	Very strong odor, no visible reaction	Some odor, no visible reaction

All materials were nonreactive with the advanced hydrocarbon fuels. However, a small quantity of residue was discovered in BCP after several days. The residue was also present in the control beaker sample; there was no immersed material sample. The BCP control test was then duplicated at AFRL. No residue was present in the AFRL storage bottle with a nitrogen ulage. After a few days of BCP being exposed to air, the AFRL achieved similar residue results. The conclusion was that the BCP residue was an oxidation product residue at the bottom of the sample container and/or a suspended particulate. During the first attempt to test fire the BCP, the test cut due to low advanced fuel venturi inlet pressure. Review of the test data revealed a dramatic pressure drop across the advanced fuel filter. Inspection of the filter yielded a residue similar to that found in the laboratory during material compatibility tests. The filter was replaced, the rig flushed, and a special filtration process developed to remove the residue prior to tanking the fuel. The two subsequent BCP tests were successful.

3.6 Thrust Measurement System

The thrust measurement system was an assembly of three parts—a stationary table, a flexure table, and a load cell. The load cell measures the thrust force exerted on the flexure table during hot fire. The system, minus the load cell, was purchased from Mason-Holodyne and delivered to MSFC with the test article. The stationary table was fastened to a support stand fabricated by MSFC to support the test article and the thrust measurement system. The flexure table was supported by four SS flexures approximately 0.03 in thick by 1.5 in wide. The load cell was supported by a structure welded to the stationary table and secured to the flexure table with all-thread rod and lock nuts. The flexure design prevented translation and rotation about undesired axes. The 100-lbf load cell was selected by MSFC and acquired from the MSFC Test and Evaluation Department's instrumentation stock. Installation of the load cell was done by MSFC test area personnel. Shims for the thrust measurement system were fabricated and installed at the time of load cell installation to accommodate the depth of the selected load cell.

Dynamic response characteristics of the thrust measurement system were measured prior to any hot-fire tests. Concerns about the accuracy of measured thrust being affected by thrust measurement system dynamic responses prompted the dynamic tests. Frequency response curves of the assembled system, including the load cell, were measured and are included in appendix E. Two random noise dynamic force input ranges were used to measure response and verify system linearity, 1- and 15-lbf rms. A dynamic load cell between the shaker and the thruster nozzle measured input force. The installed thrust measurement load cell measured output force. Force transfer function plots are included in appendix E. The dynamic tests were assembled, completed, and reported by the MSFC Dynamic Test Group, Modal Analysis Test Team.

Posttest static thrust measurement system calibration was completed to determine static effects of propellant tubing on load cell data. The static load cell calibration configuration and data are shown in figures 6 and 7, respectively. A hydraulic cylinder was used to apply force to the thruster nozzle through a load cell in 10-lbf increments from zero to 100 lb. The input load cell data were recorded by hand at each force increment at the test stand using a shunt calibration bridge data display. The static output load cell was the same unit used for dynamic testing and all hot-fire testing. It has not been removed from the thrust measurement system since installation prior to the dynamic response tests.

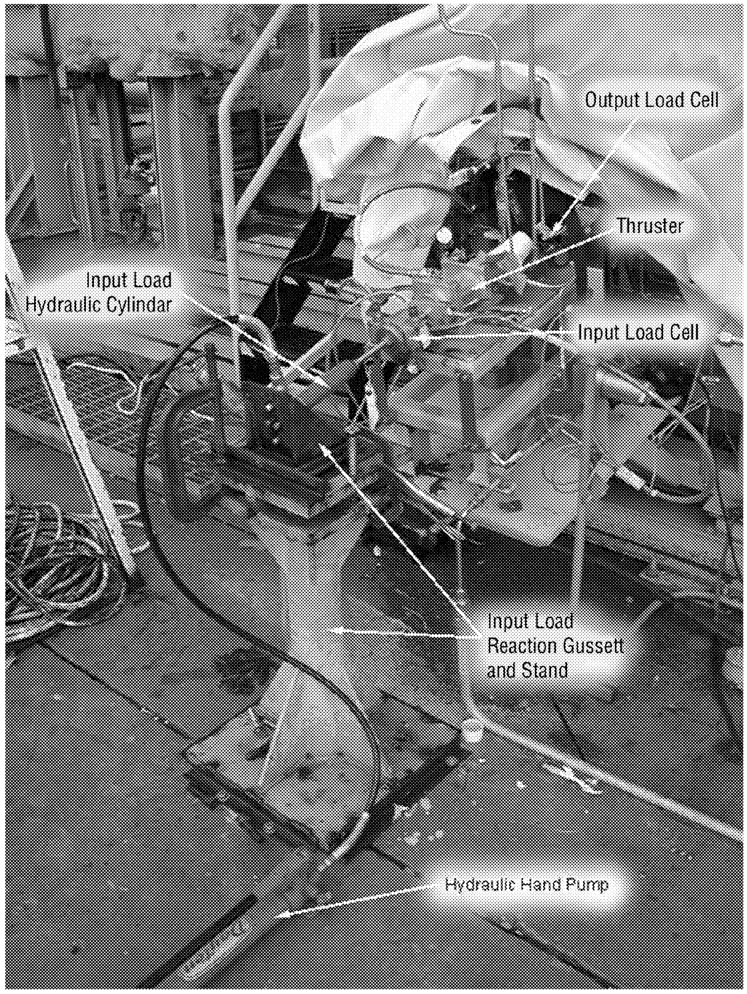

Figure 6. Thrust measurement system calibration configuration.

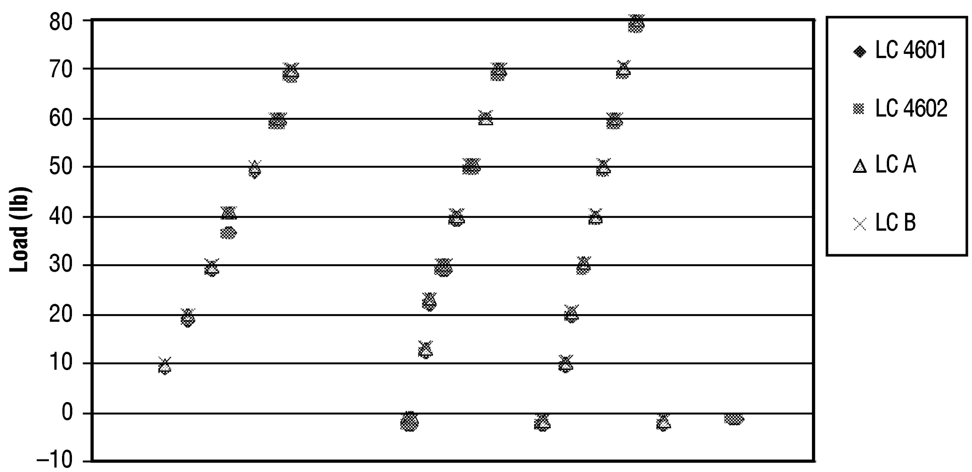

Figure 7. Thrust measurement system calibration data.

4. TEST RESULTS AND DISCUSSION

4.1 Test Data

This hydrocarbon fuel evaluation test series was composed of 39 hot-fire tests, including system checkout and fuel evaluation tests. The summary of the test runs is shown in appendix F.

Fuel performance is dependent on the fuel density, C^*, and I_{sp}. With two or three successful tests for each propellant, direct comparison of performance for the fuels is impossible. The I_{sp} and C^* of quadricyclane and RP–1 are dependent on the MR and chamber pressure and are shown in figures 8 and 9.

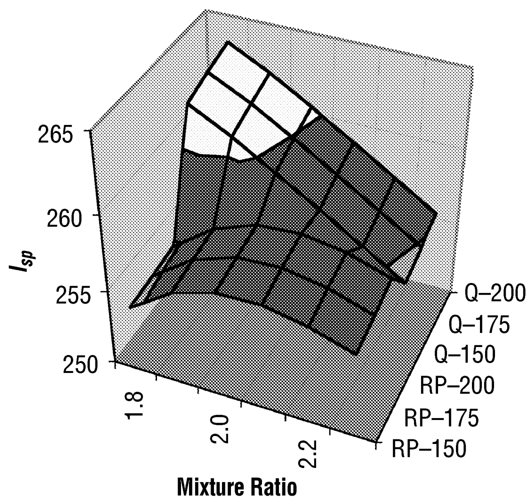

Figure 8. Theoretical C^* of quadricyclane and RP–1.

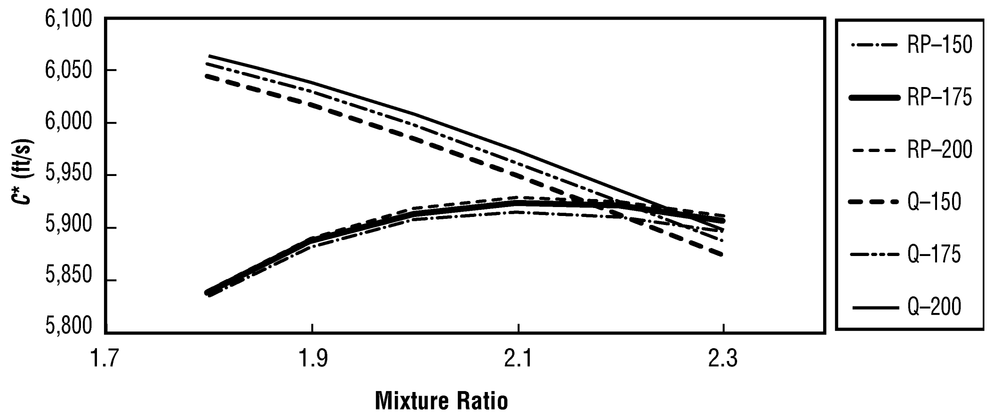

Figure 9. Theoretical I_{sp} of quadricyclane and RP–1.

As shown in figures 8 and 9, a general statement that quadricyclane was better than RP–1 is meaningless unless test conditions are specified. The performance of fuels is highly dependent on combustor design. In this Technical Publication (TP), the hot-fire test results of all fuels in the same combustor are compared with the theoretical calculation for that fuel. The experimental operating conditions for the fuel, such as the mixture ratio and chamber pressure, were applied to the experimental calculations. To determine which fuels are actually better rocket propellants, it is desirable to have separate combustion chambers for each fuel. However, use of an RP–1 chamber was justifiable because the objective was to find a fuel to replace and perform better than RP–1.

If the experimental data were consistent with theoretical data, it was assumed that the performance of a fuel was better at the given operating conditions with the given combustion chamber. The actual C^* and I_{sp} were tabulated with theoretical values at the given conditions for each fuel. If the actual C^* and I_{sp} for a fuel was better than the RP–1 for the same test, it was assumed that the fuel was a better performer than RP–1. However, accuracy of the measured thrust was not as desired. Consequently, for this test, thrust and I_{sp} were used as relative values for comparing a fuel to RP–1 at test conditions. Also, fuel density difference benefits or penalties were not considered for this TP. As a result, the data do not completely describe the benefits or liabilities of the new fuels but do indicate which fuels call for further study.

Prior to comparing the different characteristics of the fuels, the average or integrated value of the process variable, pressure, and the calculated variables, C^*, or I_{sp}, are closely examined. In a typical run, in this case, RP–1 and 1-7 octadiyne, the chamber pressure is shown (fig. 10).

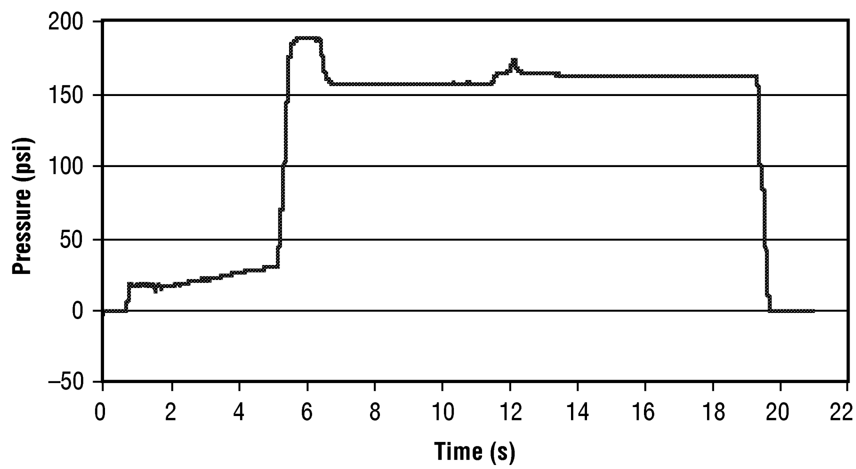

Figure 10. Chamber pressure of 1-7 octadiyne and RP–1 (test No. 24).

Since the RP–1 bypass valve is closed ≈6.4 s of the test, the data before 7 s were not used. The transition from RP–1 to advanced fuel occurred between 11.3 and 12.2 s. The data between 14 and 18 s were analyzed for this particular fuel case. Some test durations have been decreased due to the limited fuel.

In the data analysis, the first concern was data reproducibility. To eliminate this concern, 12 test data sets of selected variables spanning 4 seconds of test data were examined. The mean value, standard deviation, measurements uncertainty, and range of these tests were calculated and tabulated in table 8. Uncertainty is defined as SDOM (standard deviation of mean) that is equal to standard deviation divided by the square root of the sample size. The process capability and three standard deviations in terms of mean value and the chamber pressure of these runs were also calculated, shown in figure 11.

Table 8. Uncertainty and range data of selected test runs (raw data).

	LC 4601	*P* 4332	*P* 4334	*P* 4531	*P* 4532	*P* 4601	*N*
Test No. 17	43.617	308.242	204.669	376.675	232.357	157.487	301
Uncertainty	0.003	0.018	0.009	0.002	0.008	0.009	
Range	0.262	1.524	0.757	0.170	0.764	0.615	
Test No. 18	44.866	308.020	204.589	372.600	230.995	157.738	400
Uncertainty	0.002	0.015	0.008	0.001	0.010	0.008	
Range	0.262	1.524	0.841	0.340	0.849	0.717	
Test No. 20	44.574	307.123	203.429	328.097	223.029	155.630	400
Uncertainty	0.002	0.021	0.011	0.004	0.008	0.007	
Range	0.230	2.371	1.093	0.340	0.765	0.614	
Test No. 22	44.034	306.615	203.903	319.574	222.863	156.753	400
Uncertainty	0.002	0.016	0.006	0.002	0.014	0.007	
Range	0.311	1.524	0.672	0.339	1.274	0.819	
Test No. 23	42.648	309.375	205.708	320.296	228.722	158.097	400
Uncertainty	0.002	0.015	0.006	0.004	0.010	0.007	
Range	0.213	1.694	0.673	0.340	0.849	0.614	
Test No. 24	44.273	307.201	204.699	319.750	229.923	157.426	400
Uncertainty	0.002	0.014	0.004	0.005	0.009	0.008	
Range	0.279	1.185	0.505	0.510	0.765	0.768	
Test No. 25	43.672	306.497	204.051	318.529	223.390	156.842	400
Uncertainty	0.003	0.017	0.007	0.003	0.012	0.009	
Range	0.295	1.862	0.757	0.340	0.934	0.767	
Test No. 32	33.045	242.035	160.781	228.096	176.153	123.800	400
Uncertainty	0.003	0.009	0.008	0.003	0.009	0.010	
Range	0.271	1.098	0.671	0.254	0.763	0.716	
Test No. 33	32.955	242.466	161.249	228.406	177.912	124.265	400
Uncertainty	0.003	0.013	0.005	0.002	0.008	0.011	
Range	0.262	1.605	0.420	0.170	0.594	0.716	
Test No. 35	44.548	304.715	201.984	284.665	219.312	154.400	400
Uncertainty	0.003	0.014	0.007	0.003	0.006	0.010	
Range	0.344	1.184	0.587	0.170	0.424	0.817	
Test No. 38	45.159	306.828	205.575	367.566	229.693	158.938	400
Uncertainty	0.002	0.015	0.008	0.004	0.008	0.007	
Range	0.262	2.030	1.008	0.170	0.848	0.716	
Test No. 39	44.516	306.820	205.745	369.398	237.478	159.960	400
Uncertainty	0.003	0.016	0.008	0.003	0.007	0.008	
Range	0.295	1.860	0.840	0.170	0.594	0.614	

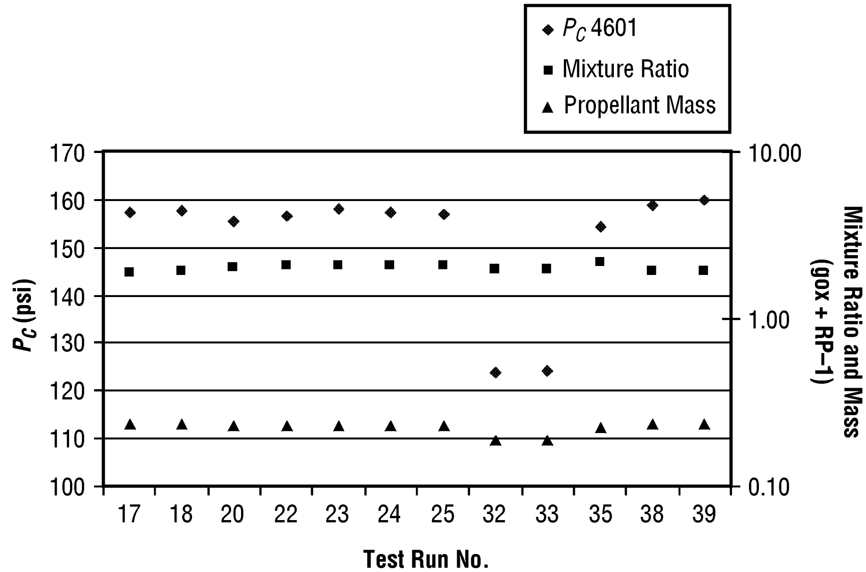

Figure 11. Chamber pressure of selected test data (repeatability).

The second concern was measurement uncertainty and its effect on a calculated value. For example, were the measurements for calculating C^* affected by how the data were measured? Did the measurements have undesired components affecting the accuracy of the measurement? The I_{sp} and C^* values of test No. 17 were examined in detail and tabulated in table 9. The standard deviation and uncertainty were obtained by two methods: (1) Discrete measurements were used to calculate a variable, then the mean and standard deviation of the calculated variable were determined, and (2) the mean and the dispersion of measured values were determined, then used to calculate the mean and dispersion of the desired calculated variable. Because the uncertainties of the calculated values were small compared to the mean value, uncertainty analyses for other tests were not done. The measurement uncertainty was considered within allowable limits for all tests.

Table 9. Uncertainty analysis of test No. 17.

	Gox	RP–1	Mixture Ratio	I_{sp}	C^*	P_C
Mean	0.1538	0.0808	1.904	196.0	5,337.3	157.56
Standard Dev.	0.0002	–	0.003	0.2	259.5	0.18
Uncertainty	–	–	–	–	13.0	0.01
N	400	400	400	400	400	400
	Gox	**AF**	**Mixture Ratio**	I_{sp}	C^*	P_C
Mean	0.1551	0.0791	1.962	201.8	5,465.6	160.91
Standard Dev.	0.0002	0.0001	0.005	0.3	6.2	0.22
Uncertainty	–	–	–	–	0.3	0.01
N	570	570	570	570	570	570

The third concern was whether a mean value was a reasonable representation of the variable. This was determined by using a statistical test known as the sign test for the difference in the product and the standard.[4] This method determines the significant difference in the product (measurement) and the standard mean, if any. The results were computed and shown in table 10. From this statistical test, it was concluded that there was no reason to believe that the average differs from the standard mean, μ, at the significant level of 0.01, since r is not less than $r(0.01{,}400)$.

Table 10. Statistical sign test of test No. 22 chamber pressure and C^*.

Time	*P*–RP			*C**–RP					Time	*P*–O	*C**–O		
7.006	157.065	0	1	5430.0324	0	1			14.01	163	5526.148		
7.016	157.116	0	1	5431.4616	0	1			14.02	163	5523.87		
7.026	157.116	0	1	5433.3833	0	1			14.03	163	5525.961		
7.036	157.116	0	1	5436.8758	0	1			14.04	163	5524.899		
⋮	⋮			⋮									
10.946	157.627	1	0	5437.57	0	1	17.946	162.437	0	1	5502.29	0	1
10.956	157.627	1	0	5435.21	0	1	17.956	162.437	0	1	5500.54	0	1
10.966	157.627	1	0	5435.21	0	1	17.966	162.437	0	1	5500.69	0	1
10.976	157.576	1	0	5435.79	0	1	17.976	162.437	0	1	5498.42	0	1
10.986	157.576	1	0	5439.21	0	1	17.986	162.437	0	1	5496.68	0	1
10.996	157.576	1	0	5442.90	1	0	17.996	162.437	0	1	5492.60	0	1
	157.426	188	212	5439.4	193	207			235	165		210	190
ave	157.4264	+	-	5439.3587	+	-		162.5486	+	-	5508.66	+	-
stdev	0.154524			3.0812623				0.256749			8.510788		
r		188			193					165			190
***r*(0.01,400)**	138												

Since r is not less than $r(0.01{,}400)$, there is no reason to believe that the average differs from μ = 157.426 for RP and octadiyne.

The fourth concern was whether the C^* of RP–1 and 1-7 octadiyne differ significantly at a given set of hardware and operating conditions. For this case, it was concluded that there was reason to believe the average of the two products was differing at the significant level of 0.01. Statistical analyses of this kind were not conducted on all the experimental data. The need for analysis was determined by the magnitude of the deviation and the authors' judgment.

4.1.1 Quadricyclane

The test results of test No. 18 are shown in figure 12. The averaged test results of quadricyclane runs are shown in table 11.

Six quadricyclane tests were attempted. The mixture ratios of both RP–1 and quadricyclane were targeted at ≈2 in the first two tests, test Nos. 17 and 18. Both tests were successful. The mixture ratio of 2 was selected because that was the combustion chamber design criteria, and RP–1 performance is best at a mixture ratio of ≈2.1. In the next two attempts, test Nos. 19 and 20, only 4 s of quadricyclane data at mixture ratios of 2.18 were recorded. The mixture ratio target of test Nos. 34 and 35 was ≈1.6. Test No. 34 terminated at RP–1 mainstage due to the low fuel pressure caused by a lower ambient temperature. Test No. 35 was successful at a mixture ratio of 1.6 for quadricyclane. All the averaged data of the runs are shown in table 11.

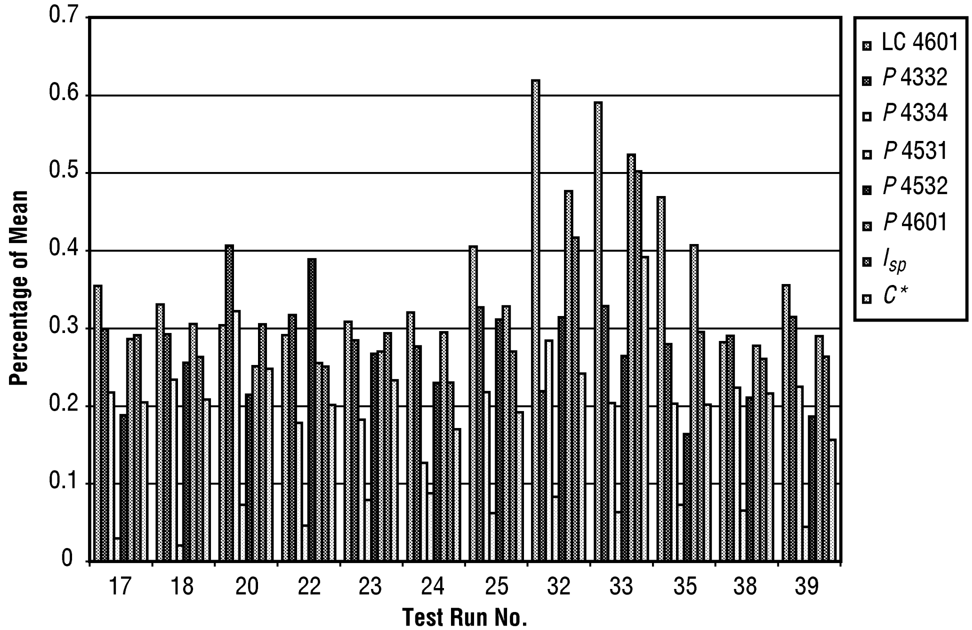

Figure 12. Deviation from mean.

Table 11. Test results of RP–1 and quadricyclane.

	RP–1 (No. 18)	RP–1 (No. 20)	RP–1 (No. 17)	RP–1 (No. 35)
Mixture Ratio	1.92	2	1.9	2.19
C^* (theory)	5,893 (100%)	5,919 (100%)	5,887 (100%)	5,919 (100%)
C^* (experiment)	5,359 (90.9%)	5,406 (91.3%)	5,350 (90.9%)	5,465 (92.3%)
I_{sp} (theory)	256.6 (100%)	257.5 (100%)	256.4 (100%)	257.0 (100%)
I_{sp} (experiment)	196.0 (76.4%)	200.6 (77.9%)	196.0 (76.4%)	199.9 (77.8%)
P_C (psig)	157.74	155.63	157.56	154.4

	Q (No. 18)	Q (No. 20)	Q (No. 17)	Q (No. 35)
Mixture Ratio	1.96	2.18	1.96	1.66
C^* (theory)	6,011 (100%)	5,931 (100%)	6,011 (100%)	6,078 (100%)
C^* (experiment)	5,468.8 (91.0%)	5,493.2 (92.6%)	5,465.8 (90.9%)	5,394 (88.7%)
I_{sp} (theory)	260.5 (100%)	250.3 (100%)	260.5 (100%)	264.4 (100%)
I_{sp} (experiment)	201.4 (77.3%)	204.8 (81.8%)	201.4 (77.3%)	200.13 (75.7%)
P_C (psig)	161.451	154.995	160.88	173.53

The results of the tests are expressed in terms of the total propellant weight (gox plus fuel). The calculated propellant weight for a mixture ratio of 1.6 and the propellant weights based on the tests are tabulated in table 12. The propellant weight savings is approximately 0.1 to 3 percent. Because the payload fraction of most launch vehicles is very low, reducing a small percentage of propellant fraction can be equivalent to a large increase in the payload fraction. A complete benefit analysis of high fuel density is not included here. However, the specific gravities of RP–1 and quadricyclane are 0.82 and 0.98, respectively. This difference will allow a reduction of fuel tank size by ≈17 percent. This, in turn, allows for smaller launch vehicle size, lower aerodynamic drag, and reduced cost, all of which satisfy the goals set forth by NASA regarding improving launch technology and reducing access-to-space costs.

Table 12. Quadricyclane test result in terms of propellant weight.

	Mixture Ratio	P_C (psig)	I_{sp}	1,000-lb_f Propellant	Comments
Theory					
RP–1	2.10	160.30	275.53	3.88	Specific gravity:
Quadricyclane	1.60	160.30	264.31	3.78	RP–1: 0.832
Difference (%)	–	–	2.63	–2.57	Quadricyclane: 0.98
					Volume benefit: 17%
Test No. 17					
RP–1	1.903	157.55	196.00	5.10	
Quadricyclane	1.960	160.90	201.80	4.96	
Difference (%)	–	–	2.96	–2.87	
Test No. 18					
RP–1	1.917	157.74	196.00	5.10	
Quadricyclane	1.963	161.04	201.41	4.96	
Difference (%)	–	–	2.76	–2.69	
Test No. 20					
RP–1	2.040	155.63	199.90	5.00	
Quadricyclane	2.180	155.16	203.20	4.92	
Difference (%)	–	–	1.65	–1.62	
Test No. 35					
RP–1	2.190	154.39	199.90	5.00	
Quadricyclane	1.655	173.53	200.13	5.00	
Difference (%)	–	–	0.12	–0.11	

4.1.2 1-7 Octadiyne

The test results of test No. 23 are shown in figure 13. The averaged test results of the 1-7 octadiyne tests are shown in table 13.

Two 1-7 octadiyne tests were attempted and both were successful. The target mixture ratios of both RP–1 and 1-7 octadiyne were ≈2.1 for test Nos. 22 and 23. As shown in figure 13, the thrust and C^* of 1-7 octadiyne are higher than RP–1 at the test conditions. Also shown is a reasonable repeatability of the test runs.

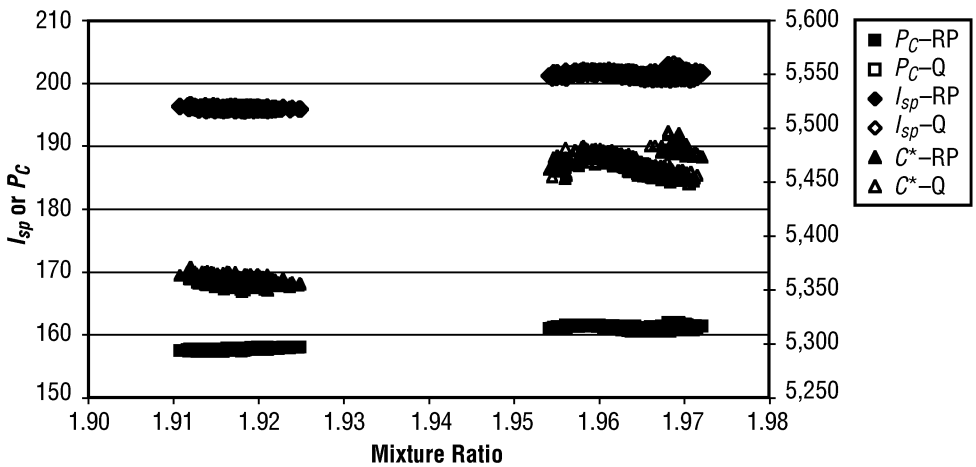

Figure 13. Test results of quadricyclane and RP–1 (test No. 18a).

Table 13. Test results of RP–1 and 1-7 octadiyne runs.

	RP–1 (No. 22)	RP–1 (No. 23)	1-7 Octadiyne (No. 22)	1-7 Octadiyne (No. 23)
Mixture Ratio	2.08	2.09	2.08	2.10
C^* (theory)	5,922 (100%)	5,923 (100%)	6,006 (100%)	5,999 (100%)
C^* (experiment)	5,432.10 (91.7%)	5,446.70 (91.96%)	5,486.40 (91.3%)	5,496.20 (91.6%)
I_{sp} (theory)	257.50 (100%)	257.50 (100%)	260.20 (100%)	259.80 (100%)
I_{sp} (experiment)	199.30 (77.4%)	199.20 (77.4%)	203.60 (78.3%)	202.20 (77.8%)
P_C (psig)	156.75	158.10	159.28	160.25

The results of the tests for 1-7 octadiyne are expressed in terms of the propellant weight, similar to the quadricyclane data in section 4.1.1. The propellant weight differences based on the calculations and measurements are tabulated in table 14. The propellant weight savings for 1-7 octadiyne is approximately 1.4 to 2.3 percent. Like quadricyclane, the propellant mass fraction is less than RP–1. However, 1-7 octadiyne has a density penalty because the specific gravity of 1-7 octadiyne is less than RP–1. The specific gravity of RP–1 and 1-7 octadiyne is 0.82 and 0.817, respectively. For 1-7 octadiyne, the slightly higher I_{sp} is offset by the slightly lower specific gravity. A launch system evaluation for both RP–1 and 1-7 octadiyne fuels is required to define the real benefit or penalty of 1-7 octadiyne.

Table 14. 1-7 octadiyne test results in terms of propellant weight.

	Mixture Ratio	P_C (psig)	I_{sp}	1,000-lb_f Propellant
Theory				
RP–1	2.08	156.75	257.50	3.88
1-7 Octadiyne	2.08	159.28	260.20	3.84
Difference (%)	–	–	1.05	–1.04
Test No. 22				
RP–1	2.08	156.75	199.30	5.02
1-7 Octadiyne	2.08	159.28	203.63	4.91
Difference (%)	–	–	2.17	–2.13
Test No. 23				
RP–1	2.09	158.10	199.20	5.02
1-7 Octadiyne	2.10	160.25	202.16	4.95
Difference (%)	–	–	1.49	–1.46

4.1.3 AFRL–1

The results of test No. 25 are shown in figure 14. The averaged test results of AFRL–1 are shown in table 15.

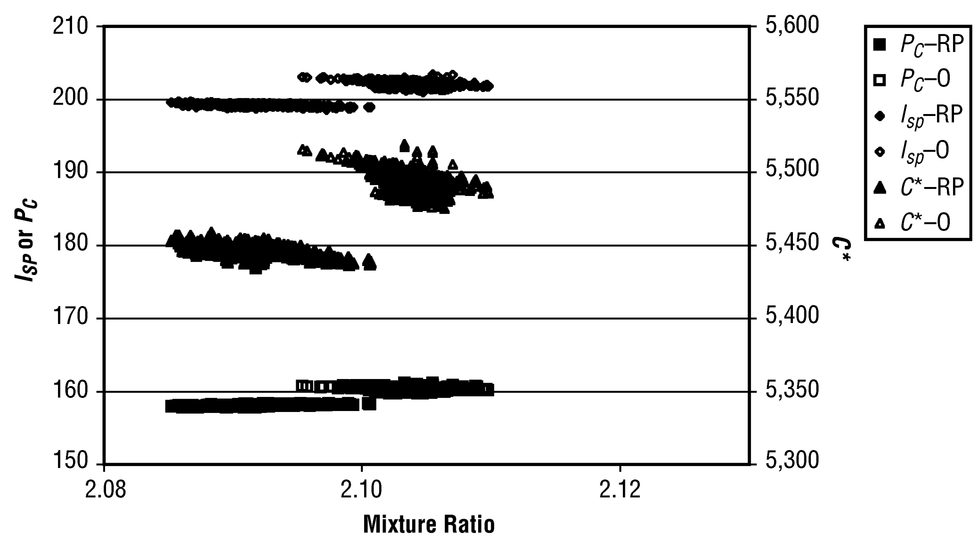

Figure 14. Test results of 1-7 ocyadiyne and RP–1 (test No. 23a).

Table 15. Test results of RP–1 and AFRL–1 runs.

	RP–1 (No. 24)	RP–1 (No. 25)	AFRL–1 (No. 24)	AFRL–1 (No. 25)
Mixture Ratio	2.08	2.08	2.03	2.03
C^* (theory)	5,924 (100%)	5,924 (100%)	6,061 (100%)	6,061 (100%)
C^* (experiment)	5,439 (91.8%)	5,436.70 (91.8%)	5,511.80 (90.9%)	5,505.60 (90.8%)
I_{sp} (theory)	257.60 (100%)	257.60 (100%)	262.60 (100%)	262.60 (100%)
I_{sp} (experiment)	199.60 (77.5%)	199.70 (77.5%)	204.30 (77.8%)	204.90 (78.0%)
P_C (psig)	162.62	161.78	157.43	156.84

Two AFRL–1 tests were attempted and both were successful. The target mixture ratio of both RP–1 and AFRL–1 was ≈2.1 in test Nos. 24 and 25. Figure 15 shows that the thrust and C^* of AFRL–1 are higher than RP–1 at the test conditions. Figure 15 also shows reasonable repeatability of the tests.

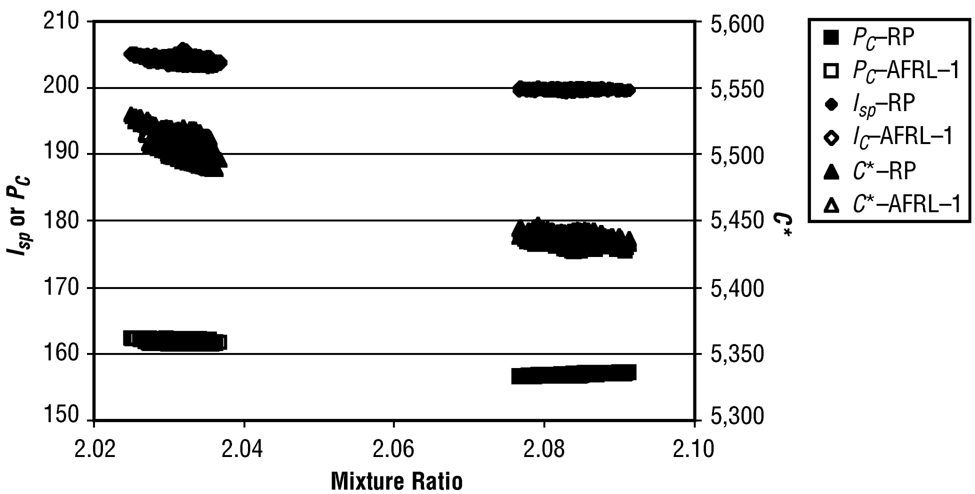

Figure 15. Test results of AFRL–1 and RP–1 (test No. 25).

The results of the tests for AFRL–1 are expressed in terms of the total propellant weight similar to previous fuel data. The propellant weight differences based on the calculations and measurements are tabulated in table 16. The propellant weight savings for AFRL–1 is approximately 2.2 to 2.5 percent. As was previously described, the AFRL–1 propellant mass fraction is less than RP–1. However, AFRL–1 has a density penalty since the specific gravity of AFRL–1 is less than RP–1. The specific gravity of RP–1 and AFRL–1 is 0.82 and 0.775, respectively. As in the 1-7 octadiyne case, the slightly higher AFRL–1 I_{sp} is offset by the slightly lower specific gravity. A launch system evaluation for both RP–1 and AFRL–1 fuels is required to define the real benefit or penalty of AFRL–1.

Table 16. AFRL–1 test results in terms of propellant weight.

	Mixture Ratio	P_C (psig)	I_{sp}	1,000-lb$_f$ Propellant
Theory				
RP–1	2.08	162.00	257.60	3.88
AFRL–1	2.03	157.00	262.60	3.81
Difference (%)	–	–	1.94	–1.90
Test No. 24				
RP–1	2.08	162.62	199.63	5.01
AFRL–1	2.03	157.43	204.31	4.89
Difference (%)	–	–	2.34	–2.29
Test No. 25				
RP–1	2.08	161.78	199.71	5.01
AFRL–1	2.03	156.84	204.92	4.88
Difference (%)	–	–	2.61	–2.54

4.1.4 Competitive Impulse Noncarcinogenic Hypergol

The technical nomenclature of CINCH is di-methyl-aminoethyl-azide. Initially, CINCH was identified as an alternative fuel to monopropellant hydrazine. MSFC, however, tested CINCH as a bipropellant fuel. The results of test Nos. 31–33 are plotted in figure 16. The averaged test results of the CINCH test runs are shown in table 17. Run No. 31 was a preparation test for CINCH, using RP–1 in both fuel tanks, with a target mixture ratio of 1.4. Run Nos. 32 and 33 were targeted at a mixture ratio of 2 for RP–1 and a mixture ratio of 1.4 for CINCH, respectively. The change in mixture ratio for RP–1 between test Nos. 31 and 32 was for proper test fixture operation.

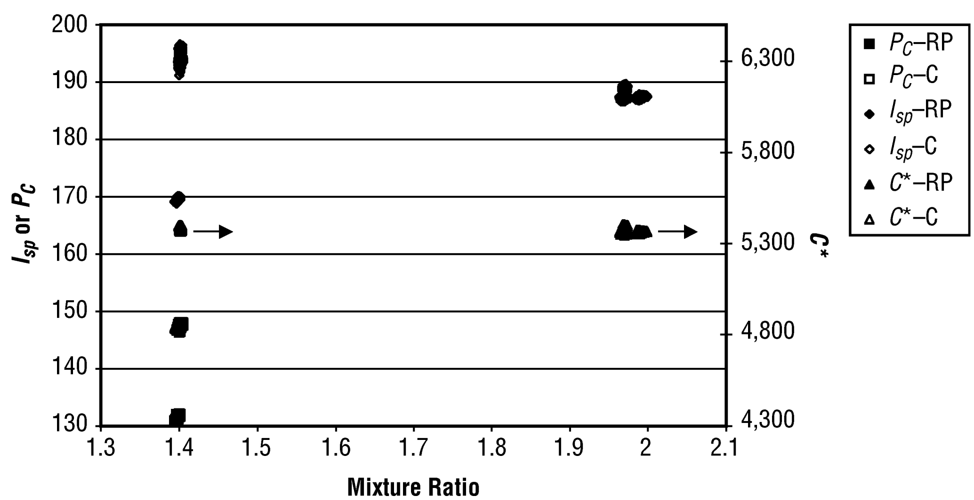

Figure 16. Test results of CINCH and RP–1 (test Nos. 31–33).

Table 17. Test results of CINCH and RP–1 runs.

	RP–1 (No. 32)	RP–1 (No. 33)	CINCH (No. 32)	CINCH (No. 33)
Mixture Ratio	1.97	1.97	1.40	1.40
C^* (theory)	5,898 (100%)	5,898 (100%)	5,900 (100%)	5,901 (100%)
C^* (experiment)	5,358 (90.8%)	5,393 (91.4%)	5,352 (90.7%)	5,387 (91.3%)
I_{sp} (theory)	256.70 (100%)	256.70 (100%)	255.40 (100%)	255.40 (100%)
I_{sp} (experiment)	187.20 (70.6%)	189.00 (73.6%)	193.70 (75.8%)	195.60 (76.6%)
P_C (psig)	123.80	124.27	147.5	147.72

The two CINCH tests were successful. As shown in figure 16, the thrust and C^* of CINCH at a mixture ratio of 1.4 are higher than RP–1 at a mixture ratio of 1.4. However, when the performance of CINCH at a mixture ratio of 1.4 is compared with RP–1 at a mixture ratio of 1.97, the results were inconclusive. The theoretical calculations shown in table 18 indicate that CINCH has lower I_{sp} than RP–1, but the measurements indicate otherwise. The data represent a reasonable repeatability.

The results of the tests for CINCH are also expressed in terms of the total propellant weight similar to previous fuel data formats. The propellant weight differences based on calculations and measurements are shown in table 18.

Table 18. CINCH and RP–1 test results in terms of propellant weight.

	Mixture Ratio	P_C (psig)	I_{sp}	1,000-lb_f Propellant	Comments
Theory					
RP–1	1.970	124.00	256.70	3.90	Specific gravity:
CINCH	1.402	147.50	255.40	3.92	RP–1: 0.832
Difference (%)	–	–	–0.51	0.51	CINCH: 0.9256
					Volume benefit: 11.25%
Test No. 32					
RP–1	1.970	123.80	187.21	5.34	
CINCH	1.402	147.72	193.74	5.16	
Difference (%)	–	–	3.49	–3.37	
Test No. 33					
RP–1	1.970	124.27	189.00	5.29	
CINCH	1.402	147.72	195.63	5.11	
Difference (%)	–	–	3.51	–3.39	

4.1.5 Bicyclopropylidene

The results of test No. 38 and 39 are shown in figure 17. The averaged test results of BCP tests are shown in table 19.

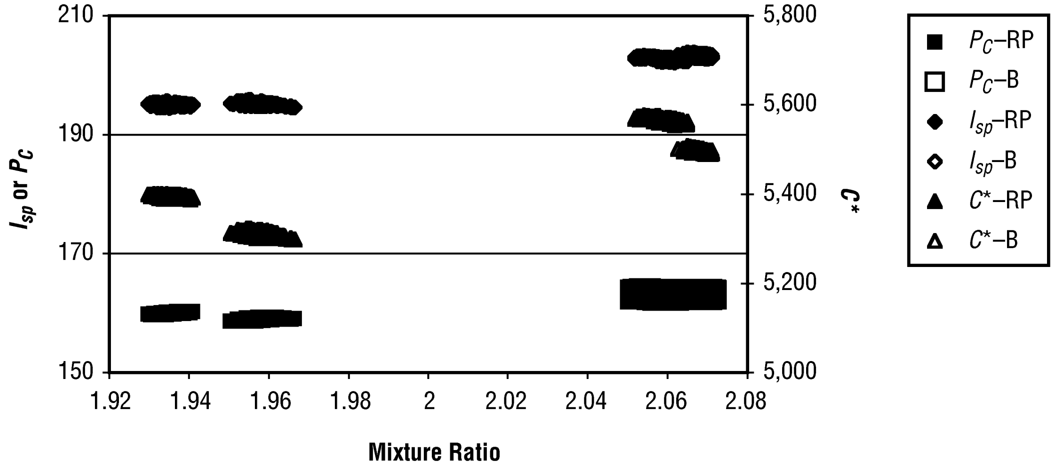

Figure 17. Test results of BCP and RP–1 (test Nos. 38 and 39).

Table 19. Test results of BCP and RP–1 runs.

	RP–1 (No. 38)	RP–1 (No. 39)	BCP (No. 38)	BCP (No. 39)
Mixture Ratio	1.96	1.94	2.068	2.059
C^* (theory)	5,906 (100%)	5,900 (100%)	6,058 (100%)	6,060 (100%)
C^* (experiment)	5,311 (90.0%)	5,394.50 (91.4%)	5,498 (90.8%)	5,568 (91.9%)
I_{sp} (theory)	257.10 (100%)	256.90 (100%)	262.5 (100%)	262.60 (100%)
I_{sp} (experiment)	195.20 (75.9%)	195.00 (75.9%)	203.3 (77.4%)	202.70 (77.2%)
P_C (psig)	158.94	159.56	163.08	163.11

Three BCP tests were attempted. The first test was terminated at the end of the RP–1 mainstage due to a BCP venturi inlet pressure-low cut. Inspection of the rig discovered a restricted fuel filter. The filter trapped fuel particulate as discussed earlier in this document. It was determined that the BCP would have to be filtered just prior to attempting further testing. After the filter process was complete, two tests were attempted and both were successful. The target mixture ratio of both RP–1 and BCP was ≈2 in test Nos. 38 and 39. As shown in figure 17, the thrust and the C^* of BCP are higher than RP–1 at the test conditions. Also shown is a reasonable repeatability of the test runs.

The results of the tests for BCP are expressed in terms of the total propellant weight, similar to the other fuels in this TP. The propellant weight differences based on the calculations and measurements are tabulated in table 20. The propellant weight savings for BCP is approximately 3.8 to 4 percent, whereas the theoretical savings are 2.5 percent. Like other advanced fuels, the propellant mass fraction is less than RP–1. Note that BCP has a density benefit of only 1.56 percent. The specific gravity of RP–1 and BCP is 0.82 and 0.846, respectively. As in the quadricyclane case, the higher I_{sp} yields volume savings for a flight vehicle.

Table 20. BCP and RP–1 test results in terms of propellant weight.

	Mixture Ratio	P_C (psig)	I_{sp}	1,000-lb_f Propellant	Comments
Theory					
RP–1	1.960	158.94	256.70	3.90	Specific gravity: RP–1: 0.832 BCP: 0.845 Volume benefit: –1.56%
BCP	2.068	163.08	262.50	3.80	
Difference (%)	–	–	2.30	–2.20	
Test No. 28					
RP–1	1.960	158.94	195.15	5.12	
BCP	2.068	163.08	203.30	4.92	
Difference (%)	–	–	4.18	–4.01	
Test No. 39					
RP–1	1.940	159.56	195.02	5.13	
BCP	2.059	163.11	202.70	4.93	
Difference (%)	–	–	3.94	–3.79	

5. CONCLUSIONS/SUMMARY

As stated in section 4.1, making a general statement proclaiming a particular fuel better than RP–1 without considering all of the performance and economical issues is premature after so few tests. The main objective for the advanced fuels is the economic benefit of the density differences in fuels for a flight vehicle. However, several additional issues in the fuel performance comparison exist and can dramatically affect the economic gain. The primary issue of this set is that the combustor used for these tests was not optimized for RP–1 or advanced fuels. Another issue is that test conditions were limited to single or few mixture ratios per fuel.

The original design calculation shows that C^* for the gox/RP combustor was 90 percent of theoretical value. The experimental values of C^* for various fuels, in terms of theoretical values, are shown in table 21. The experimental values of mixture ratios, chamber pressure, and I_{sp} are tabulated in table 22.

Table 21. Experimental C^* as a percentage of theoretical C^* for tested fuels.

Fuels	RP–1	Quadricyclane	1-7 Octadiyne	AFRL–1	CINCH	BCP
Range	90.0–92.3	88.7–92.6	91.3–91.6	90.8–90.9	90.7–91.3	90.8–91.9
Mean	91.4	90.80	91.45	90.9	91.0	91.4
Std Dev	0.62	–	–	–	–	–
No. Data	12	4	2	2	2	2

The experimental C^* for RP–1 as a percentage of the theoretical value indicated that the experimental C^* values were above the chamber design target of 90 percent. This demonstrated that even after the injector was modified for gox use from the designed lox use, the injector and chamber performed well for fuels with densities similar to RP–1.

The densities of quadricyclane and CINCH are approximately 17 and 11 percent higher than RP–1, respectively, yet CINCH has a higher C^* (table 21). It was speculated that CINCH achieved a higher C^* than quadricyclane, even considering the density advantage of quadricyclane, because CINCH was more reactive. During the CINCH tests, the flame was almost invisible. All other fuels had a yellow to white-yellow flame. The injector wall temperature was also higher than the other fuels during CINCH testing. The fact that the fuels with the largest density differences both performed just below and above the 90-percent mark in the test chamber indicates that the chamber worked well for all fuels, even though it was not optimized for any of the tested fuels.

The quantity of fuel consumed by combustion for the various fuels was not measured during testing as a parameter of quantifying fuel performance. The performance of the fuels varied due to combustion characteristics, such as the burning rate and combustor design. However, the tests proved that these fuels can be used as propellants and that the performance measured at the given test conditions in a well-designed chamber agrees with the theoretical performance calculations.

Table 22. Experimental values of mixture ratios, chamber pressure, and I_{sp}.

Test No.	Fuel	Mixture Ratio	P_C (psig)	I_{sp}	Comments
Prediction	RP–1 Quadricyclane	2.100 1.600	160.30 160.30	257.53 264.31	Specific gravity: RP–1: 0.832 CINCH: 0.9256 Volume benefit: 17%
No. 17	RP–1 Quadricyclane	1.903 1.960	157.55 160.90	196.00 201.80	
No. 18	RP–1 Quadricyclane	1.917 1.963	157.74 161.04	196.00 201.41	
No. 20	RP–1 Quadricyclane	2.040 2.180	155.63 155.16	199.90 203.20	
No. 35	RP–1 Quadricyclane	2.190 1.655	154.39 173.53	199.90 200.13	
Theory	RP–1 1-7 Octadiyne	2.080 2.080	156.75 159.28	257.50 260.20	Specific gravity: RP–1: 0.832 Octadiyne: 0.817 Volume benefit: –1.8%
No. 22	RP–1 1-7 Octadiyne	2.080 2.080	156.75 159.28	199.30 203.63	
No. 23	RP–1 1-7 Octadiyne	2.090 2.100	158.10 160.25	199.20 202.16	
Theory	RP–1 AFRL–1	2.080 2.030	162.00 157.00	257.60 262.60	Specific gravity: RP–1: 0.832 AFRL: 0.7746 Volume benefit: –6.9%
No. 24	RP–1 AFRL–1	2.080 2.030	162.62 157.43	199.63 204.31	
No. 25	RP–1 AFRL–1	2.080 2.030	161.78 156.84	199.71 204.92	
Theory	RP–1 CINCH	1.970 1.402	124.00 147.50	256.70 255.40	Specific gravity: RP–1: 0.832 AFRL: 0.9256 Volume benefit: 11.25%
No. 32	RP–1 CINCH	1.970 1.402	123.80 147.72	187.21 193.74	
No. 33	RP–1 CINCH	1.970 1.402	124.27 147.72	189.00 195.63	
Theory	RP–1 BCP	1.960 2.068	158.94 163.08	256.70 262.50	Specific gravity: RP–1: 0.832 BCP: 0.845 Volume benefit: –1.56%
No. 38	RP–1 BCP	1.960 2.068	158.94 163.08	195.15 203.30	
No. 39	RP–1 BCP	1.940 2.059	159.56 163.11	195.02 202.70	

The effect of evaluated fuels, Quadricyclane and CINCH, on a launch vehicle are examined with a baseline case RP–1 and Space Shuttle. For comparison, the system is based on a 35K-lb payload to the *International Space Station*. The only variables examined are the effect of I_{sp} and the specific gravity of the fuel. The reduction of GLOW by Quadricyclane, Cinch, and a potential monopropellant indicated approximately 33, 31, and 15 percent less than the RP–1 case, respectively. The results are shown in figure 18. The cost of propellant is not compared since the propellant cost is dependent on the demand of propellant.

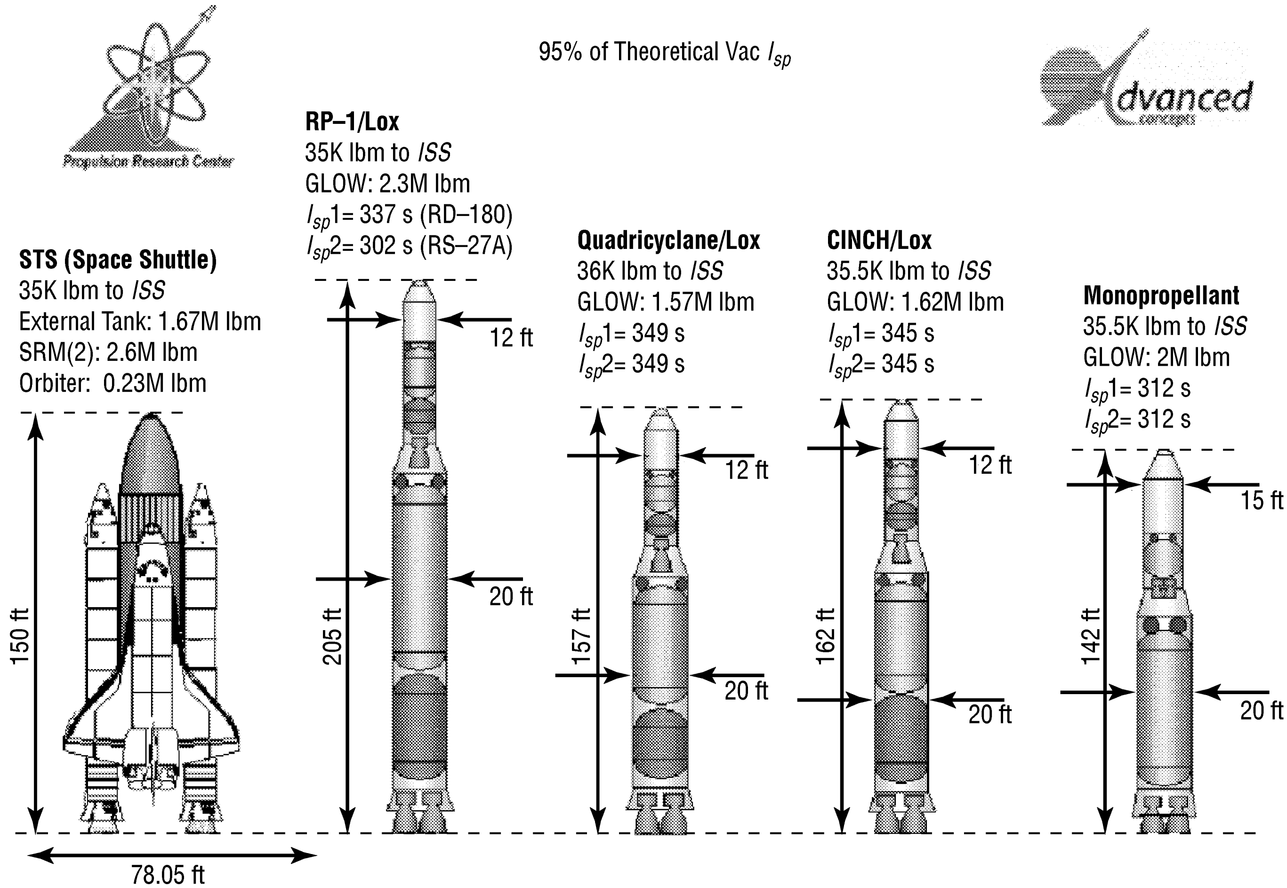

Figure 18. Advanced chemical propulsion.

Other important issues, such as fuel aging, material compatibility, and hazard properties, were also investigated. Although not an exhaustive study, assessments were completed to determine if the fuels affected the test article in a negative manner. Minor engineering changes were implemented based on these studies to ensure the safety of the test article and the people working on the test article. Studies regarding handling, storage, disposal, etc. were not attempted.

As the synthesis of new hydrocarbon fuels progresses at AFRL, MSFC is working on upgrades for the thrust measurement system. Upgrades will improve data acquisition and data analysis for better small-scale comparisons of new hydrocarbon fuels.

The MSFC ASTP program office and PRC are interested in pursuing advanced hydrocarbon fuel technology. The directions NASA and the DoD partners must consider are inexpensive, commercially available chemical fuels, and HEDM that may require techniques and process development. MSFC provides a host of assets to aid the pursuit of hydrocarbon fuel technology in one location: material testing, test fixture design and fabrication, propulsion technology, and propulsion testing. These assets centralize the tools and resources for chemical fuel development. The ASTP program office and PRC can partner with various agencies and programs to continue its pursuit. Partnerships such as these are mutually beneficial through the exchange of information and ideas. The results of these efforts and partnerships could take DoD and NASA to new levels of vehicle performance and payload delivery.

APPENDIX A—FUEL MATERIAL SAFETY DATA SHEET INFORMATION

GFS CHEMICALS, INC.

P.O. Box 245 Powell, OH 43065
740-881-5501(Tel.) 740-881-5989(Fax)
1-800-424-9300(Chemtrec 24Hr. Info.)

MATERIAL SAFETY DATA SHEET

3248

1,7-OCTADIYNE

CHEMICAL NAME & SYNONYMS
1,7-Octadiyne
Farchan Prod. No. 180403

DOT CLASS	SARA TITLE 313
3/II	No
TSCA listed	- Yes

FORMULA
$HC{\equiv}C(CH_2)_4C{\equiv}CH$

REPORTABLE QUANTITY	F.W.	CAS#
N/A	106.17	871-84-1

PHYSICAL DATA
Boiling point 135-136°C. Density 0.817.

APPEARANCE & ODOR
Clear, colorless liquid. Characteristic organic odor.

REACTIVITY & CONDITIONS TO AVOID
Stable. Incompatible with acids, bases and oxidizing agents.

FIRE HAZARDS
Flammable liquid, will emit toxic fumes of carbon monoxide, carbon dioxide. Firefighters wear SCBA.

EXTINGUISHER
C^ ABC dry powder, foam, water spray or fog.

FLASHPOINT	LEL	UEL
23°C	Not known	

[illegible]TH HAZARDS
[illegible] be irritating to skin, eyes and mucous membranes. The HEALTH RISKS of this product HAVE NOT BEEN FULLY DETERMINED. Avoid contact with skin and eyes. Avoid breathing vapor. This product must only be used under conditions of PRUDENT LABORATORY PRACTICE as described at 40 CFR 720.36. This product is supplied SOLELY for use in RESEARCH AND DEVELOPMENT by or under the supervision of a TECHNICALLY QUALIFIED INDIVIDUAL, Who should be FULLY COGNIZANT of the procedures for working with chemical products of this type as described at 40 CFR 720.36. No LD/TD data found. PEL/TLV not established. This material is not a listed carcinogen. It DOES NOT indicate absence of carcinogenicity.

FIRST AID
Remove contaminated clothing immediately and launder before reuse. Discard contaminated shoes. No specific medical information has been found. For eyes, flush with plenty of water for at least fifteen minutes. Seek medical attention immediately. For skin, wash thoroughly with soap and water, while removing clothing. Seek medical attention if rash should occur. For inhalation, remove to fresh air. If not breathing give mouth to mouth resuscitation. If breathing is difficult, give oxygen. Seek medical attention at once.

SPECIAL PRECAUTIONS
Goggles, rubber gloves, protective clothing are required. Use only with adequate ventilation and/or suitable respiratory protection. Avoid all contact.

SPILLS & LEAKS
V[illegible]tilate area. Equip personnel with SCBA and full protective clothing. Take [illegible]pill in absorbent and dispose to incinerator or other suitable hazardous [illegible]e. Wash spill area thoroughly with water after absorbent is picked up.

CATALOG #	PREPARED BY	DATE
3248	MDM	December 19, 1997

G F S CHEMICALS, INC.
Columbus, Ohio 43223

LOT ANALYSIS

ITEM: 3248 1,7-OCTADIYNE **LOT#: L81891(**

TEST	PASS/ FAIL	NUMERICAL RESULT
1. Boiling point 135-136 C	PASS	135-136C
2. Index of refraction 1.4464	PASS	1.4464
3. Assay (by GC)	PASS	99.6%

TRACEABLE TO N.I.S.T. (Y/N)? Y

Comment:

Re..rted by: Steve Eckert Date: 7/22/98

QC Supervisor: Steve Eckert Retest Date: NOT REQUIRED

ΔH_f = 79.9 Kcal/Mol (exp, liquid)

→ Isp_o = 308 sec ρ = 0.817 g/cc

MATERIAL SAFETY DATA SHEET
Air Force Research Laboratory
PRS/AREA 1-30
EDWARDS AFB, CALIFORNIA 93524
(661) 275 – 5191
(661) 275 - 5769

NO. 1
October 30, 2001

SECTION I - MATERIAL IDENTIFICATION

Proper Shipping Name: Bicyclopropylidene (BCP)

Hazard Class: Highly Flammable Liquid

Description: Liquid Propellant

NFPA Rating: Health 1, Flammability 4, Reactivity 0

SECTION II - HAZARDOUS INGREDIENTS

The propellant consists of

Contents:	**95 %**	**Bicyclopropylidene (BCP)**
	1 %	**Pentane**
	4 %	**Impurities**

SECTION III - PHYSICAL DATA

Description: Clear Light Yellow Liquid

Appearance: Liquid

Color: Light Yellow

Odor: Strong Hydrocarbon Odor

Specific Gravity: 0.8454 @ 20 °C

Boiling Point : 101 °C @ 760 mm Hg

Melting Point: –12 °C

Vapor Pressure: 85.9 mm Hg @ 25 °C

Reactivity In Water: None

SECTION IV - FIRE AND EXPLOSION HAZARD

Flash Point : - 6.4 °C

Autoignition Temperature: Unknown

Flammable Limits in Air (% by Volume)

Lower: Unknown
Upper: Unknown
Fire: Unknown

Extinguishing Media: Carbon dioxide, dry chemical, foam . Use water to cool, disperse vapors and flush spills.

Special Firefighting Procedures: Wear full fire resistant protective clothing and self contained breathing apparatus. Keep fire away from exposed containers by cooling with water spray. Approach from upwind side. Avoid breathing smoke.

Department of Transportation Regulations
Proper Shipping Name: Flammable Liquids, N.O.S., (bicyclopropylidene), Class 3, UN 1993, PG I

SECTION V - HEALTH HAZARD DATA

Toxicity: Not Toxic , LD 50 , > 1.95 mg/l

Health Hazards : Skin irritant, depression of the central nervous system

Combustion Toxicity: Unknown

SECTION VI - REACTIVITY DATA

Stability: Stable at room temperature. Avoid excess heat, sparks, and flame

Incompatability: strong oxidizers such as chlorine, oxygen or sodium/calcium hypochlorite (bleach)

Decomposition Products: Carbon monoxide, carbon dioxide

SECTION VII - DISPOSAL PROCEDURES

Disposal: Burn under controlled conditions consistent with safe practices. Empty drums should be properly drained, bunged, and placed in storage. All other containers should be disposed in an environmentally safe manner.

Discharge/Combustion Products: Water, oxides of carbon

SECTION VIII - SPECIAL PROTECTION INFORMATION

Protective Clothing: Fire-retardant coveralls and NBR or neoprene gloves recommended

Eye Protection: Goggles (full eye protection) recommended (ANSI Z87 140 approved)

Respiratory Protection: NiOSH approved respiratory protection for organic vapors

SECTION IX - SPECIAL PRECAUTIONS

Handling and Storage: Keep away from high temperature, fire, other ignition sources. Keep container closed when not in use.

In Case of Accident: Shut off all ignition sources; no flares or smoking. Absorb and or confine liquid with inert noncombustible material. Keep spills out of municipal sewers and open waterways.

Fire Fighting: **Approach from upwind side. Avoid breathing smoke, fumes, mist, or vapors. Firefighters should wear protective clothing and self-contained breathing apparatus.**

All information contained on this MSDS is based on available data and is subject to change.

MATERIAL SAFETY DATA SHEET

EXCITON, INC.
P.O. Box 31126
Dayton, Ohio 45437-0126

Date of Preparation: 11/4/98
Person to contact: Larry Knaak
Telephone number for information: 937-252-2989

SECTION I. IDENTIFICATION

* Product Name: Quadricyclane

* Synonym(s): Quadricyclo[2.2.1.$0^{2,6}$.$0^{3,5}$]heptane

* Cat No.: 22100

SECTION II. PRODUCT AND COMPONENT HAZARD DATA

COMPONENT(s):	Percent	TLV	CAS Reg. No.
Quadricyclane	>97%	N/A	278-06-8

SECTION III. PHYSICAL DATA

Appearance and odor: Colorless, Yellow or Amber liquid
Melting Point: -40°C
* Vapor Pressure: 23mm Hg at room temperature
* Evaporation Rate (n-butyl acetate=1): Rapid
* Volatile fraction by Weight: >99%
* Specific Gravity (water=1): 0.98
* Solubility in Water: Not soluble

SECTION IV. FIRE AND EXPLOSION HAZARD DATA

* Flash Point: +2°C (Flammable Liquid)
* Extinguishing Media: Water spray; Dry chemical; Carbon dioxide.
* Special Fire Fighting Procedures: Wear self-contained breathing apparatus and protective clothing.
* Unusual Fire and Explosion Hazards: Fire or excessive heat may produce hazardous decomposition products.

SECTION V. REACTIVITY DATA

* Stability: Converts rapidly to Norbornadiene upon heating to >100°C or by catalysis at room temperature.
* Incompatibility: Strong oxidizers, acids, catalytic metals.
* Hazardous Decomposition Products: Combustion will produce carbon dioxide and probably carbon monoxide.

Hazardous Polymerization: Will not occur.

SECTION VI. TOXICITY AND HEALTH HAZARD DATA

A. EXPOSURE LIMITS: Not established.
IARC: Not Listed
NTP: Not Listed
IHL-RAT LC50: 780 MG/M3/4H; RTECS# XB743600
No mortality in dermal exposure of 2g/kg.
100% mortality in rats upon ingestion of 3.5g/kg.
Neither acute nor chronic effects have fully been investigated.

B. EXPOSURE EFFECTS:
Inhalation: Toxic if inhaled.
Skin: Contact may cause transient irritation. May be absorbed. May Cause irritation.
Eye: Contact may cause transient irritation. May be absorbed. May cause irritation.
Ingestion: Harmful if swallowed.

C. FIRST AID:
Inhalation: Remove to fresh air. Call a physician. If not breathing give artificial respiration. If breathing is difficult, give oxygen.
Skin: Wash thoroughly after contact. Remove contaminated clothing.
Eye: Immediately flush eyes with plenty of water for at least 15 minutes and get medical attention if symptoms are present.
Ingestion: Drink 1-2 glasses of water. Seek medical attention. Remove contaminated clothing.

SECTION VII. VENTILATION AND PERSONAL PROTECTION

* Ventilation: Use only in fume hood or wear appropriate NIOSH/MSHA approved respirator.
* Respiratory Protection: Wear approved respirator.
* Skin and Eye Protection: Protective gloves should be worn. Safety glasses should be worn.
* Remove contaminated clothing to minimize vapor exposure.
* Avoid prolonged or repeated exposure.

SECTION VIII. SPECIAL STORAGE AND HANDLING PRECAUTIONS

* Keep from contact with oxidizing materials. Keep from contact with acids. Keep from contact from metals that catalyze reversion to norbornadiene.
* Handling Precautions: Do not breath vapor. For **laboratory** use by technically qualified individual only. Wear appropriate gloves, respirator, and clothing.
* Shipping and Storing Precautions: Keep container tightly closed when not in use and during transport. Shipping class UN2929, Packing Group I, Hazard zone B. Flush with inert gas to preserve purity after opening.
* Personal Hygiene: Wash thoroughly after handling.

SECTION IX. SPILL, LEAK, AND DISPOSAL PROCEDURES

Burn in a chemical incinerator equipped with an afterburner and scrubber but exert extra care in igniting as this material is highly flammable. Observe all federal, state and local environmental regulations.

Evacuate area. Shut off all ignition sources.

SECTION X. REGULATORY INFORMATION

* DOT Proper Shipping Name: UN2929, Toxic Liquid, Flammable, Organic N.O.S. (quadricyclane)
* DOT Class: 6.1
* RCRA Status: Not a hazardous waste under RCRA (40 CFR 261).
* CERCLA Status: Not listed.
* SARA/Title III - Toxic Chemicals List: This product does not contain a toxic chemical for routine annual "Toxic Chemical Release Reporting" under SEC. 313 (40 CFR 372).
* TSCA Inventory Status: Chemical components not listed on TSCA inventory.

organic
TECHNOLOGIES

Material Safety Data Sheet

Ethynylcyclopropane **MSDS No. 000052T**

Date of Preparation: 04-28-00 Supersedes: 03/11/98

Section 1 - Chemical Product and Company Identification

Product/Chemical Name: Ethynylcyclopropane
Chemical Formula: C5H6
CAS Number: 6746-94-7
Other Designations: Cyclopropyl Acetylene, ECP.
General Use: N/a.
Manufacturer: Organic Technologies, 1245 South 6th Street, Coshocton, Ohio 43812 Telephone number (740)622-0755. Fax number (740)622-3231. 24 Hour Emergency Telephone number (800)424-9300.

Section 2 - Composition / Information on Ingredients

Ingredient Name	CAS Number	%wt *or* %vol
Ethynylcyclopropane	6746-94-7	>97%

Trace Impurities:

	OSHA PEL		ACGIH TLV		NIOSH REL		NIOSH
Ingredient	**TWA**	**STEL**	**TWA**	**STEL**	**TWA**	**STEL**	**IDLH**
Ethylcyclopropane	None established	None established	None established	None established	None established	None established	None established

Section 3 - Hazards Identification

Emergency Overview

HMIS	
H	2
F	3
R	0
PPE†	

†Sec. 8

Potential Health Effects

Primary Entry Routes: Eyes, skin, lungs, ingestion..
Target Organs: Eyes, skin, lungs.
Acute Effects
Inhalation: May cause irritation.
Eye: Can cause severe eye irritation.
Skin: Can cause severe skin irritation.
Ingestion: May cause irritation.
Carcinogenicity: IARC, NTP, and OSHA do not list any components of this material as a carcinogen.
Medical Conditions Aggravated by Long-Term Exposure: None known.
Chronic Effects: None established. May cause central nervous system effects.

Section 4 - First Aid Measures

Inhalation: Remove to fresh air. If problems persist, seek appropriate medical attention.
Eye Contact: Flush with copious amounts of water for at least fifteen minutes. Seek appropriate medical attention.
Skin Contact: Flush with copious amounts of water for at least fifteen minutes. Seek appropriate medical attention.

Ingestion: Do not induce vomiting. Immediately drink two glasses of water. Seek appropriate medical attention. An activated charcoal slurry may be used. Never give anything to an unconscious person.
Note to Physicians: To the best of our knowledge the toxicological properties of this material have not been fully evaluated.
Special Precautions/Procedures: Keep material of the skin and out of the eyes.

Section 5 - Fire-Fighting Measures

Flash Point: -42 °F
Flash Point Method: CC.
Burning Rate: None established.
Autoignition Temperature: None established.
LEL: 1% v/v
UEL: None established.
Flammability Classification: Flammable liquid.
Extinguishing Media: Dry chemical, water spray, CO2, or foam.
Unusual Fire or Explosion Hazards: None established.
Hazardous Combustion Products: Carbon monoxide, carbon dioxide.
Fire-Fighting Instructions: Do not release runoff from fire control methods to sewers or waterways.
Fire-Fighting Equipment: Because fire may produce toxic thermal decomposition products, wear a self-contained breathing apparatus (SCBA) with a full facepiece operated in pressure-demand or positive-pressure mode.

Section 6 - Accidental Release Measures

Spill /Leak Procedures:
Small Spills: Cover spill with absorbent, pick up, and place in a suitable container.
Large Spills
Containment: For large spills, dike far ahead of liquid spill for later disposal. Do not release into sewers or waterways.
Cleanup: Follow all applicable local, state, and federal regulations pertaining to decon measures.
Regulatory Requirements: Follow all applicable local, state, and federal regulations.

Section 7 - Handling and Storage

Handling Precautions: Do not breath vapor or mist. Wash thoroughly after handling. Do not consume or store food, drink, or tobacco in areas where this material is handled. Wear appropriate personal protective equipment.
Storage Requirements: Store in a well ventillated area. Extremely volatile material. Vapors can travel considerable distance to a source of ignition and flash back. Keep material away from heat, sparks, and flames.
Regulatory Requirements: Follow all applicable local, state, and federal regulations.

Section 8 - Exposure Controls / Personal Protection

Engineering Controls:
Ventilation: Provide general or local exhaust ventilation systems to maintain airborne concentrations below OSHA PELs (Sec. 2). Local exhaust ventilation is preferred because it prevents contaminant dispersion into the work area by controlling it at its source.
Administrative Controls:
Respiratory Protection: Seek professional advice prior to respirator selection and use. Follow OSHA respirator regulations (29 CFR 1910.134) and, if necessary, wear a MSHA/NIOSH-approved respirator. Select respirator based on its suitability to provide adequate worker protection for given working conditions, level of airborne contamination, and presence of sufficient oxygen. *Warning! Air-purifying respirators do not protect workers in oxygen-deficient atmospheres.* If respirators are used, OSHA requires a written respiratory protection program that includes at least: medical certification, training, fit-testing, periodic environmental monitoring, maintenance, inspection, cleaning, and convenient, sanitary storage areas.
Protective Clothing/Equipment: Wear chemically protective gloves, boots, aprons, and gauntlets to prevent prolonged or repeated skin contact. Wear protective eyeglasses or chemical safety goggles, per OSHA eye- and face-protection regulations (29 CFR 1910.133). Contact lenses are not eye protective devices. Appropriate eye protection must be worn instead of, or in conjunction with contact lenses.
Safety Stations: Make emergency eyewash stations, safety/quick-drench showers, and washing facilities available in work area.
Contaminated Equipment: Separate contaminated work clothes from street clothes. Launder before reuse. Remove this material from your shoes and clean personal protective equipment.
Comments: Never eat, drink, or smoke in work areas. Practice good personal hygiene after using this material, especially before eating, drinking, smoking, using the toilet, or applying cosmetics.

Section 9 - Physical and Chemical Properties

Physical State: Liquid.
Appearance and Odor: Clear, colorless liquid with strong, pungent, persistent odor.
Odor Threshold: None established.
Vapor Pressure: 34.1 kPA
Vapor Density (Air=1): None established.
Formula Weight: 66.1
Density: None established.
Specific Gravity (H_2O=1, at 4 °C): 0.7801
pH: Neutral.

Water Solubility: 3.96 g/L @ 20 degrees C
Other Solubilities: Ethanol, dimethylsulfoxide, toluene, and acetone.
Boiling Point: 52-65 degrees C
Melting Point: <-25 degrees C
Viscosity: None established.
Refractive Index: None established.
Surface Tension: None established.
% Volatile: None established.
Evaporation Rate: None established.

Section 10 - Stability and Reactivity

Stability: This material is stable at room temperature in closed containers under normal storage and handling conditions.
Polymerization: Hazardous polymerization cannot occur.
Chemical Incompatibilities: None known.
Conditions to Avoid: Sources of ignition.
Hazardous Decomposition Products: Thermal oxidative decomposition will not occur if handled and stored properly.

Section 11- Toxicological Information

Toxicity Data:

Eye Effects: Based on the information from the skin irritation study, the material is expected to be a severe eye irritant.

Skin Effects: The acute lethal dermal dose is greater than 2000 mg/kg in the rat. This material was a moderate to severe skin irritant in rabbits. Two or three rabbits had reactions which persisted at the time of study termination day 14. The material was not a skin sensitizer or irritant in guinea pigs.

Acute Inhalation Effects: Rats exposed to an acute vapor concentration of 3.3 and 22.3 mg/L of cyclopropylactelyene exhibited reduced response to stimuli and partial closing of the eyes. Additional signs of muscle contractions, unsteady gait, piloerection, and shallow respiration were observed in the high dose animals.

Acute Oral Effects: An acute dose of 2000 mg/kg in the rat produced mortality, ataxia, piloerection, respiratory distress, and hunched posture. Lethargy, pallid extremities, and body tremors were less frequently noted.
Chronic Effects: None established.
Carcinogenicity: None established.
Mutagenicity: It was not genotoxic in the Ames and rat micronucleus. However, it was genotoxic in the human lymphocyte chromosome aberration assay.
Teratogenicity: None established.

Section 12 - Ecological Information

Ecotoxicity: May cause long term adverse effects to the aquatic environment. Prevent this material from entering low areas, sewers, or waterways.
Environmental Fate: None established.
Environmental Degradation: None established.
Soil Absorption/Mobility: None established.

Section 13 - Disposal Considerations

Disposal: Follow all applicable all applicable local, state, and federal regulations.

Section 14 - Transport Information

DOT Transportation Data (49 CFR 172.101):

Shipping Name: Flammable liquids, n.o.s. **Shipping Symbols:** Flammable liquid **Hazard Class:** 3 **ID No.:** UN1993 **Packing Group:** II **Label:** Flammable liquid.		

Section 15 - Regulatory Information

EPA Regulations:
RCRA Hazardous Waste Number: Not listed (40 CFR 261.33).
RCRA Hazardous Waste Classification (40 CFR 261.21): D001
SARA Toxic Chemical (40 CFR 372.65): Not listed.
SARA EHS (Extremely Hazardous Substance) (40 CFR 355): Not listed.
OSHA Regulations:
Air Contaminant (29 CFR 1910.1000, Table Z-1, Z-1-A): Not listed.

Section 16 - Other Information

Prepared By: The Safety Department.
Revision Notes: The information of this form is furnished solely for the purpose of compliance with OSHA's Hazard Communication Standard, 29 CFR 1910.1200 and shall not be used for any other purpose.

Disclaimer: The information contained herein is believed to be accurate, but is not warranted to be. Recipients are advised to confirm in advance of need that the information is current, applicable, and suitable to their circumstances. Wiley Organics shall not be liable for any loss or damage arising out of the use thereof.

MATERIAL SAFETY DATA SHEET (Experimental)

3M
3M Center
St. Paul, Minnesota
55144-1000
1-800-364-3577 or (651) 737-6501 (24 hours)

DIVISION: 3M SPECIALTY MATERIALS
MATERIAL:
L-15686 DEVELOPMENTAL MATERIAL
ISSUED: March 19, 1999
SUPERSEDES: INITIAL ISSUE
DOCUMENT: 09-0400-3

1. INGREDIENT

INGREDIENT	C.A.S. NO.	PERCENT
DIMETHYL-2-AZIDOETHYLAMINE.............	86147-04-8	100

This material is not listed on the TSCA inventory and should be used for research and development purposes only under the direct supervision of a technically qualified individual. This material is not on EINECS and should be used in Europe only for research purposes in order to establish its properties.

2. PHYSICAL DATA

BOILING POINT:................. 135 C
VAPOR PRESSURE:................ 11 - 50 mmHg
VAPOR DENSITY:................. N/D
EVAPORATION RATE:.............. N/D
SOLUBILITY IN WATER:........... slight
SPECIFIC GRAVITY:.............. 0.93 Water=1
PERCENT VOLATILE:.............. 100 %
pH:............................ N/A
VISCOSITY:..................... < 10 centipoise
MELTING POINT:................. N/A

APPEARANCE AND ODOR:
Clear mobile liquid. Strong amine-type odor.

Abbreviations: N/D - Not Determined N/A - Not Applicable CA - Approximately

3. FIRE AND EXPLOSION HAZARD DATA

FLASH POINT:.................. 30 C
FLAMMABLE LIMITS - LEL:........ N/A
FLAMMABLE LIMITS - UEL:........ N/A
AUTOIGNITION TEMPERATURE:...... N/D

EXTINGUISHING MEDIA:
Water, Carbon dioxide, Dry chemical, Foam

SPECIAL FIRE FIGHTING PROCEDURES:
Wear full protective clothing, including helmet, self-contained, positive pressure or pressure demand breathing apparatus, bunker coat and pants, bands around arms, waist and legs, face mask, and protective covering for exposed areas of the head.

UNUSUAL FIRE AND EXPLOSION HAZARDS:
See Hazardous Decomposition section for products of combustion.

4. REACTIVITY DATA

STABILITY: Stable

INCOMPATIBILITY - MATERIALS/CONDITIONS TO AVOID:
Strong Oxidizing Agents.

HAZARDOUS POLYMERIZATION: Hazardous polymerization will not occur.

HAZARDOUS DECOMPOSITION PRODUCTS:
Carbon Monoxide and Carbon Dioxide, Toxic Vapors, Gases or Particulates.

5. ENVIRONMENTAL INFORMATION

SPILL RESPONSE:
Refer to other sections of this MSDS for information regarding physical and health hazards, respiratory protection, ventilation, and personal protective equipment. Ventilate area. Extinguish all ignition sources. Contain spill. Evacuate unprotected personnel from hazard area. Cover with absorbent material. Cover spill area with Light Water Brand or other ATC foam. (For further information on ATC foam usage, contact 3M Fire Protection Systems.) Collect using non-sparking tools. Clean up residue. Place in an approved metal container. Seal the container.

Abbreviations: N/D - Not Determined N/A - Not Applicable CA - Approximately

---

5. ENVIRONMENTAL INFORMATION (continued)

RECOMMENDED DISPOSAL:
Incinerate in a permitted hazardous waste incinerator.

ENVIRONMENTAL DATA:
Not determined.

REGULATORY INFORMATION:
Volatile Organic Compounds: N/D.
VOC Less H2O & Exempt Solvents: N/A.

Since regulations vary, consult applicable regulations or authorities before disposal. In the event of an uncontrolled release of this material, the user should determine if the release qualifies as a reportable quantity. U.S. EPA Hazardous Waste Number = D001 (Ignitable)

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6. SUGGESTED FIRST AID

EYE CONTACT:
Immediately flush eyes with large amounts of water. Get immediate medical attention.

SKIN CONTACT:
Wash affected area with soap and water.

INHALATION:
If signs/symptoms occur, remove person to fresh air. If signs/symptoms continue, call a physician.

IF SWALLOWED:
Drink two glasses of water. Call a physician.

---

7. PRECAUTIONARY INFORMATION

EYE PROTECTION:
Avoid eye contact. Wear vented goggles.

SKIN PROTECTION:
Avoid skin contact. Wear appropriate gloves when handling this material. Use one or more of the following personal protection items as necessary to prevent skin contact: apron.

Abbreviations: N/D - Not Determined N/A - Not Applicable CA - Approximately

7. PRECAUTIONARY INFORMATION (continued)

RECOMMENDED VENTILATION:
Provide appropriate local exhaust ventilation at transfer points. Provide appropriate local exhaust ventilation on open containers. If exhaust ventilation is not adequate, use appropriate respiratory protection.

RESPIRATORY PROTECTION:
Avoid breathing of vapors, mists or spray. Select one of the following NIOSH approved respirators based on airborne concentration of contaminants and in accordance with OSHA regulations: Half-mask organic vapor respirator with dust/mist prefilter, full-face supplied air respirator.

PREVENTION OF ACCIDENTAL INGESTION:
Wash hands after handling and before eating.

RECOMMENDED STORAGE:
Keep container closed when not in use. Keep container in well-ventilated area.

FIRE AND EXPLOSION AVOIDANCE:
Keep container tightly closed. Flammable liquid and vapor. Keep away from heat, sparks, open flame, and other sources of ignition. Ground containers securely when transferring contents. Wear low static or properly grounded shoes. No smoking while handling this material. Vapors may ignite explosively.

EXPOSURE LIMITS

INGREDIENT	VALUE	UNIT	TYPE	AUTH	SKIN*
DIMETHYL-2-AZIDOETHYLAMINE...........	NONE	NONE	NONE	NONE	

* SKIN NOTATION: Listed substances indicated with 'Y' under SKIN refer to the potential contribution to the overall exposure by the cutaneous route including mucous membrane and eye, either by airborne or, more particularly, by direct contact with the substance. Vehicles can alter skin absorption.

SOURCE OF EXPOSURE LIMIT DATA:
- NONE: None Established

8. HEALTH HAZARD DATA

EYE CONTACT:
No information was found regarding effects from eye contact.

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8. HEALTH HAZARD DATA (continued)

SKIN CONTACT:
No information was found regarding effects from skin contact.

INHALATION:
No information was found regarding effects from inhalation exposure.

IF SWALLOWED:
No information was found regarding effects from swallowing.

Abbreviations: N/D - Not Determined N/A - Not Applicable CA - Approximately

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APPENDIX B—TEST REQUEST DOCUMENT (TEST REQUEST/TEST SEQUENCE)

PROJECT 2073 TEST REQUEST
SIGNATURE SHEET

NEW HYDROCARBON FUELS TEST

TEST #: P2073 - 00- 20

DATE REQUESTED: Aug 31, 00

DATE CONDUCTED: ______________

MSFC TEST REQUESTER

MSFC TEST ENGINEER

Notes:

Special Instructions:

RP-1 Tank Quantity: ~ 2 qts

AF Tank Quantity: remaining quadricyclane after tests 17 & 18

Revision summary:

TEST REQUEST
LIGHTWEIGHT THRUST CELL TECHNOLOGY DEMONSTRATION
(Items in gray not active for test)

TEST NO. P2073 - 00 – **20**

DATE REQUESTED: Aug 31, 00

DATE SCHEDULED: Aug 31, 00

OBJECTIVE: Achieve mainstage

P_c =	175	$\dot{m}_o$ =	.16
MR (O/F) =	2.0	$\dot{m}_f$ =	.08

Chamber cooled with deionized water at 1.0 lb_m/s

TEST MAINSTAGE DURATION (s): ~~14.2 secs~~
Tank A: 6.4 secs RP-1
Tank B: 7.8 secs RP-1

HARDWARE:

Component	**P/N**	**S/N**
INJECTOR	GG52007	1999-002
CHAMBER	GG52003	1999-001

TEST RIG ORIFICE / VENTURIES:

System	S/N	**Throat Diameter (in)**	C_d
GOX Bypass (orifice)	n/a	0.0730	0.88
GOX Main (orifice)	n/a	0.1735	0.83
RP-1 Bypass	934	0.0187	0.97*
RP-1 Main	935	0.0373	0.97*
Adv Fuel	936	0.0356	0.97*
DI Water	n/a	0.2344	0.6*

* assumed

PROPELLANT / PURGE PRESSURES:

GOX / Fuel Purge	(P4261):	275
RP-1 Tank	(P4501):	352
Adv Fuel Tank	(P4401):	354
GOX Supply	(P4305):	465

SEQUENCE:

REFERENCE SEQUENCE DATED – **00JUL25Test14 + redlines for test 15**

Timer Name:	Installed	Sequence Identifier	**Duration (ms):**
Spark Delay:	Y	T2	100
Spark:	Y	T3	2000
~~Ignition Detect (P4601):~~	~~Y~~	~~T5~~	~~1100~~
~~Mainstage Valve Delay~~	~~Y~~	~~T6~~	~~300~~
Duration RP-1:	-Y	T7	2400
Duration Adv Fuel	N	T8	2800
C/O Fuel Valve Close Delay	Y	T9	100

CUTOFF PARAMETERS:

	Description	Limit	MID	Value	Disarm
Arm at A/S -					
(1)	Water Pressure	Low	P4102	250	C/O
(2)	AF Tank Pressure	Low	P4401	310	C/O
(3)	RP-1 Tank Pressure	Low	P4501	300	C/O
(4)	GOX Sys Pressure	Low	P4305	430	C/O
Arm at T0+400ms					
(5)	GOX Bypass Orifice Inlet Press	Low	P4322	400	T7 Start
(6)	GOX Bypass Orifice Inlet Press	High	P4322	490	T7 Start
(7)	RP-1 Bypass Venturi Inlet Press	Low	P4521	315	T7 Start
(8)	~~Ignition Detect~~	~~High~~	~~P4601~~	~~15~~	~~T6 Start~~
(9)	ROV4321 Limit Switch Open			OFF	T=5800 ms
(10)	ROV4545 Limit Switch Open			OFF	C/O
(11)	ROV4424 Limit Switch Closed			OFF	T=7300ms
Arm at T7 Start+300 ms (Mainstage)					
(12)	GOX Main Orifice Inlet Press	Low	P4332	280	C/O
(13)	GOX Main Orifice Inlet Press	High	P4332	340	C/O
(14)	RP-1 Main Venturi Inlet Press	Low	P4531	315	T8 Start
(15)	Chamber Pressure	Low	P4601	30	C/O
(16)	Chamber Pressure	High	P4601	225	C/O
(17)	Water Exit Temp	High	T4115	230	C/O
(18)	ROV4331 Limit Switch Open			OFF	C/O
Arm at T=11700ms					
(19)	AF Venturi Inlet Press	Low	P4421	300	C/O
(20)	ROV4523 Limit Switch Closed			OFF	C/O
(21)	ROV4424 Limit Switch Open			OFF	C/O
Arm at T=12400ms					
(22)	ROV4534 Limit Switch Closed			OFF	C/O

TEST NO. P2073 - 00 - 20

RESULTS:

DATE REQUESTED: ____________________

DATE CONDUCTED: ____________________

P_c = $\dot{m}_o$ =

MR (O/F) = $\dot{m}_f$ =

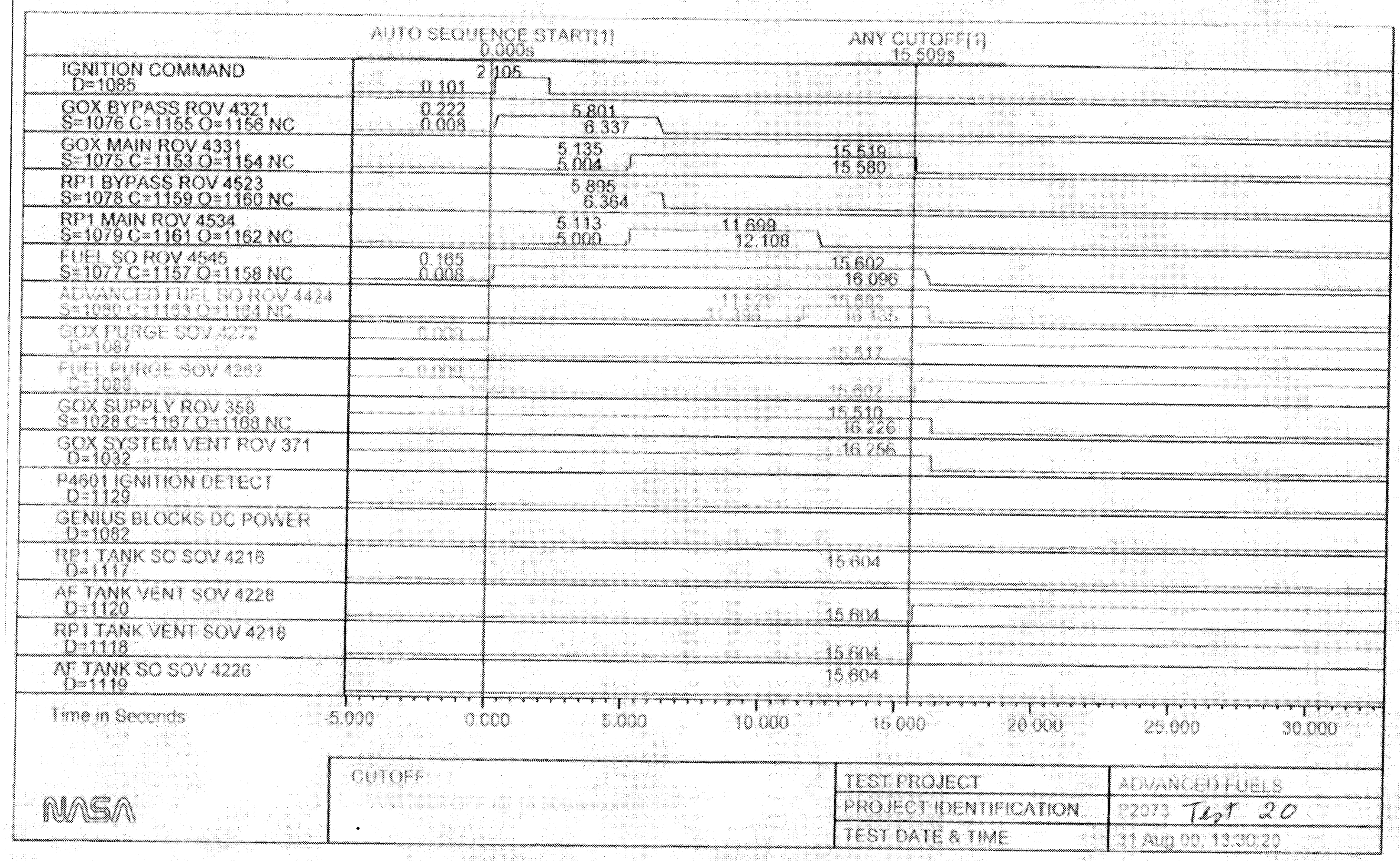
Water Flowrate

DURATION:

CUT:

HARDWARE INSPECTIONS:

	PRE-TEST	POST-TEST
THROAT DIA. MEASUREMENT #1 (12:00)		
THROAT DIA. MEASUREMENT #2 (1:30)		
THROAT DIA. MEASUREMENT #3 (3:00)		
THROAT DIA. MEASUREMENT #4 (4:30)		


AUTO SEQUENCE START[1]
0.000s
ANY CUTOFF[1]
15.509s
IGNITION COMMAND
D=1085
GOX BYPASS ROV 4321
S=1076 C=1155 O=1156 NC
GOX MAIN ROV 4331
S=1075 C=1153 O=1154 NC
RP1 BYPASS ROV 4523
S=1078 C=1159 O=1160 NC
RP1 MAIN ROV 4534
S=1079 C=1161 O=1162 NC
FUEL SO ROV 4545
S=1077 C=1157 O=1158 NC
ADVANCED FUEL SO ROV 4424
S=1080 C=1163 O=1164 NC
GOX PURGE SOV 4272
D=1087
FUEL PURGE SOV 4262
D=1088
GOX SUPPLY ROV 358
S=1028 C=1167 O=1168 NC
GOX SYSTEM VENT ROV 371
D=1032
P4601 IGNITION DETECT
D=1129
GENIUS BLOCKS DC POWER
D=1082
RP1 TANK SO SOV 4216
D=1117
AF TANK VENT SOV 4228
D=1120
RP1 TANK VENT SOV 4218
D=1118
AF TANK SO SOV 4226
D=1119
0.101
2.105
0.222
0.008
5.801
6.337
5.135
5.004
15.519
15.580
5.895
6.364
5.113
5.000
11.699
12.108
0.165
0.008
15.602
16.096
11.529
15.602
16.135
0.009
15.517
0.009
15.602
15.510
16.226
16.256
15.604
15.604
15.604
15.604
Time in Seconds
-5.000
0.000
5.000
10.000
15.000
20.000
25.000
30.000
CUTOFF
TEST PROJECT
ADVANCED FUELS
PROJECT IDENTIFICATION
P2073 Test 20
TEST DATE & TIME
31 Aug 00, 13:30:20

TEST 16

A	15:59:27.071	#18	33	Cutoff Bus ON	
A	15:59:27.071	#18	34	P4322, GOX Bypass Orifice Inlet Pressure Low ON	
A	15:59:27.071	#18	36	P4332, GOX Main Orifice Inlet Pressure Low ON	
A	15:59:27.071	#18	42	P4601, Chamber Pressure Low ON	
A	15:59:27.071	#18	47	DSU Off Line, Cutoff ON	
A	15:59:27.071	#18	49	Circular Cutoff Bus ON	
A	**16:00:04.549**	**#17**	**21**	**AF - Test Duration ON**	
A	16:00:04.550	#17	22	Event Marker ON	
A	16:00:04.556	#17	52	GOX Bypass Cmd, ROV 4321 Open ON	0.007
A	16:00:04.556	#17	53	Fuel SO Cmd, ROV 4545 Open ON	0.007
N	16:00:04.556	#17	63	GOX Purge Cmd, SOV 4272 Open OFF	0.007
N	16:00:04.556	#17	64	Fuel Purge Cmd, SOV 4262 Open OFF	0.007
A	16:00:04.657	#17	61	Ignitor Command ON	0.108
N	16:00:04.659	#19	5	Fuel Shutoff ROV 4545 LSC OFF	
N	16:00:04.678	#19	3	GOX Bypass ROV 4321 LSC OFF	
A	16:00:04.729	#19	6	Fuel Shutoff ROV 4545 LSO ON	
N	16:00:04.767	#18	34	P4322, GOX Bypass Orifice Inlet Pressure Low OFF	
A	16:00:04.792	#19	4	GOX Bypass ROV 4321 LSO ON	
N	16:00:05.048	#17	22	Event Marker OFF	
N	16:00:06.658	#17	61	Ignitor Command OFF	2.109
N	16:00:08.620	#18	42	P4601, Chamber Pressure Low OFF	
A	16:00:09.551	#17	55	RP-1 Main Cmd, ROV 4534 Open ON	5.002
A	16:00:09.555	#17	51	GOX Main Cmd, ROV 4331 Open ON	5.006
N	16:00:09.649	#19	9	RP-1 Main Shutoff ROV 4534 LSC OFF	
A	16:00:09.664	#19	10	RP-1 Main Shutoff ROV 4534 LSO ON	
N	16:00:09.675	#19	1	GOX Main Shutoff ROV4331 LSC OFF	
A	16:00:09.678	#19	2	GOX Main Shutoff ROV4331 LSO ON	
N	16:00:09.741	#18	36	P4332, GOX Main Orifice Inlet Pressure Low OFF	
N	16:00:10.348	#17	52	GOX Bypass Cmd, ROV 4321 Open OFF	5.799
N	16:00:10.446	#17	54	RP-1 Bypass Cmd, ROV 4523 Open OFF	5.897
N	16:00:10.678	#19	4	GOX Bypass ROV 4321 LSO OFF	
N	16:00:10.837	#19	8	RP-1 Bypass Shutoff ROV 4523 LSO OFF	
A	16:00:10.858	#19	3	GOX Bypass ROV 4321 LSC ON	
A	16:00:10.886	#18	34	P4322, GOX Bypass Orifice Inlet Pressure Low ON	
A	16:00:10.903	#19	7	RP-1 Bypass Shutoff ROV 4523 LSC ON	
A	16:00:15.947	#17	56	AF SO Cmd, ROV 4424 Open ON	11.398
N	16:00:16.055	#19	11	AF Shutoff ROV 4424 LSC OFF	
A	16:00:16.088	#19	12	AF Shutoff ROV 4424 LSO ON	
N	16:00:16.250	#17	55	RP-1 Main Cmd, ROV 4534 Open OFF	11.701
N	16:00:16.553	#19	10	RP-1 Main Shutoff ROV 4534 LSO OFF	
A	16:00:16.633	#19	9	RP-1 Main Shutoff ROV 4534 LSC ON	
A	16:00:23.749	#17	22	Event Marker ON	
N	**16:00:23.751**	**#17**	**21**	**AF - Test Duration OFF**	**19.202**
N	16:00:23.752	#17	4	GOX Supply Cmd, ROV 358 Open OFF	0.001
A	16:00:23.757	#17	63	GOX Purge Cmd, SOV 4272 Open ON	0.006
N	16:00:23.759	#17	51	GOX Main Cmd, ROV 4331 Open OFF	0.008
N	16:00:23.818	#19	2	GOX Main Shutoff ROV4331 LSO OFF	
A	16:00:23.820	#19	1	GOX Main Shutoff ROV4331 LSC ON	
N	16:00:23.845	#18	29	RP-1 Tank SO Cmd, SOV 4216 Open OFF	0.094
A	16:00:23.845	#18	30	RP-1 Tank Vent Cmd, SOV 4218 Open ON	0.094
N	16:00:23.845	#18	31	AF Tank SO Cmd, SOV 4226 Open OFF	0.094
A	16:00:23.845	#18	32	AF Tank Vent Cmd, SOV 4228 Open ON	0.094
N	16:00:23.847	#17	53	Fuel SO Cmd, ROV 4545 Open OFF	0.096

N	16:00:23.847	#17	56	AF SO Cmd, ROV 4424 Open OFF	0.096
A	16:00:23.847	#17	64	Fuel Purge Cmd, SOV 4262 Open ON	0.096
A	16:00:23.866	#18	36	P4332, GOX Main Orifice Inlet Pressure Low ON	
A	16:00:24.066	#18	42	P4601, Chamber Pressure Low ON	
N	16:00:24.180	#19	12	AF Shutoff ROV 4424 LSO OFF	
N	16:00:24.190	#19	6	Fuel Shutoff ROV 4545 LSO OFF	
N	16:00:24.242	#17	22	Event Marker OFF	
A	16:00:24.282	#19	11	AF Shutoff ROV 4424 LSC ON	
A	16:00:24.325	#19	5	Fuel Shutoff ROV 4545 LSC ON	
A	16:00:24.386	#18	45	P4401, AF Tank Pressure Low ON	
N	16:00:24.431	#19	16	HCF GOX Supply ROV 358 LSO OFF	
A	16:00:24.438	#19	15	HCF GOX Supply ROV 358 LSC ON	
N	16:00:24.471	#17	8	GOX Vent Cmd, ROV 371 Open OFF	
N	16:00:25.373	#19	13	HCF GOX Vent Closed, ROV 371 LSC OFF	
A	16:00:25.378	#18	38	P4305, GOX System Pressure Low ON	
A	16:00:25.900	#18	50	P4421, AF Venturi Inlet Pressure Low ON	
A	16:00:26.138	#18	46	P4501, RP-1 Tank Pressure Low ON	
A	16:00:26.406	#18	39	P4521, RP-1 Bypass Venturi Inlet Pressure Low ON	
A	16:00:26.918	#18	40	P4531, RP-1 Main Venturi Inlet Pressure Low ON	
N	16:01:17.820	#17	62	DI Water Pump Start Cmd OFF	
N	16:01:17.828	#19	14	DI Water Pump PWR OFF	
A	16:01:17.958	#18	44	P4115, Water Pressure ON	
N	16:01:40.060	#18	33	Cutoff Bus OFF	
N	16:01:40.060	#18	34	P4322, GOX Bypass Orifice Inlet Pressure Low OFF	
N	16:01:40.060	#18	36	P4332, GOX Main Orifice Inlet Pressure Low OFF	
N	16:01:40.060	#18	38	P4305, GOX System Pressure Low OFF	
N	16:01:40.060	#18	39	P4521, RP-1 Bypass Venturi Inlet Pressure Low OFF	
N	16:01:40.060	#18	40	P4531, RP-1 Main Venturi Inlet Pressure Low OFF	
N	16:01:40.060	#18	42	P4601, Chamber Pressure Low OFF	
N	16:01:40.060	#18	44	P4115, Water Pressure OFF	
N	16:01:40.060	#18	45	P4401, AF Tank Pressure Low OFF	
N	16:01:40.060	#18	46	P4501, RP-1 Tank Pressure Low OFF	
N	16:01:40.060	#18	47	DSU Off Line, Cutoff OFF	
N	16:01:40.060	#18	49	Circular Cutoff Bus OFF	
N	16:01:40.060	#18	50	P4421, AF Venturi Inlet Pressure Low OFF	
A	16:01:48.802	#17	22	Event Marker ON	
N	16:01:48.814	#17	22	Event Marker OFF	

APPENDIX C—TEST OPERATIONS PRODEDURE

TEST CHECKOUT PROCEDURE

HFD-TCP-001 Rev B

New Hydrocarbon Fuel Development Test

(Advanced Fuel Test)

Signature Page

Submitted by:

TD71 Paul Dumbacher Test Project & System Engineer	Date
TD71 Bobby Hubbard Mechanical Group Lead	Date
TD40 Don Bai Test Requester	Date
QS10 Quality Representative	Date
QS10 Safety Representative	Date

Table of Contents

1.0 INTRODUCTION

1.1 Purpose

This document establishes the procedures for testing the Advanced Fuel Test rig at th Hydrogen Coldflow Facility (HCF) Bldg 4626.

1.2 Scope

This procedure applies to all components of the Advanced Fuel Test rig and the supportin test pneumatic systems.

1.3 System Description

The Advanced Fuel Test rig is made up of two fuel systems and a gaseous oxygen systen The rig is designed to start with RP-1 and gox, then switch to the second fuel systeı containing an advanced fuel. The rig is configured to provide a direct comparison of a advanced fuel to RP-1 at the same conditions. Three separate advanced fuels will be teste(Fuel system pressures are between 250 to 300 psi and gox system pressures ar approximately 400 psi. Fuel is tanked on the rig prior to test. Gox is provided by gox trail(with pressure regulation on the test rig. Cooling water is provided via pump from a DI wat(trailer. Nitrogen purges and fuel tank pressurants are provided via the HCF 750 psi and 15 psi gN2 systems.

1.4 General

The TD71 Test Engineer is responsible for assuring adherence to all appropriate procedure and policies. All activities pertaining to the TCP shall be coordinated through the te: engineer. The following organizations will participate in the activities contained hereiı AB35/TBE, CR20, CR30, TD71, TD72, and TD73.

2.0 APPLICABLE DOCUMENTS

MPG 1700.1	MSFC Industrial Safety Procedures & Guidelines
MWI 8715.6	Hazardous Operations
TD70-9001	Test Program Control
TD70-9002	Test Operation Procedure Preparation and Change Contro
TD70-9003	Test Preparation Sheet (TPS) Implementation Instruction
MSFC-SPEC-164B	Cleanliness of Components for use in Oxygen, Fuel ε Pneumatic Systems.

3.0 SAFETY

The operating policies and procedures set forth in MPG 1700.1, " MSFC Industrial Safe Procedures & Guidelines," will be followed during all operations at HCF.

3.1 Emergency Telephone Numbers:

Medical Center...911

Ambulance..911

Fire 911

Security.. 4-4357

Safety 4-0046

Utilities 4-3919

Environmental..911

IF SERIOUS INJURY TO PERSONNEL OCCURS, IMMEDIATELY CALL AMBULANCE. DO NOT MOVE THE INJURED PERSONNEL UNLESS NECESSARY TO PREVENT FURTHER SERIOUS INJURY."

3.2 Hazards & Controls

Hazard: High Pressure gN2
Controls: High Pressure Gasses: gloves and goggles

Hazard: High Noise
Controls: Hearing Protection

Hazard: Advanced Fuel
Control: Personal Protective Equipment

Hazard: High pressure GOX
Control: Limit access to area

4.0 TEST PROCEDURE

4.1 Pretest Setup   Test ID #: _____ _____ _____

1. Verify test request has been distributed. .... _____ _____ _____
2. Verify DI Water trailer delivered, connected, & adequate level .... _____ _____ _____
3. Verify GOX trailer delivered, connected, & adequate pressure .... _____ _____ _____
4. Verify HCF 1500 psi gN2 pressurized and ready .... _____ _____ _____
5. Verify instrumentation systems have zeros .... _____ _____ _____
6. Verify control systems have completed E/M checks .... _____ _____ _____
7. Verify all redline cuts are set per test request........................ _____ _____ _____
8. Verify ignitor wire replaced if necessary........................ _____ _____ _____
9. Verify Water Pump power set-up complete .... _____ _____ _____
10. Perform system walkdown of required systems .... _____ _____ _____
11. Verify video camera setup is complete .... _____ _____ _____
12. Verify Control Systems have normal panel........................ _____ _____ _____
13. Verify no constraints for all applicable systems:
    a. Instrumentation .... _____ _____ _____
    b. Control .... _____ _____ _____
    c. DSU .... _____ _____ _____
    d. Mechanical .... _____ _____ _____

4.2 Test Rig and Test Stand Setup

14. Barricade Saturn Road south of HCF. .... _____ _____ ___
15. Barricade SW gravel driveway to HCF. .... _____ _____ ___
16. Barricade road that runs south at Helium Pumping Station .... _____ _____ ___
17. Red Light Test Stand B OR barricade Saturn Rd at SE corner of TSB................ _____ _____ ___
18. Make area announcement on page number 177 and 123:

    "The time is T-minus 1 hour for the Advanced Fuel test at the HCF facility. The HCF facility is clear for the designated crew only." .... _____ _____ _____

19. Setup firex by the following steps:
    a. Verify Control systems ready for firex setup.. _____ _____ _____
    b. Energize SOV201 and verify green light ON.. _____ _____ _____
    c. **HOV-2014** HCF Firex Drain .... Close . _____ _____ _____
    d. **HOV-2011** HCF Firex Iso .... Open . _____ _____ _____
20. Setup 150 psi gN2 by the following steps:
    a. Verify **HOV-4270** Trickle Purge Panel Shut Off Valve .... Closed _____ _____ _____
    b. Verify **HOR 4280** AF Trickle Purge Hand Reg .... Fully CCW _____ _____ _____
    c. Verify **HOR 4285** RP-1 Trickle Purge Hand Reg .... Fully CCW _____ _____ _____
    d. Verify **HOR 4290** GOX Trickle Purge Hand Reg......................... Fully CCW _____ _____ _____
    e. Verify **HOR 4295** Fuel Trickle Purge Hand Reg.......................... Fully CCW _____ _____ _____
    f. Verify HCF **HOV-5450** Test Article Panel 150 psi Iso.......................... Open _____ _____ _____
    g. Verify HCF **HOV-5451** Test Article 150 psi gN2 SO .... Open _____ _____ _____
    h. **HOV-4270** Trickle Purge Panel Shut Off Valve.................................. Open _____ _____ _____
    i. **HOV-4203** SOV Cabinet Purge SO .... Open only for adequate box purge _____ _____ _____

21. Setup 750 psi gN2 by the following steps:

    a. Verify HCF **HOV-5250** Test Article 750 psi gN2 Supply Iso .... Closed _____ _____ ____

    b. Verify **HOV-4209** Test Rig gN2 Supply SO .... Closed _____ _____ ____

    c. Verify **HOV-4201** GOX Motor Drive Box Purge SO .... Closed _____ _____ ____

    d. Verify **HOV-4207** Genius Box Purge SO .... Closed _____ _____ ____

    e. Verify **HOR-4205** ROV-4331 Control Press Hand Reg fully CCW................_____ _____ ____

    f. **HOV-5250** Test Article 750 psi gN2 Supply Iso .... **Open SLOWLY** _____ _____ ____

    g. **HOR-4205** ROV-4331 Control Press Hand Reg .... Adjust to 400 psi _____ _____ ____

    h. **HOV-4207** Genius Box Purge SO .... Open only for adequate box purge _____ _____ ____

22. Prime test rig cooling system by the following steps:

    a. DI Water trailer SO Valve ....Open _____ _____ ____

    b. Remove prime plug on pump until water runs from plug ...._____ _____ ____

    c. Install prime plug..._____ _____ ____

    d. Verify water leaks at loose fitting at water exit, ..._____ _____ ____

23. **HOV-4282** AF Tank Trickle Purge SO .... Closed _____ _____ ____

24. **HOV-4287** RP-1 Tank Trickle Purge SO .... Closed _____ _____ ____

25. **HOV-4292** GOX Trickle Purge SO .... Closed _____ _____ ____

26. **HOV-4297** Fuel Trickle Purge SO .... Closed _____ _____ ____

4.3 Tank RP-1

1. Make area announcement on page number 177 and 123:
   "The time is T-minus 30 minutes for the Advanced Fuel test at HCF. The HCF facility is clear for the designated test crew only. All other personnel should remain in safe area." .... _____ _____ _____

2. Place fuel tanking access steps next to test rig and secure. .... _____ _____ _____

3. Verify **ROV-4545** Fuel Shut Off .... Closed _____ _____ _____

4. Verify **ROV-4424** AF Shut Off .... Closed _____ _____ _____

5. **ROV-4523** RP-1 Bypass SO .... OPEN _____ _____ _____

6. **ROV-4534** RP-1 Main SO .... OPEN _____ _____ _____

7. Verify **HOV-4243** RP-1 Trickle Purge Iso .... Closed _____ _____ _____

8. Verify **HOV-4542** Fuel High Point Bleed .... Cracked Open _____ _____ _____

9. Verify **Fuel Low Point Bleed** Cap .... Closed and Tight _____ _____ _____

10. Verify **HOV-4505** RP-1 Tank Bottom Drain .... Closed _____ _____ _____

11. Install clean funnel on RP-1 tank fill fitting and tighten .... _____ _____ _____

12. Tank RP-1. Quantity noted on test request .... _____ _____ _____

13. Remove RP-1 funnel and return to storage bag.. .... _____ _____ _____

14. Cap RP-1 fill fitting and tighten .... _____ _____ _____

15. Verify **HOR-4285** RP-1 Trickle Hand Reg .... Fully CCW _____ _____ _____

16. **HOV-4243** RP-1 Trickle Purge Iso .... OPEN _____ _____ _____

17. **HOV-4287** RP-1 Trickle Purge SO .... OPEN _____ _____ _____

18. Very carefully rotate **HOR-4285** to establish very low positive pressure in RP-1 system. When RP-1 begins to drip from the Fuel High Point Bleed, rotate **HOR-4285** fully CCW .... _____ _____ _____

19. **HOV-4243** RP-1 Trickle Purge Iso .... Closed _____ _____ _____

20. **HOV-4542** Fuel High Point Bleed .... Closed _____ _____ _____

21. **ROV-4534** RP-1 Main SO .... Closed _____ _____ _____

22. Move access stairs to Adv Fuel tank side of test rig if required .... _____ _____ _____

4.4 Tank Advanced Fuel

1. Install clean funnel on Adv Fuel tank fill fitting and tighten .... _____ _____ _____
2. Verify **HOV-4405** AF Tank Bottom Drain .... Closed _____ _____ _____
3. Verify **HOV-4233** AF Trickle Purge Iso .... Closed _____ _____ _____

NOTE: No More than 2 personnel should prepare for handling Adv Fuel.

4. Don proper PPE for fuel handling .... _____ _____ _____
5. ***<u>CAUTION: All personnel near Adv Fuel tanking operations should make all attempts to stand up-wind during tanking operations.</u>*** Measure quantity of Adv Fuel listed on test request into clean poor container. .... _____ _____ _____
6. **AF High Point Bleed Cap** .... Cracked Open _____ _____ _____
7. **AF Low Point Bleed Cap** .... Tight _____ _____ _____
8. Poor Adv Fuel into Adv Fuel tank. .... _____ _____ _____
9. Verify drip at **AF High Point Bleed Cap** .... _____ _____ _____
10. Tighten **AF High Point Bleed Cap** .... _____ _____ _____
11. Seal Adv Fuel poor container in clean bag. Remove from immeadiate test rig area to safe place in case of spontaneous combustion. .... _____ _____ _____
12. Remove Adv Fuel funnel and seal in clean storage bag. Remove from immeadiate test rig area to safe place in case of spontaneous combustion. .... _____ _____ _____
13. Cap Adv Fuel fill fitting and tighten. .... _____ _____ _____
14. Move access steps away from test rig .... _____ _____ _____

4.5 Pressurize Fuel Tanks

1. Verify **HOV-4213** RP-1 Press Sys Bleed .... Closed _____ _____ ____
2. Verify **HOV-4243** RP-1 Trickle Purge Iso.. Closed _____ _____ ____
3. Verify **HOV-4223** AF Press Sys Bleed .... Closed _____ _____ ____
4. Verify **HOV-4233** AF Trickle Purge Iso .... Closed _____ _____ ____
5. Verify **HOV-4241** RP-1 Tank Press Iso..Open _____ _____ ____
6. Verify **HOV-4231** AF Tank Press Iso ....Open _____ _____ ____
7. DSU ....SLOW _____ _____ ____
8. **HOV-4209** Test Rig gN2 Supply SO .... SLOWLY Open _____ _____ ____
9. **SOV-4216** RP-1 Press SO .... OPEN _____ _____ ____
10. Verify **SOV-4218** RP-1 Tank Vent.. Closed _____ _____ ____
11. **SOV-4226** AF Press SO .... OPEN _____ _____ ____
12. Verify **SOV-4228** AF Tank Vent.. Closed _____ _____ ____
13. **HOR-4250** GOX/ Fuel Purge Hand Regulator
    Adjust to _____ psig on P4261. ....Record P4261 _____ _____ ____
14. **HOR-4211** RP-1 Tank Press Hand Reg
    Adjust to _____ psig on P4501. ....Record P4501 _____ _____ ____
15. **HOR-4221** Adv Fuel Tank Press Hand Reg
    Adjust to _____ psig on P4401. ....Record P4401 _____ _____ ____
16. Verify no audible leaks on rig.._____ _____ ____

4.6 GOX System Setup

1. Make area announcement on page number 177 and 123:
   "The time is T-minus 10 minutes for the Advanced Fuel test at HCF. All personnel should remain in safe area until further notice." .... _____ _____ _____

2. Verify **HOV-355** GOX Trailer Connection Vent .... Closed _____ _____ _____

3. **ROV-358** GOX Supply SO .... OPEN _____ _____ _____

4. **ROV-371** GOX System Vent ....CLOSED _____ _____ _____

5. **CAUTION: OPEN GOX TRAILER HOV VERY SLOWLY** .... OPEN _____ _____ _____

6. **HOR-4305** GOX Supply Regulator.
   Slowly adjust to ______ psi on P4305. .... Record P4305 _____ _____ _____

7. Verify no audible leaks on GOX system. .... _____ _____ _____

8. Designated crew retreat to safe area and verify area clear. .... _____ _____ _____

4.7 Test Fire

1. Verify all pressures within ranges of test request. Adjust any if necessary. .... _____ _____ _____
2. **SOV-4262** Fuel Purge SO .... OPEN _____ _____ _____
3. **SOV-4272** GOX Purge SO .... OPEN _____ _____ _____
4. **P-405** DI Water Pump .... ON _____ _____ _____
5. Cutoff Reset ON.. _____ _____ _____
6. Cutoff Reset OFF.. _____ _____ _____
7. Cutoff ARM.. _____ _____ _____
8. Verify PREP COMPLETE.. _____ _____ _____
9. Video .... ON _____ _____ _____
10. DSU .... FAST _____ _____ _____
11. High Speed Data Acq .... ON _____ _____ _____
12. **"Auto-sequence Start"**.. _____ _____ _____

4.8 After Cutoff

1. Verify **ROV-4331** GOX Main SO .... Closed _____ _____ _____
2. Verify **ROV-4321** GOX Bypass.. Closed _____ _____ _____
3. Verify **ROV-4545** Fuel SO .... Closed _____ _____ _____
4. Verify **ROV-4534** Rp-1 Main.. Closed _____ _____ _____
5. Verify **ROV-4523** RP-1 Bypass .... Closed _____ _____ _____
6. Verify **SOV-4272** GOX Purge ....Open _____ _____ _____
7. Verify **SOV-4262** Fuel Purge ....Open _____ _____ _____
8. **P-405** DI Water Pump.. OFF _____ _____ _____
9. High Speed Data Acq .... OFF _____ _____ _____
10. DSU ....SLOW _____ _____ _____
11. Video .... OFF _____ _____ _____
12. Cut Off Arm.. OFF _____ _____ _____
13. Record cut: ____________________ ____________________ ____________________
14. Autosequence Start.. OFF _____ _____ _____
15. Cut Off Reset.. ON _____ _____ _____
16. Cut Off Reset.. OFF _____ _____ _____
17. DSU .... OFF _____ _____ _____

NOTE: Recycle can only be used for simple redline changes or non-significant changes to the sequence. If any cut parameters are changed or added, time must be allotted for verification and a new TCP released.

18. Recycle for next test if desired to Section 4.1 and note test # at top of check column ...._____ _____

4.9 Safe Test Stand

1. Make area announcement on page number 177 and 123:

   "The Adv Fuel Test complete at the HCF facility. HCF is clear for the designated crew only." .... _____

2. GOX Trailer Valve .... Closed _____
3. **ROV-358** GOX Supply SO........ Open _____
4. Contact crew on radio and announce:

   "The Adv Fuel GOX system is about to be vented." .... _____

5. ***Caution: NOISE*** **ROV-371** HCF GOX System Vent .... Open _____
6. **HOR-4305** Gox Hand Reg .... Closed _____
7. **ROV-358** GOX Supply SO........ Closed _____
8. **HOR-4250** GOX/Fuel Purge Hand Reg .... Closed _____
9. **SOV-4262** Fuel Purge SO .... Closed _____
10. **SOV-4272** GOX Purge SO .... Closed _____
11. **HOR-4221** AF Tank Press Hand Reg .... Closed _____
12. ***Caution: NOISE*** HOV-4223 AF Tank Press Sys Bleed .... Open _____
13. **HOV-4223** AF Tank Press Sys Bleed .... Closed _____
14. **SOV-4226** AF Tank Press SO........ Closed _____
15. **SOV-4228** AF Tank Vent .... Closed _____
16. **HOR 4211** RP-1 Tank Press Hand Reg........ Closed _____
17. ***Caution: NOISE*** HOV-4213 RP-1 Tank Press Sys Bleed........ Open _____
18. **HOV-4213** RP-1 Tank Press Sys Bleed .... Closed _____
19. **SOV-4216** RP-1 Tank Press SO .... Closed _____
20. **SOV-4218** RP-1 Tank Vent .... Closed _____
21. If pentane flush is required, complete the Pentane Flush SOP. .... _____
22. HCF **HOV-5250** Test Article Panel 750 psi gN2 Supply Iso .... Closed _____
23. ***Caution: NOISE*** **HOV-4201** GOX Motor Drive Box Purge SO .... Open _____

24. **HOV-4201** GOX Motor Drive Box Purge SO .... Closed _____

25. **HOR-4205** ROV-4331 Control Press Hand Reg .... Closed _____

26. **HOV-4207** Genius Box Purge So .... Closed _____

27. **HOV-4209** Test Rig gN2 Supply SO .... Closed _____

28. **HCF HOV-2011** HCF Firex Iso .... Closed _____

29. **HCF HOV-2014** HCF Firex Drain .... Open _____

30. Secure HCF Firex Panel .... _____

31. Secure Waterpump power .... _____

32. **HCF HOV-401** DI Water Supply SO .... Closed _____

33. DI water trailer HOV .... Closed _____

34. Verify Normal Panel .... _____

35. Control System Secure .... _____

5.0 EMERGENCY PROCEDURES

5.1 On Stand Fuel / GOX Leaks

1. Assess severity of leak and proceed per following as required:

   a. Implement / verify cutoff .... _____

   b. Proceed to "**After Cutoff**" section of TCP .... _____

5.2 On Stand Fire / Explosion

1. Assess severity of situation and proceed per following as required:

   a. Firex .... ON _____

   b. Implement / verify cutoff .... _____

   c. Proceed to "**After Cutoff**" section of TCP .... _____

2. Firex .... OFF _____

5.3 Test Stand Safety Verification Prior to Designated Crew Entry

1. Scan area with IR and / or visible cameras for fires .... _____
2. Monitor instrumentation for propellant leaks .... _____
3. Monitor hand held flame detectors .... _____

5.4 Fuel Spills

1. Assess situation and proceed as required.
2. Monitor hand held flame detectors .... _____
3. Spread oil dry over spill and around spill to contain .... _____
4. Call environmental office if necessary.. _____

6.0 POST PROCEDURE VERIFICATION

Procedure HFD-TCP-001 has been completed and documentation resulting from it's conduct has bee generated as listed below:

1. All permanent deviations to the procedure have been generated and given to the CCM for inclusion in existing copies of this procedure until it is revised. ______ TC ______ QC

2. All anomaly documents (QTP's) have been generated and their numbers are: ______ TC ______ QC

______________________ ______________________

______________________ ______________________

____
Test Conductor

____
Date

____
Quality

____
Date

APPENDIX D—INSTRUMENTATION LIST

MID	DESCRIPTION	LOW	HIGH	UNITS	MANUFACTURER
P4522	RP-1 Bypass Venturi Outlet Press	0	500	Psig	Sensotec
P4205	ROV Control Pressure	0	200	Psig	Sensotec
P4601	Chamber Press	0	250	Psig	Sensotec
P4265	Fuel Trickle Purge Pressure	0	300	Psig	Taber
P4531	RP-1 Main Venturi Inlet Press	0	500	Psig	Taber
P4334	GOX Main Venturi Outlet Press	0	500	Psig	Taber
P4532	RP-1 Main Venturi Outlet Press	0	500	Psig	Taber
P4402	AF Tank Bottom Press	0	500	Psig	Stellar
P4421	AF Venturi Inlet Press	0	500	Psig	Stellar
P4501	RP-1 Tank Top Press	0	500	Psig	Stellar
P4322	GOX Bypass Venturi Inlet Press	0	500	Psig	Taber
P4332	GOX Main Venturi Inlet Press	0	500	Psig	Taber
P4324	GOX Bypass Venturi Outlet Press	0	500	Psig	Taber
P4399	Injector GOX Press	0	500	Psig	Taber
P4401	AF Tank Top Press	0	500	Psis	Stellar
P4521	RP-1 Bypass Venturi Inlet Press	0	500	Psig	Stellar
P4115	Cooling Water Outlet Press	0	500	Psig	Taber
P4275	GOX Trickle Purge Pressure	0	300	Psig	Taber
P4305	GOX Press	0	500	Psig	Taber
P4225	AF Tank Supply Press	0	500	Psig	Taber
P4261	Fuel/GOX Purge Press	0	500	Psig	Stallar
P4215	RP-1 Tank Supply Pressure	0	500	Psis	Stellar
P4502	RP-1 Tank Bottom Press	0	500	Psig	Stellar
P4301	GOX Trailer Press	0	300	Psig	Stellar
P4599	Injector Fuel Press	0	500	Psig	Stellar
P4422	AF Venturi Outlet Press	0	500	Psig	Stellar
P4102	Cooling Water Supply Press	0	500	Psig	Stellar
FM4115	Cooling Water Flow	0	1	lb/sec	
FM4412	AF Flow Rate	0	0.15	lb/sec	
FM4530	RP-1 Flow Rate	0	0.15	lb/sec	
LC4601	Measured Thrust A	0	100	Lb	
LC4602	Measured Thrust B	0	100	Lb	
T4102	Cooling Water Supply Temp	0	200	DegF	Nanmac
T4115	Cooling Water Outlet Temp	0	400	DegF	Nanmac
T4322	GOX Bypass Venturi Inlet Temp	40	150	DegF	Nanmac
T4324	GOX Bypass Venturi Outlet Temp	40	150	DegF	Nanmac
T4332	GOX Main Venturi Inlet Temp	40	150	DegF	Nanmac
T4334	GOX Main Venturi Outlet Temp	40	150	DegF	Nanmac
T4399	Injector GOX Temp	40	150	DegF	Nanmac
T4402	AF Tank Bottom Temp	40	150	DegF	Nanmac
T4421	AF Venturi Inlet temp	40	150	DegF	Nanmac
T4422	AF Venturi Outlet Temp	40	150	DegF	Nanmac
T4502	RP-1 Tank Bottom Temp	40	150	DegF	Nanmac
T4521	RP-1 Bypass Venturi Inlettemp	40	150	DegF	Nanmac
T4522	RP-1 Bypass Venturi Outlet Temp	40	150	DegF	Nanmac
T4531	RP-1 Main Venturi Inlet Temp	40	150	DegF	Nanmac
T4532	RP-1 Main Venturi Outlet Temp	40	150	DegF	Nanmac
T4599	Injector Fuel Temp	40	150	DegF	Nanmac
T4600	Ambient Temp	32	150	DegF	
T4601	Chamber Temp	40	200	DegF	
T4602	Ignition Verification Temp	0	500	DegF	Omega
T4603	Ignition Verification Temp	0	500	DegF	Omega

APPENDIX E—THRUST MEASUREMENT SYSTEM DYNAMIC ANALYSIS TEST REPORT

National Aeronautics and
Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

Reply to Attn of: ED27-00-044 March 21, 2000

TO: TD71/Bobby Hubbard

FROM: ED27/Timothy C. Driskill

SUBJECT: Advanced Fuel Thrust Measurement Assembly Frequency Response Function Test Data Package, AFP-DEV-00-025

The Modal and Control Dynamics Team (ED27) performed a series of dynamic tests on the Advance Fuel propulsion test article thrust measurement assembly at the West Propulsion Test Area of Marshall Space Flight Center on March 7-8, 2000. The purpose of the tests was to determine force output/force input transfer functions of the assembly and included load cell. Frequency response functions (FRF) due to random excitation input by a modal shaker were acquired to characterize the force output/force input relationship. The test article was excited in a 0-2000 Hz, 0-400 Hz, and 0-100 Hz bandwidth. The tests were conducted at the request of TD71/Bobby Hubbard per memorandum TD71 (00-002), "Advanced Fuel Thrust Measurement Assembly Dynamic Test."

The enclosed data package contains the following information: test description, test preparation sheet, test equipment, test photographs, FRF plots, and input power spectrum plots. The data contained in this data package has also been provided to TD71 in a variety of formats.

Questions concerning this test report should be directed to Mr. Timothy C. Driskill at (256) 544-1139 or Mr. Russel Parks at (256) 961-1124.

Timothy C. Driskill
Team Leader
Modal and Control Dynamics Team

CONCURRENCE:

Alan F. Patterson, Deputy Group Leader
Structural and Dynamics Testing Group

Enclosure

cc:

ED27/Messrs. Kirby/Patterson (w/o encl.)
ED27/Messrs. Driskill/Parks
ED27/File Copy (2 copies)
ED20/Mr. Owen (w/o encl.)
TD71/Mr. Dumbacher
TD72/Messrs. Wiley/Smith/Hamilton

AFP-DEV-00-025
March 13, 2000

Advanced Fuel Thrust Measurement Assembly Frequency Response Function Test Data Package

Modal and Control Dynamics Team
Structural and Dynamics Testing Group
Structures, Mechanics, and Thermal Department

Test Description

The Mechanical Design Group (TD71) of the Technology Evaluation Department in the Space Transportation Directorate requested, per TD71 (00-002), ED27 to perform a dynamic test on the Advanced Fuel propulsion test article thrust measurement assembly. The purpose of the test was to determine a force ouput/force input transfer function of the assembly and included load cell. The transfer functions acquired during the test can be used to quantify the uncertainty of the thrust load measurements taken during propulsion test firings of the test article.

Random excitation was applied to the Advanced Fuel propulsion test article outlet, see Figure 1, using an Unholtz-Dickie Model 1 Modal Shaker. Input force measurements were made using a PCB model 208B03 load cell. Acceleration data parallel to the axis of excitation was measured at the drive point using a PCB model 353B17 accelerometer, see Figure 2. The pre-existing load cell incorporated into the Advanced Fuel propulsion test article for measuring thrust loads was used to measure an output force, see Figure 3.

Data was acquired using a HP 3562 Dynamic Signal Analyzer, see Figure 6, for 10 different tests.

Advanced Fuel Propulsion Test Article
Thrust Measurement Assembly Dynamic Test Description

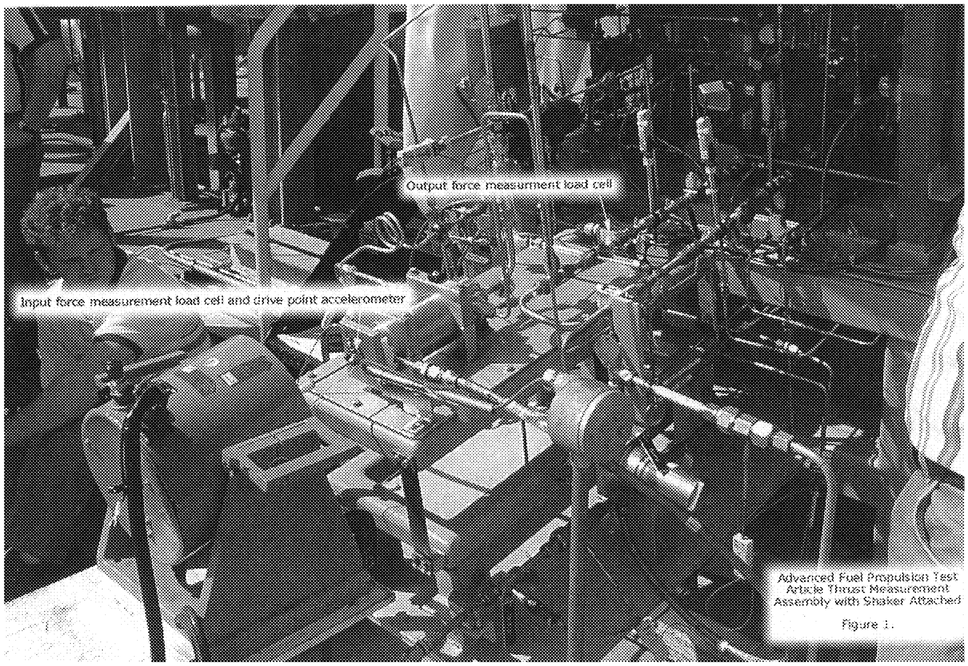
Test Number	Test Description
1	Force output/force input frequency response function, 0-2000Hz, 1 lb. rms random input
2	Force output/force input frequency response function, 0-2000Hz, 15 lb. rms random input
3	Force output/force input frequency response function, 0-400Hz, 1 lb. rms random input
4	Force output/force input frequency response function, 0-100Hz, 1 lb. rms random input
5	Drive point acceleration/input force frequency response function, 0-2000 Hz, 1 lb. rms random input
6	Drive point acceleration/input force frequency response function, 0-2000 Hz, 15 lb. rms random input
7	Drive point acceleration/input force frequency response function, 0-400 Hz, 1 lb. rms random input
8	Drive point acceleration/input force frequency response function, 0-100 Hz, 1 lb. rms random input
9	Force output/force input frequency response function, 0-100Hz, 1 lb. rms random input, w/jack (see figure 5)
10	Force output/force input frequency response function, 0-100Hz, 1 lb. rms random input, w/jack and wood (see figure 6)

Tests 1-4 determined a relationship between the force input at the Advanced Fuel propulsion test article outlet and the force output at the thrust measurement load cell. Test 1 gave a wide band relationship, while tests 3 and 4 focused on smaller bandwidths with higher resolution. A higher force level was applied in test 2 to determine if any nonlinearities were present in the structure. Force output/force input frequency response functions and input power spectrums from these tests have been provided in the appendix.

Drive point frequency response functions were acquired in tests 5-8 to determine the frequency content of the Advanced Fuel propulsion test article thrust measurement assembly. A wide band frequency response function was acquired in test 5, while tests 7 and 8 focused on smaller bandwidths with higher resolution. A higher force level was applied in test 6 to determine if any nonlinearities were present in the structure. The drive point frequency response functions and input power spectrums from these tests are provided in the appendix.

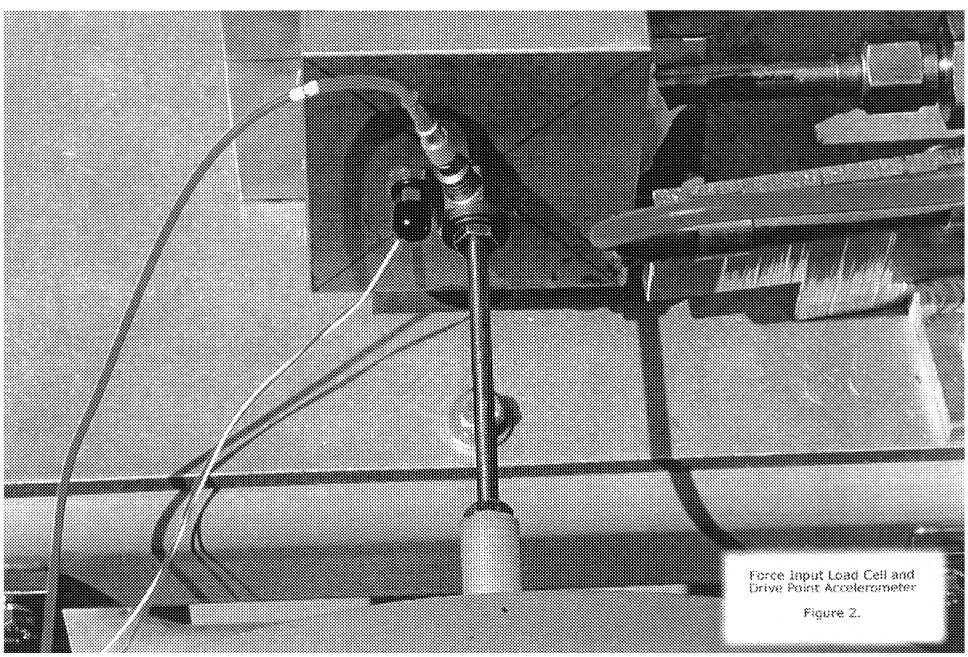
Tests 9 and 10 were performed on the test configurations show in Figures 5 and 6. These tests were run to determine what effects the jack had on the force output/force input frequency response functions. The force output/force input frequency response functions and input power spectrums acquired from these tests are provided in the appendix.

The "As Run" Test Preparation Sheet and test equipment list are provided in this data package.



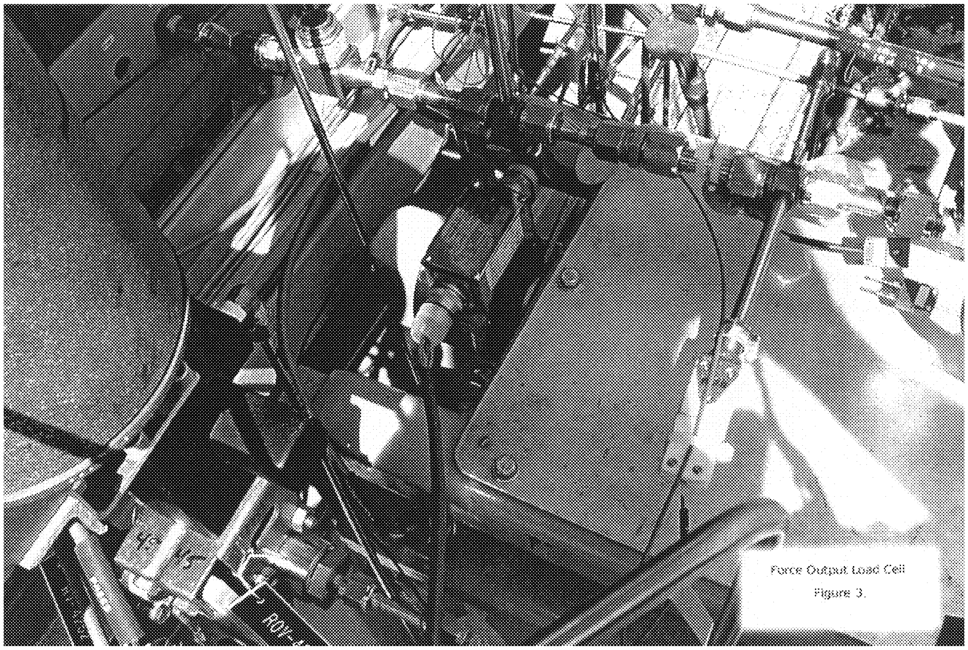
Advanced Fuel Propulsion Test Article Thrust Measurement Assembly with Shaker Attached

Figure 1.



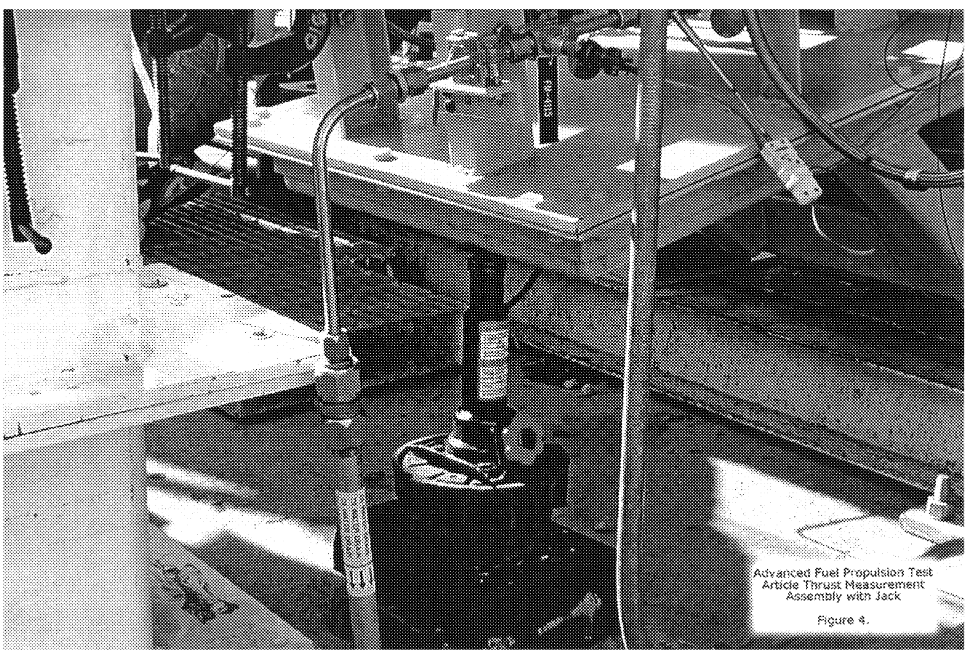
Force Input Load Cell and Drive Point Accelerometer

Figure 2.



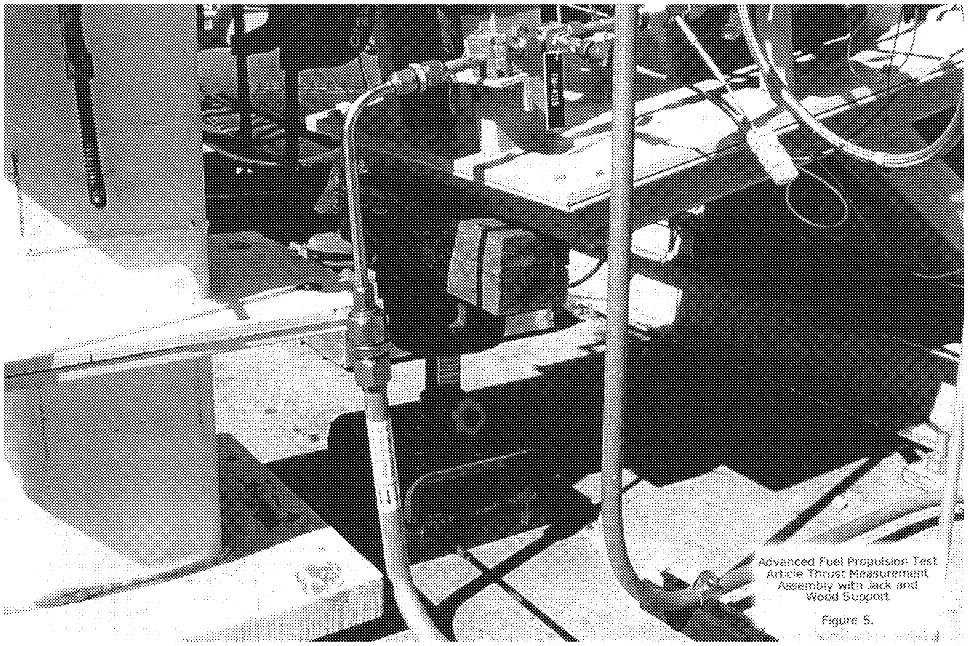
Force Output Load Cell

Figure 3.



Advanced Fuel Propulsion Test Article Thrust Measurement Assembly with Jack

Figure 4.



Advanced Fuel Propulsion Test Article Thrust Measurement Assembly with Jack and Wood Support

Figure 5.

Data Acquisition System

Figure 6.

TYPE:	TEST PREPARATION SHEET	TPS NUMBER: AFP-DEV-00-025
☐ A. CONFIGURATION CHANGE ☐ B. NON-CONFIGURATION CHANGE		S/C: / CATEGORY: / NUMBER:

MOD. SHEET NUMBER: **PAGE** **OF**

TPS SHORT TITLE:	
Advanced Fuel Thrust Measurement Assembly Frequency Response Function Test	SAFETY HAZARD ☐ YES ☒ NO
	LIMITED LIFE EQUIPMENT ☐ YES ☒ NO
EXPERIMENT/MODEL NUMBER: / DATE: 03-07-2000 / NEED DATE:	WEIGHT REQUIRED ☐ YES ☒ NO
DRAWING(S) DOCUMENTS, TCP(S) AND PART NUMBER(S):	MATERIAL ENGINEER SIGNATURE ☐ YES ☒ NO

INITIATING ORGANIZATIONS:	SYSTEM:
ED27	

REASON FOR WORK:

Generate F/F frequency response functions to quantify a measurement uncertainty for thrust load measurements taken during propulsion test firings of the Advanced Fuel Propulsion Test Article. 3/7-8/00

NO.	DESCRIPTION (PRINT OR TYPE)	TECH	INSPECTION CONT.	INSPECTION NASA
1	Acquire F/F frequency response function @ 0-2000Hz @ 1 lb. Store FRF and input power spectrum.			[initials]
2	Acquire F/F frequency response function @ 0-2000Hz @ 15 lb. Store FRF and input power spectrum.			[initials]
3	Acquire F/F frequency response function @ 0-400Hz @ 1 lb. Store FRF and input power spectrum.			[initials]
4	Acquire F/F frequency response function @ 0-100Hz @ 1 lb. Store FRF and input power spectrum.			[initials]
5	Acquire A/F drive point FRF @ 0-2000Hz @ 1 lb. Store FRF and input power spectrum.			[initials]
6	Acquire A/F drive point FRF s @ 0-2000Hz @ 15 lb. Store FRF and input power spectrum.			[initials]
7	Acquire A/F drive point FRF @ 0-400Hz @ 1 lb. Store FRF and input power spectrum.			[initials]
8	Acquire A/F drive point FRF @ 0-100Hz @ 1 lb. Store FRF and input power spectrum.			[initials]
9	Complete other additional tests as requested. 0-100Hz F/F w/ JACK			[initials]
	" " w/ JACK + WOOD			[initials]

SPECIAL NOTES:

PREPARED BY:	PHONE EXT.:	FINAL ACCEPTANCE:	DATE:
Timothy C. Driskill [signature]	4-1139		

REFER TO LOCAL PROCEDURES FOR SPECIFIC APPROVALS	REFER TO LOCAL PROCEDURES FOR SPECIFIC APPROVALS
1. Alan F. Patterson [signature]	1.
2.	2.
3.	3.
4.	4.

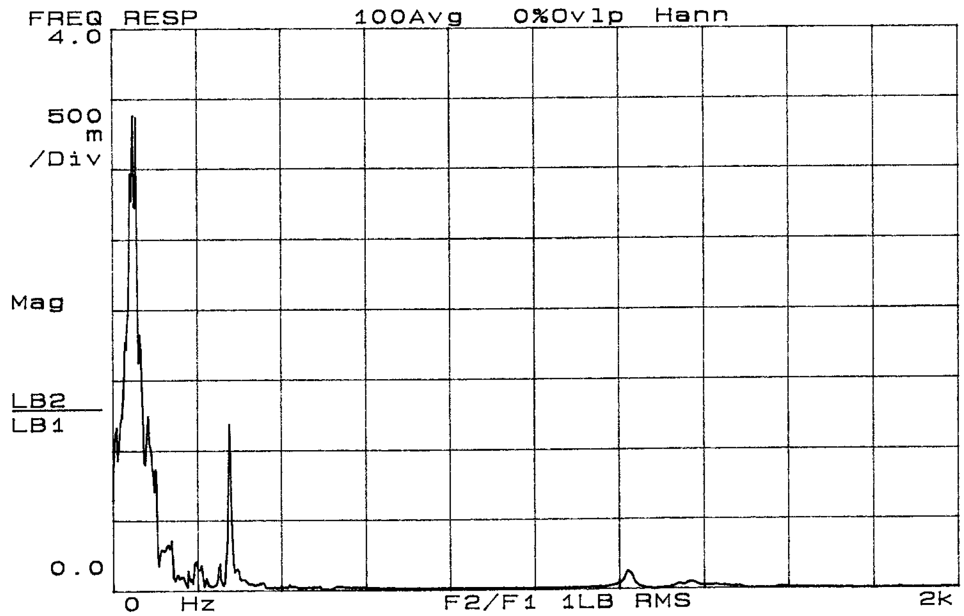
MSFC Form 248 (December 1971) Informed 2.8

Advanced Fuel Propulsion Test Article
Thrust Measurement Assembly
Dynamic Test Equipment List

Item	Model	Serial #	Calibration Value	Calibration Due Date
Unholtz-Dickie Modal Shaker	1	210	NA	NA
Signal Conditioner	483A07	551	NA	5/23/2000
HP Dynamic Analyzer	3562	2738A02785	NA	10/20/2000
Wavetek Filter	852	E90010498	NA	8/3/2000
PCB Accelerometer	353B17	18081	103 mV/g	3/8/2001
PCB Load Cell	208A03	12486	117.3 mV/lb	2/2/2001
Keithley Multimeter	2000	0584572	NA	9/21/2000
PCB Hand Held Calibrator	394C06	1494	1 g rms	5/17/2000
Toroid Load Cell	36U 223 1A	61018	60 mV/lb*	*

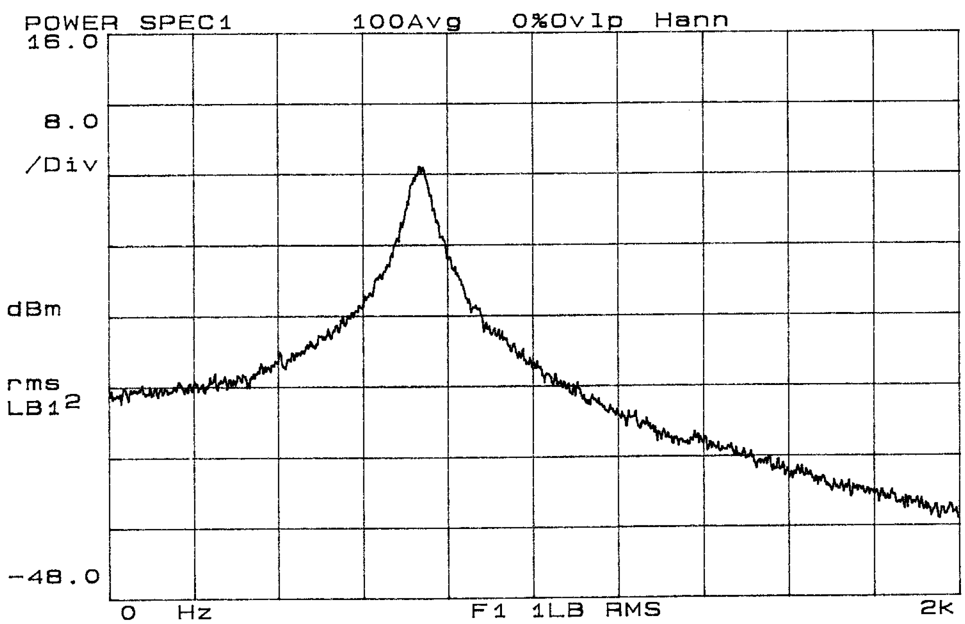
* the Toroid load cell and calibration value was supplied by TD72.

Test Data Plots



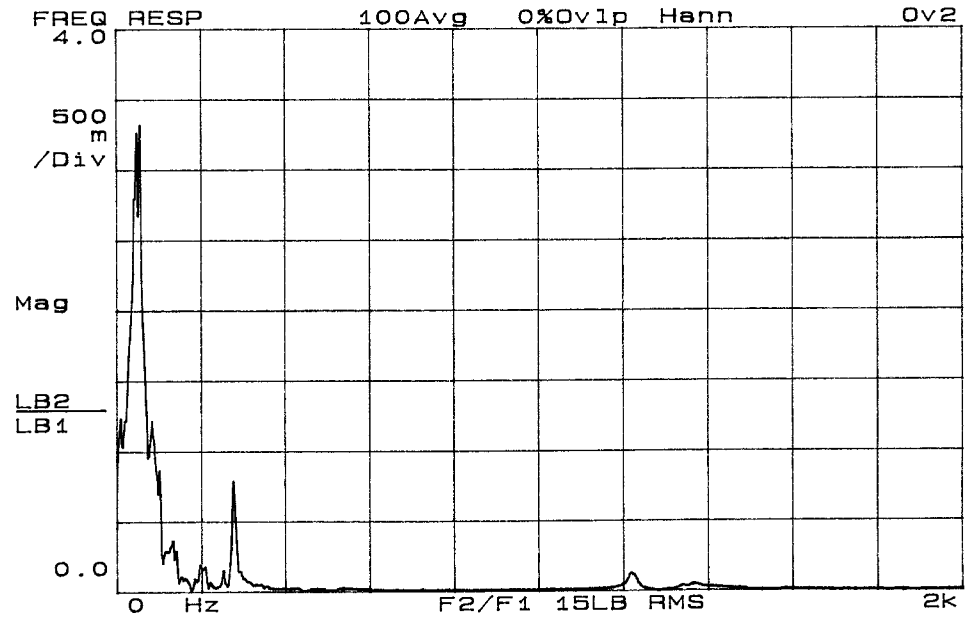
Test 1

Force output/force input FRF
1 lb. rms random input
0-2000 Hz



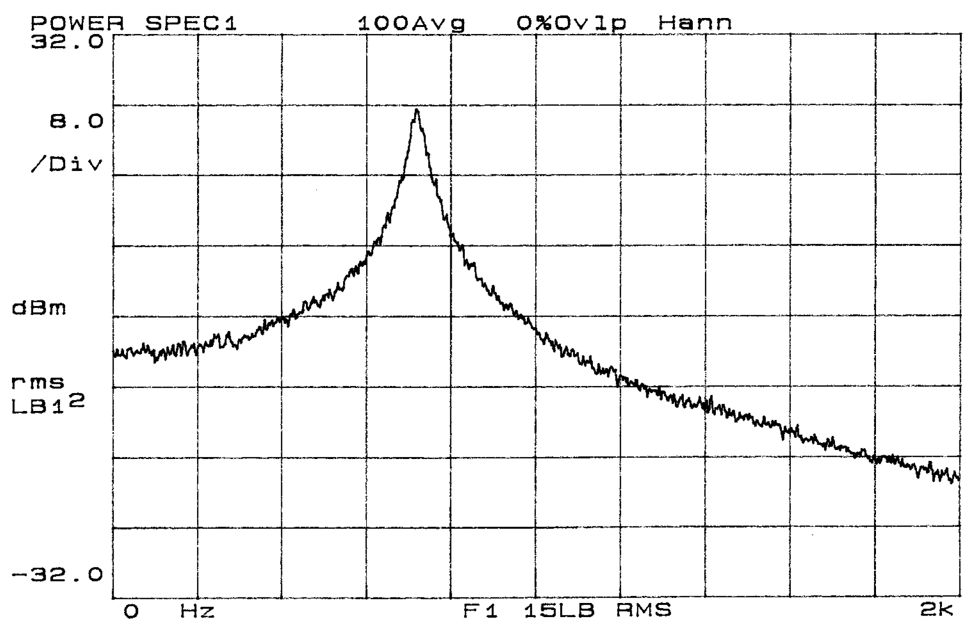
Test 1

Input power Spectrum
1 lb. rms random input
0-2000 Hz



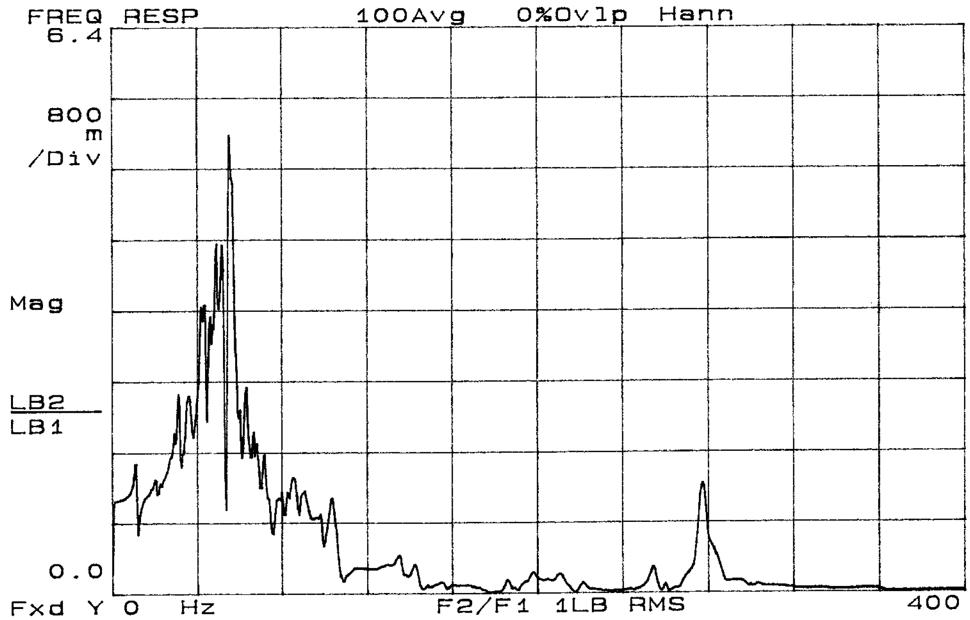
Test 2

Force output/force input FRF
15 lbs. rms random input
0-2000 Hz



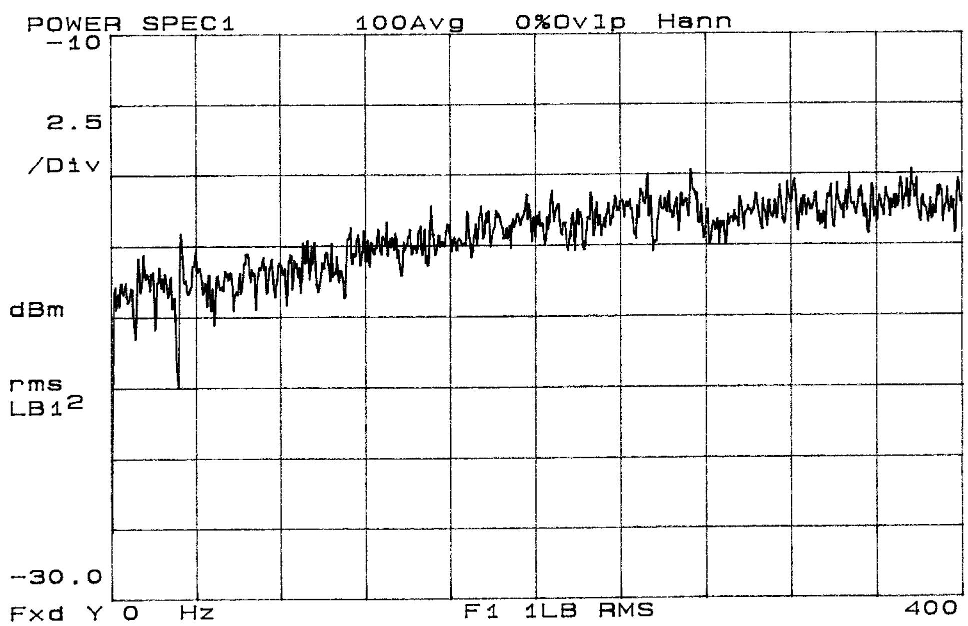
Test 2

Input power Spectrum
15 lbs. rms random input
0-2000 Hz



Test 3

Force output/force input FRF
1 lb. rms random input
0-400 Hz

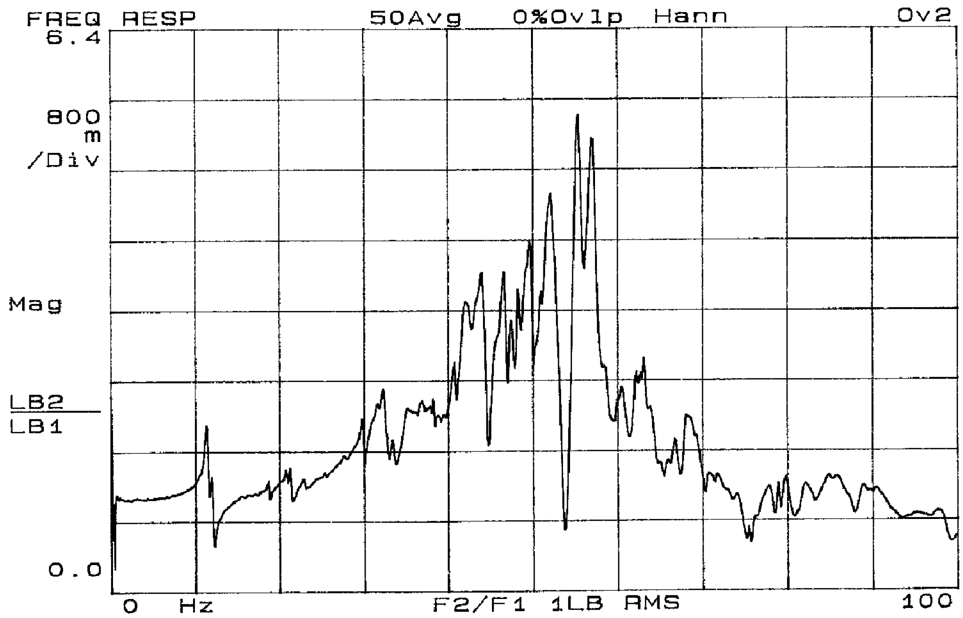


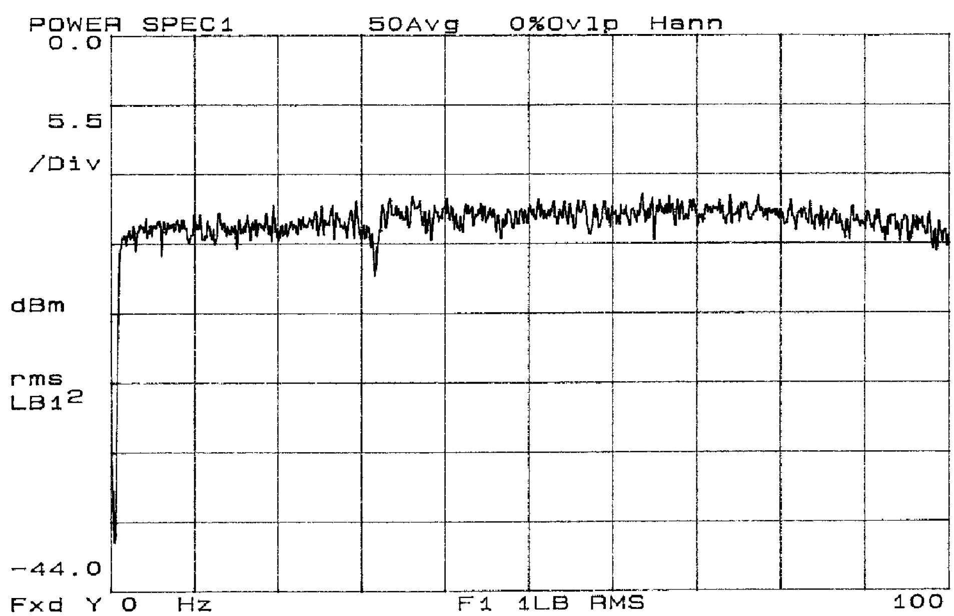
Test 3

Input power Spectrum
1 lb. rms random input
0-400 Hz

Test 4

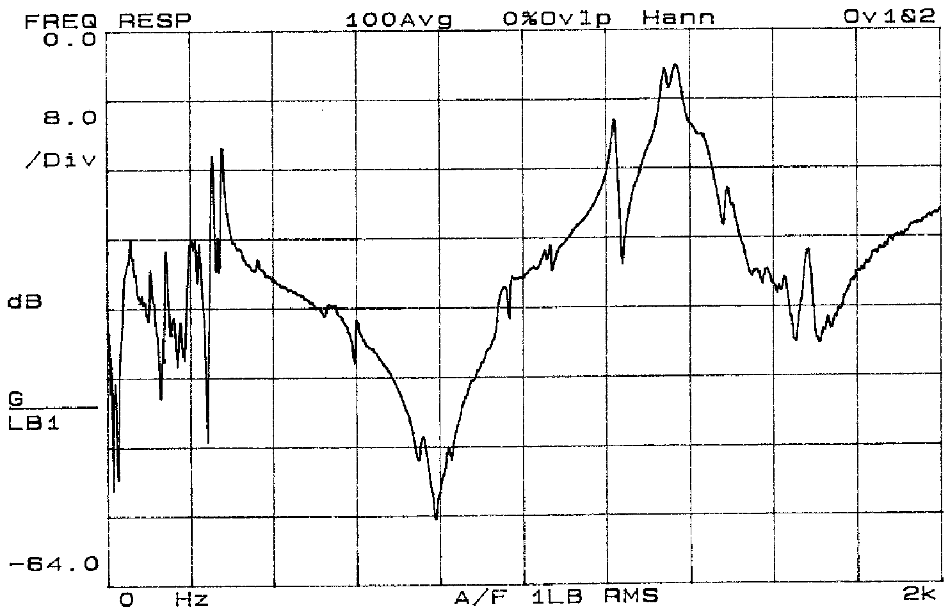
Force output/force input FRF
1 lb. rms random input
0-100 Hz





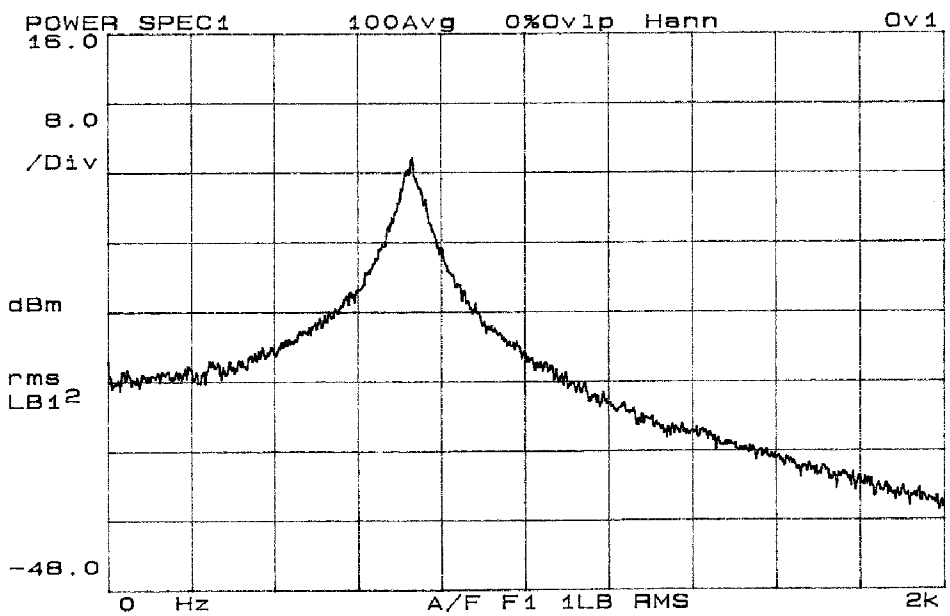
Test 4

Input power Spectrum
1 lb. rms random input
0-100 Hz



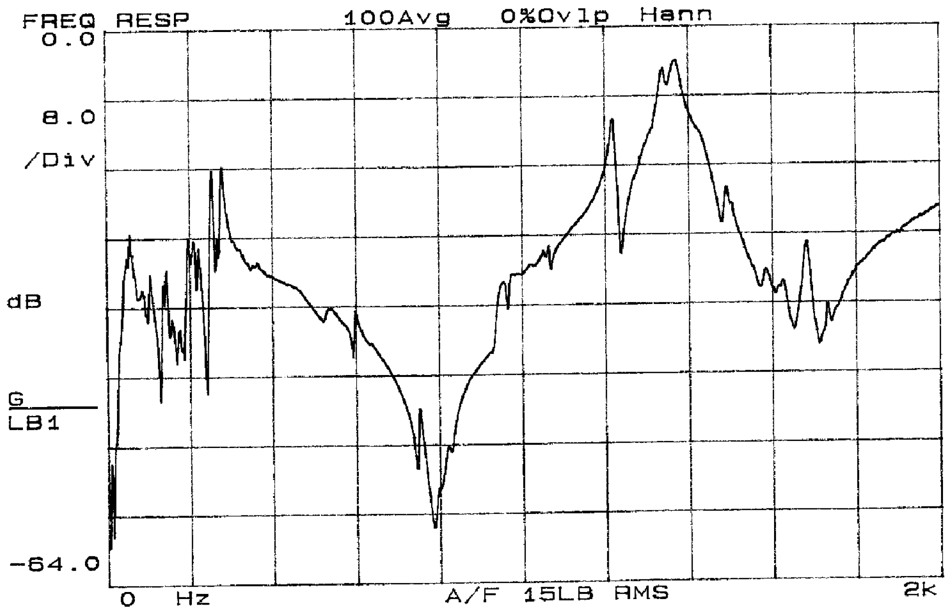
Test 5

Drive point accel./ input force FRF
1 lb. rms random input
0-2000 Hz



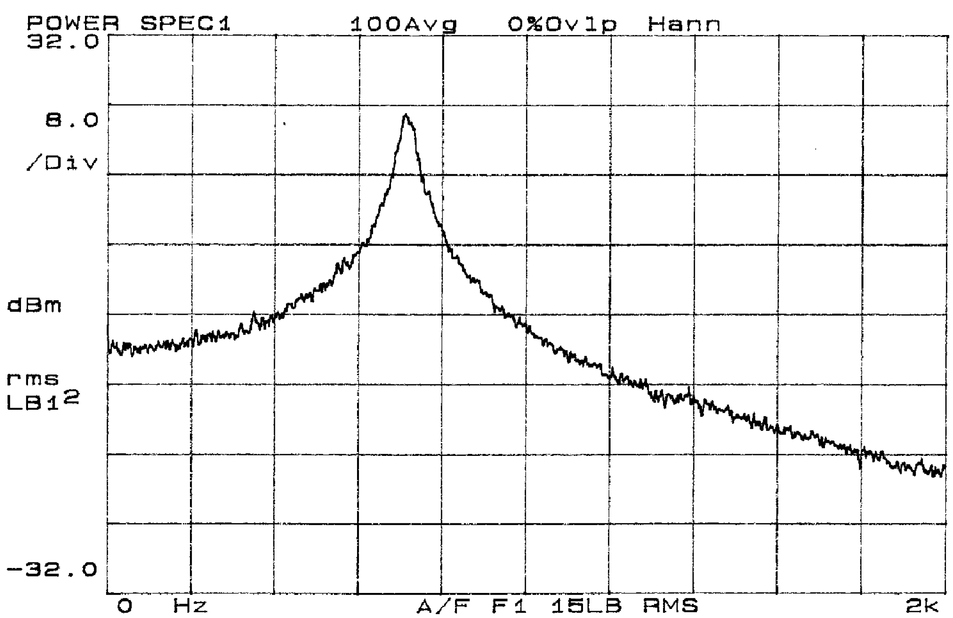
Test 5

Input power Spectrum
1 lb. rms random input
0-2000 Hz



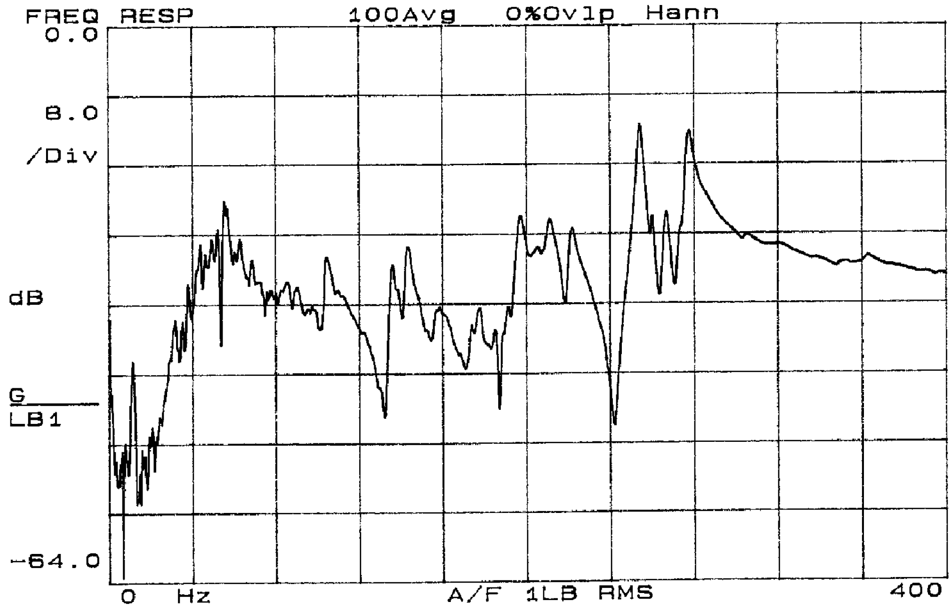
Test 6

Drive point accel./ input force FRF
15 lbs. rms random input
0-2000 Hz



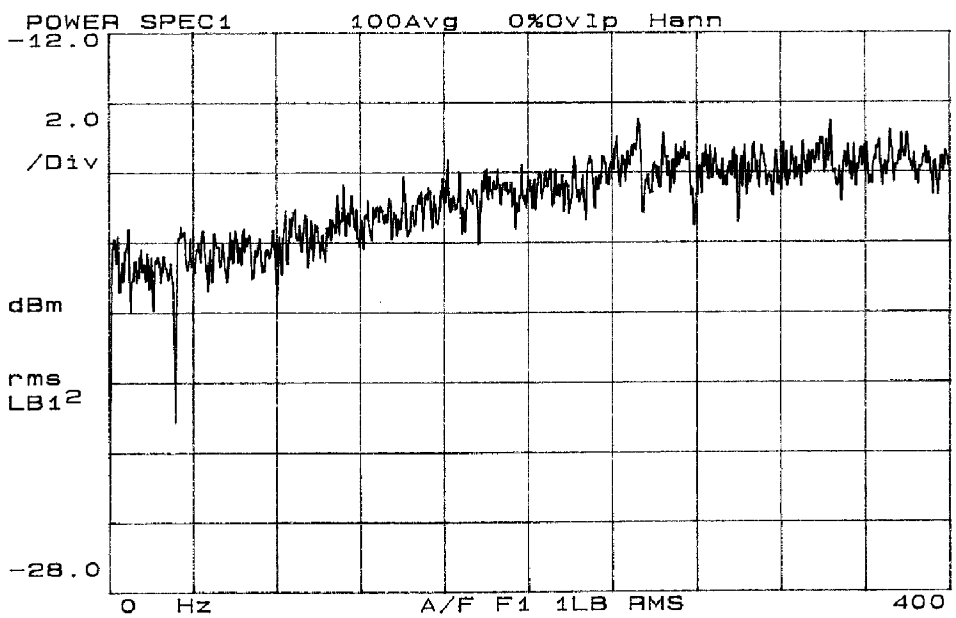
Test 6

Input power Spectrum
15 lbs. rms random input
0-2000 Hz



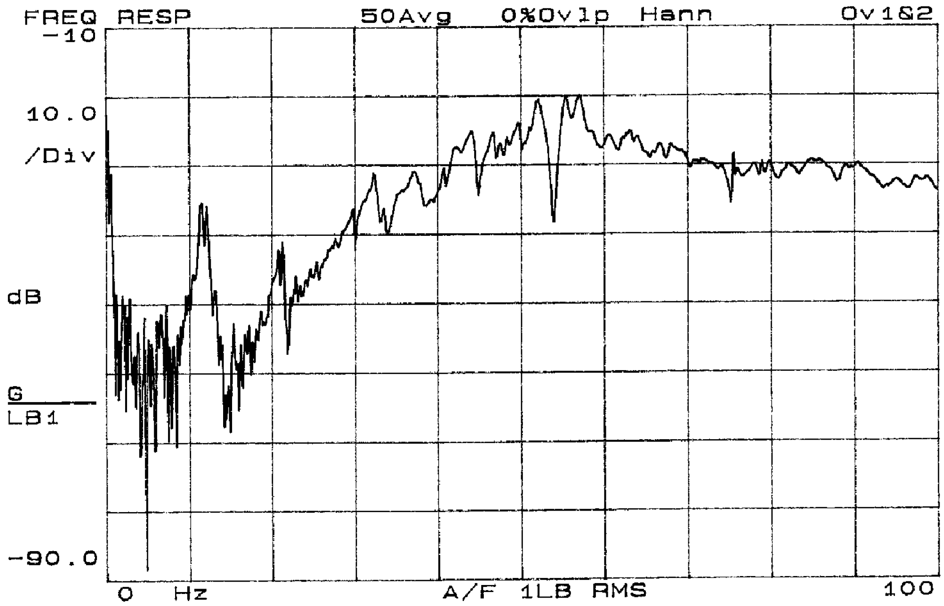
Test 7

Drive point accel./ input force FRF
1 lbs. rms random input
0-400 Hz



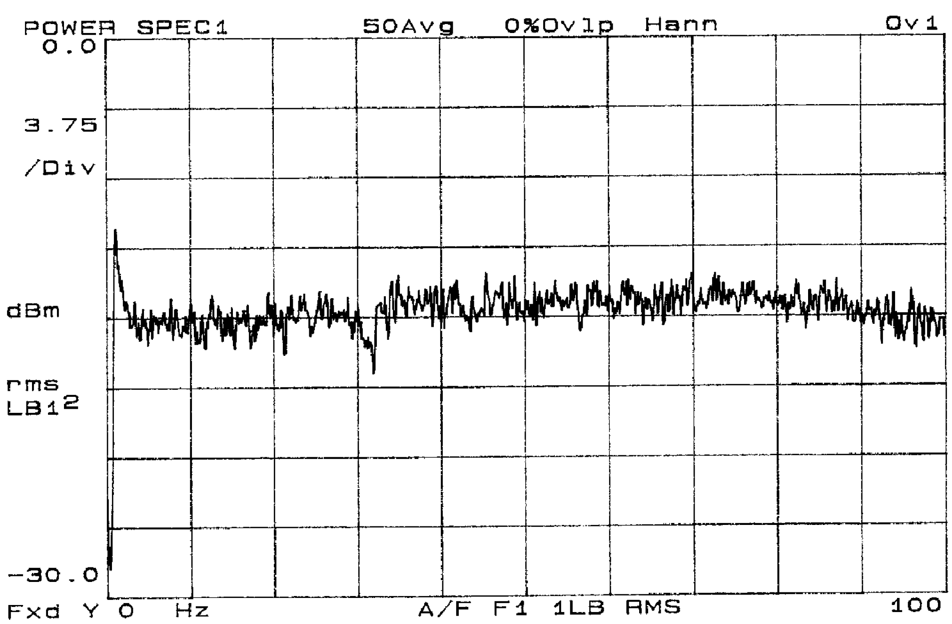
Test 7

Input power Spectrum
1 lb. rms random input
0-400 Hz



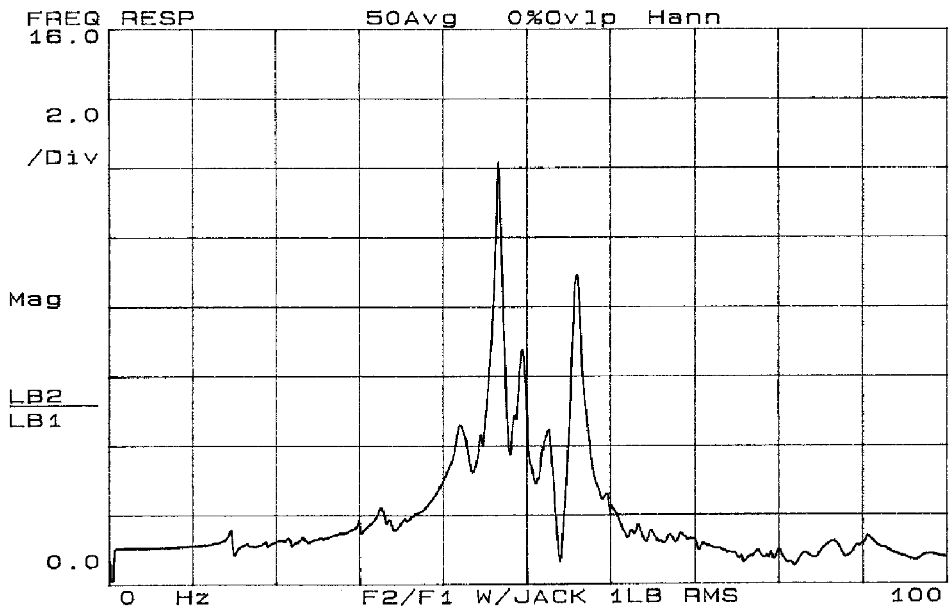
Test 8

Drive point accel./ input force FRF
1 lbs. rms random input
0-100 Hz



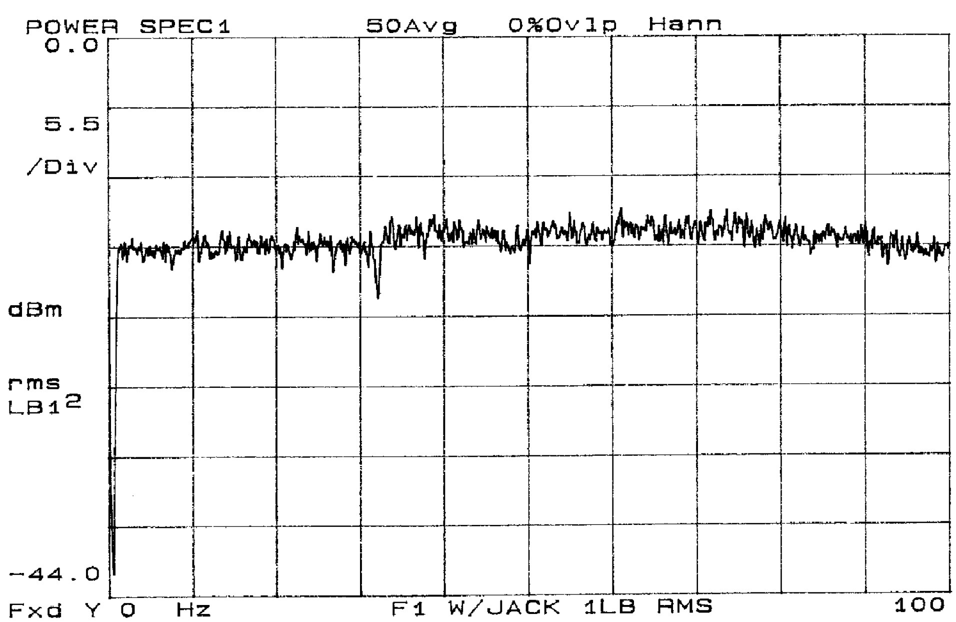
Test 8

Input power Spectrum
1 lb. rms random input
0-100 Hz



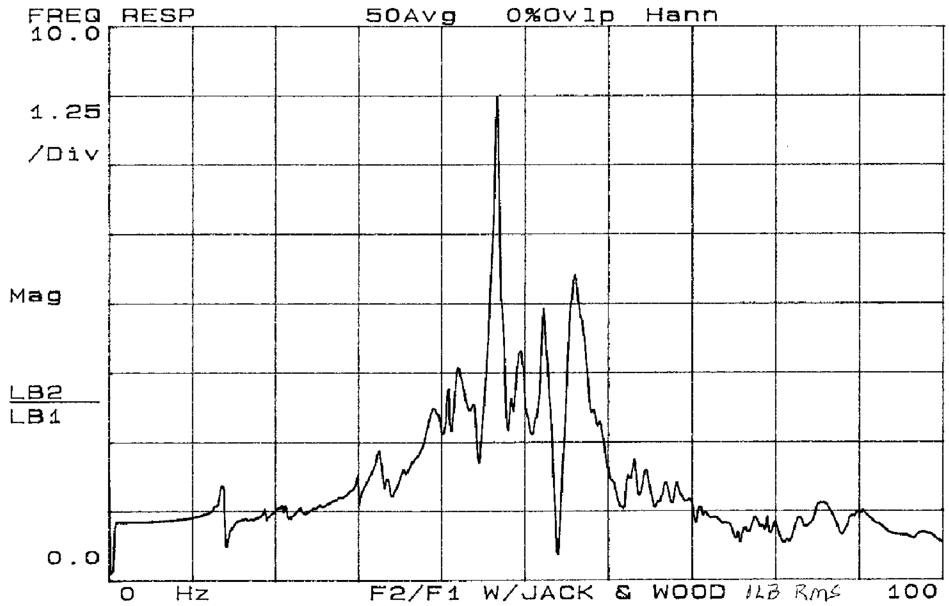
Test 9

Force output/force input FRF
with jack
1 lb. rms random input
0-100 Hz



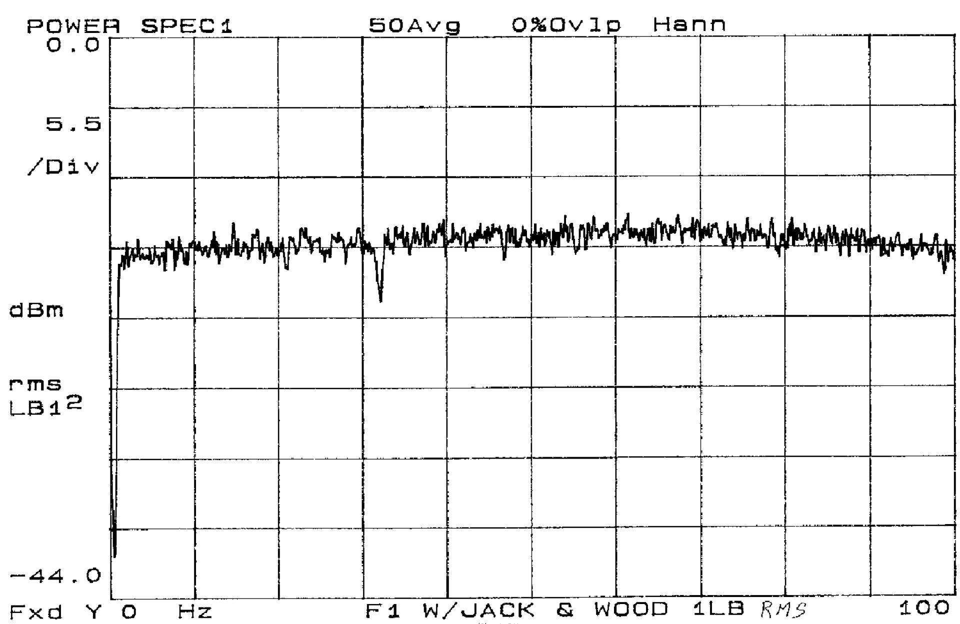
Test 9

Input power Spectrum
with jack
1 lb. rms random input
0-100 Hz



Test 10

Force output/force input FRF
with jack and wood
1 lb. rms random input
0-100 Hz



Test 10

Input power Spectrum
with jack and wood
1 lb. rms random input
0-100 Hz

APPENDIX F—SUMMARY OF TEST RUNS

Test	Date	OBJECTIVE:		COMMENTS:
P2073-01		Ignition Check	1.2 seconds	Ignited.
P2073-02		Ignition Check	1.2 seconds	Lower Purge Pressure. Ignited
P2073-03	07-Jul-00	Verify ignition to mainstage.	1.2 seconds of Mainstage	Ignition was achieved, but the transition to mainstage failed. Low Pc Cut.
P2073-04	11-Jul-00	Verify ignition to mainstage.	1.2 seconds of Mainstage	Ignition was achieved, but the transition to mainstage failed. Revert to #3 sequence and eliminate GOX purges. Keep go to main after 1.2 sec.
P2073-05	July 11, 2000	Verify ignition to mainstage.	1.3 seconds of Mainstage	Ignition was achieved and the transition to mainstage did occur. Test was cut in mainstage due to Pc low. Need work on what adjustments can be made to assure continued combustion into mainstage.
P2073-06	14-Jul-00	Verify ignition to mainstage	1.3 seconds of Mainstage	No Ignition. Check the ignitor wire & repeat
P2073-07	14-Jul-00	Verify ignition to mainstage	1.3 seconds of Mainstage	Adjustments to the spark wire were implemented. Ignition was not achieved, but the transition to mainstage did occur and was cut in mainstage because of Pc low just as test 006.
P2073-08	18-Jul-00	Verify ignition to mainstage	1.4 seconds of Mainstage	Adjusted the sequence of purges and bypass valve closure times. Ignition was not achieved, but the transition to mainstage did occur. Test duration was 1.4 seconds total. Changed the spark command at t0.
P2073-09	18-Jul-00	Verify ignition to mainstage.	1.4 seconds of Mainstage	Adjusted the sequence of purges & spark timing. Achieve ignition. Failed transition to main stage due to Pc low. Test durations were 1.4 seconds. Further changes will be made to purge pressures and spark verification to achieve ignition.
P2073-10	18-Jul-00			Repeat of P2073-09
P2073-11	21-Jul-00	Verify ignition to mainstage.	1.4 seconds of Mainstage	Adjusted the sequence of purges, spark timing, and bypass stage duration. Ignition and mainstage were achieved and the tests cut at duration. The next test is scheduled for the objective of switching from fuel tank A to fuel tank B, both with RP-1.
P2073-12	21-Jul-00	Verify ignition to mainstage.	2.4 seconds of Mainstage	Repeat of P2073-11
P2073-13	24-Jul-00	Verify ignition to mainstage.	2.4 secs of Mainstage	The GOX set pressure was lowered to adjust the mixture ratio. No ignition occurred and mainstage was not achieved. The test was cut due to a low GOX orifice pressure. Test duration was 0.4 seconds.
P2073-14	02-Aug-00	Verify transition from Tank A to Tank B.	2.4 secs of Tank A & 2.8 secs of Tank B	Verified a transition from RP-1 tank to AF tank (RP-1). Transition was successful. Total duration was, as desired, 10.2 seconds.
P2073-15	03-Aug-00	Verify transition from Tank A to Tank B.	6.4 secs of RP-1 & 7.8 secs of RP-1	Repeat of test 14 and the transition from RP 1tank to AF tank (RP-1) with longer duration. Test was successful. Total duration was, as desired, 19.2 seconds. The next test will be a checkout for post pentane flush of Advanced Fuel tank anomalies.
P2073-16	08-Aug-00	Verify transition from Tank A to Tank B.	6.4 secs of Tank A & 7.8 secs of Tank B	Verified a transition from RP-1 tank to AF tank (RP-1) and fuel flow rates at a new tank A set pressure. Both fuel tanks contained RP-1 for today's test. Transition was successful Total duration was, as desired, 19.2 seconds.
P2073-17	29-Aug-00	Advanced Fuel Test; Quadricyclane	6.4 secs of RP-1 & 7.8 secs of **Quadricyclane**	**Successful Quadricyclane Run**

P2073-18	29-Aug-00	Advanced Fuel Test; Quadricyclane	6.4 secs of RP-1 & 7.8 secs of **Quadricyclane**	**Successful Quadricyclane Run**
P2073-19	30-Aug-00	Advanced Fuel Test; Quadricyclane	6.4 secs of RP-1 & 7.8 secs of Quadricyclane	Adjusted MR to target value. Both the RP-1 and quadricyclane tank pressures were lowered. The test cut at 11.7 seconds as the transition from RP-1 to quadricyclane was taking place. Lo advanced fuel venturi inlet pressure terminated the test.
P2073-20	31-Aug-00	Advanced Fuel Test; Quadricyclane – Optimize MR	6.4 secs RP-1 & 7.8 secs of **Quadricyclane**	Repeat of test 19 with an adjusted adv fuel low pressure cut value. Terminated due to adv fuel pressure low. Duration was 15.5 seconds. **Sufficient data was obtained to declare the test successful regardless of the cut.**
P2073-21	11-Sep-00	Verify rig performance after first adv fuel.	6.4 secs of RP-1 & 7.8 secs of RP-1	Verified rig performance after the first advanced fuel and to repeat the last test prior to the first advanced fuel tests. Both fuel tanks contained RP-1 for today's test. Rig performance appeared nominal.
P2073-22	13-Sep-00		6.4 secs of RP-1 & 7.8 secs of **1,7 Octadiyne**	**Successful 1,7 Octadiyne Run**
P2073-23	13-Sep-00		6.4 secs of RP-1 & 7.8 secs of **1,7 Octadiyne**	**Successful 1,7 Octadiyne Run**
P2073-24	15-Sep-00		6.4 secs of RP-1 & 7.8 secs of **AFRL-1**	**Successful AFRL-1 Run**
P2073-25	15-Sep-00		6.4 secs of RP-1 & 7.8 secs of **AFRL-1**	**Successful AFRL-1 Run**
P2073-26	20-Sep-00		6.4 secs of RP-1 & 5.8 secs of BCP	During the transition to advanced fuel the test cut due to advanced fuel venturi inlet pressure low. Duration was 11.7 of scheduled 17.2 seconds. Troubleshooting of the advanced fuel system has begun and focuses on the fuel filter.
P2073-27	25-Sep-00	Check out after BCP	6.4 secs of RP-1 & 5.8 secs of RP-1	RP-1/Pentane Flush Before this run. AF Filter is changed System check out run was successful.
P2073-28	25-Sep-00	Adjust for Low MR 1.35	6.4 secs ofRP-1 & 5.8 secs of RP	Lowered GOX Pressure & Raised both RP-1 Tank Pressure. **No ignition**
P2073-29	25-Sep-00	Adjust for Low MR 1.35	6.4 secs of RP-1 & 5.8 secs of RP	Lowered RP-1 Tank Pressure to 350 psi. (MR=2.0). AF tank pressure remained at 640 psig. Low GOX inlet cut. Cut values are not adjusted.
P2073-30	26-Sep-00	Adjust for Low MR 1.35	6.4 secs of RP-1 & 5.8 secs of RP	Successful Run - MR 1.35 for AF tank and ~2.0 for RP-1 tank
P2073-31	26-Sep-00	Adjust for Low MR 1.35		Repeat of Test P2073-30
P2073-32	27-Sep-00	RP-1: MR=2, Azide: MR=1.35	6.4 secs ofRP-1 & 5.8 secs of **CINCH**	CINCH(Azide) Run MR for the azide was 1.35. Both tests were nominal with expected / actual durations of 17.2 seconds. Injecter plate Temp was high. ~1200.
P2073-33	27-Sep-00	RP-1: MR=2, Azide: MR=1.35		Repeat of Test P2073-32. Injector Plate temp was ~485F max.
P2073-34	11-Oct-00	RP-1: MR=2.1 Quadricyclane: MR=1.6	5.2 secs of RP-1	The test #34 was to run at a lower MR than #17-#20. AFT-34 run 5.2 seconds due to GOX system pressure low. The GOX pressure drop was caused by lower ambient temp. than previous tests.

P2073-35	11-Oct-00	RP-1: MR=2.1 Quadricyclane: MR=1.6	6.4 secs of RP-1 & 7.8 secs of **Quadricyclane**	The cut was disabled and test AFT-34 is repeated. Actual duration of #35 was 19.2 seconds.
P2073-36	13-Oct-00	RP-1: MR=2.1 & RP-1 (AF): MR=2.7	5.2 secs of RP-1	Run the test at MR=2.7 Test AFT-36 cut at 5.5 seconds due to high chamber pressure. Too much mass flow rate (MR=2.7 -> high Gox rate -> high RP-1 rate)
P2073-37	13-Oct-00	RP-1: MR=2.1 & RP-1 (AF): MR=2.7	6.4 secs of RP-1 & 7.8 secs of RP-1	For #37, the GOX pressures were lowered and RP-1 tank MR is set high. Full duration run.
P2073-38	20-Oct-00	RP-1: MR=2.0 & RP-1 (AF): MR=2.0	6.4 secs of RP-1 & 5.8 secs of BCP	For #38, the GOX pressures were lowered and RP-1 tank MR is set high. Full duration run.
P2073-39	20-Oct-00	RP-1: MR=2.0 & RP-1 (AF): MR=2.0	6.4 secs of RP-1 & 5.8 secs of RP-1	For #39, the GOX pressures were lowered and RP-1 tank MR is set high. Full duration run.

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13. ABSTRACT *(Maximum 200 words)*

This was a small-scale, hot-fire test series to make initial measurements of performance differences of five new liquid fuels relative to rocket propellant–1 (RP–1). The program was part of a high-energy-density materials development at Marshall Space Flight Center (MSFC), and the fuels tested were quadricyclane, 1-7 octodiyne, AFRL–1, biclopropylidene, and competitive impulse noncarcinogenic hypergol (CINCH) (di-methyl-aminoethyl-azide). All tests were conducted at MSFC. The first four fuels were provided by the U.S. Air Force Research Laboratory (AFRL), Edwards Air Force Base, CA. The U.S. Army, Redstone Arsenal, Huntsville, AL, provided the CINCH. The data recorded in all hot-fire tests were used to calculate specific impulse and characteristic exhaust velocity for each fuel, then compared to RP–1 at the same conditions. This was not an exhaustive study, comparing each fuel to RP–1 at an array of mixture ratios, nor did it include important fuel parameters, such as fuel handling or long-term storage. The test hardware was designed for liquid oxygen (lox)/RP–1, then modified for gaseous oxygen/RP–1 to avoid two-phase lox at very small flow rates. All fuels were tested using the same thruster/injector combination designed for RP–1. The results of this test will be used to determine which fuels will be tested in future test programs.

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