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Thruster Injector Faceplate Testing in Support of the Aerojet Rocket-Based Combined Cycle (RBCC) Concept

M.M. Fazah and J.M. Cramer
Marshall Space Flight Center, Marshall Space Flight Center, Alabama

May 1998

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Space Administration

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DEFINITION OF SYMBOLS

Symbol	Definition
A	Venturi flow meter throat area
A_t	Chamber throat section area
C_D	Venturi flow meter discharge coefficient
C^*	Characteristic velocity
GH_2	Gaseous hydrogen
GN_2	Gaseous nitrogen
GO_2	Gaseous oxygen
γ	Ratio of specific heat
g_c	Conversion constant
H_2O	Water
I_{sp}	Specific impulse
MR	Mixture ratio
$\dot{m}$	Mass flow rate
Pc	Chamber pressure
P1	Upstream pressure
ΔP	Delta pressure
R	Universal gas constant
T_1	Upstream temperature

TECHNICAL MEMORANDUM

THRUSTER INJECTOR FACEPLATE TESTING IN SUPPORT OF THE AEROJET ROCKET-BASED COMBINED CYCLE (RBCC) CONCEPT

I. INTRODUCTION

A. Background

The advanced reusable technology (ART) project has initiated several contracted activities with the goal of furthering the development of the rocket-based combine cycle (RBCC) system. This system will be the primary propulsion system for a space launch vehicle. The RBCC concept integrates small rocket thrusters into a conventional ramjet and scramjet engine flowpath. The RBCC engine can be operated in several modes. The first mode of operation is as an ejector. In this mode, the rockets provide the primary thrust of the engine. As the vehicle accelerates, air, i.e., secondary flow, is drawn into the engine inlet due to an ejector effect and the rocket thrust is augmented by the additional air mass flow entrained and accelerated in the rocket exhaust. When the vehicle accelerates to approximately Mach 2.5–3.0, the rockets are turned off and the engine mode switches from ejector to ramjet. A large jump in engine specific impulse (I_{sp}) is obtained by operating in ramjet mode. As the vehicle accelerates through Mach 5.0, at some point the engine will be switched to scramjet operation. The engine will continue to operate in the scramjet mode until either the scramjet I_{sp} approaches that of a pure rocket, or the velocity approaches a point where active or passive cooling of the vehicle and engine cannot overcome the vehicle aerodynamic heating. At this point the engine is operated in an all-rocket mode with the engine inlet closed and the rockets ignited for orbit insertion.

Many studies[1] have shown that the performance of the rockets have a large impact on the performance of the entire RBCC system. The rockets must produce enough thrust to accelerate the vehicle to ramjet takeover conditions as quickly as possible to take advantage of the increased ramjet I_{sp}. The challenge to the thruster injector design presented in the RBCC system is that any unburned hydrogen remaining in the plume, typically exhausted to the atmosphere in a conventional rocket, is now contained in a duct and available to burn with the secondary air flow. This has the potential of causing the flow to thermally choke prematurely. In addition, the weight of the thruster is an important parameter since many thrusters are typically used in an RBCC engine. Therefore, a short as possible thrust chamber is desired in order to minimize the weight. The thruster injector must be highly efficient to minimize the free hydrogen and provide complete combustion within the shortest possible chamber length.

The GenCorp Aerojet Corporation was awarded one of the ART contracts to design, fabricate, and test an RBCC engine concept. As part of the engine, Aerojet has designed a rocket thruster that will be integrated into a ramjet/scramjet flowpath.

B. Need

In order to satisfy the rocket thruster requirement of high performance and to minimize the amount of free hydrogen at the plume boundary, Aerojet has designed a new impinging injector element which uses gaseous hydrogen (GH_2) and gaseous oxygen (GO_2) as the propellants. In addition, the design operating point necessary to meet these two requirements is a high nominal chamber pressure (Pc), 2,000 psia, and a high nominal mixture ratio (MR), 7.0. Analysis has shown that this injector design has the potential to minimize the amount of free hydrogen that is available to be burned with the incoming secondary flow. Studies and test programs[2] that were performed in the past have shown that gas/gas-impinging elements typically result in high injector face temperatures, due to combustion occurring close to the face. In addition, there was a concern that the high Pc and MR would compound the face heating issue. Since the Aerojet design is new, there is no hot fire experience with this element.

C. Objective

The objective of this test program was to qualitatively assess the condition and erosion characteristics of the injector faceplate and element design. In addition, it was desired to test at conditions representative of the actual rocket operating conditions: chamber pressure of 2,000 psia and a mixture ratio of 7.0, for the ejector mode and a chamber pressure of 1,000 psia and a mixture ratio of 5.0 for the rocket only mode. Two hot fire test programs were initiated, one at the Aerojet facilities in Sacramento, CA and the second at the Marshall Space Flight Center (MSFC) in Huntsville, AL. The test program conducted at Aerojet was chamber pressure and duration limited due to facility constraints. The MSFC test program allowed higher chamber pressures and durations to be tested. The MSFC test program is the focus of this report.

II. TEST ARTICLE

A. Injector Element Design

The design of the new injector element is shown in figure 1 below and is termed the "Pentad Plus." The element configuration has one core orifice in a "plus" shape and four circular impinging orifices that impinge upon the core stream at the inside corners of the plus shape. The dimensions of the element are 0.074 in. by 0.006 in. for the core orifice and 0.010 in. by 0.011 in. for the impinging orifices. The resulting flow area per element is approximately 0.00043 in.^{2} for the core orifice and 0.00034 in.^{2} for the impinging orifices. The injector face is constructed using platelets made from zirconium copper (ZrCu). The individual platelets, which can be as thin as 0.010 in., have fluid passages and openings chemically etched in simple or complicated patterns. These platelets are then stacked in a predetermined sequence to form the hydraulic passages and then diffusion-bonded together.[3]

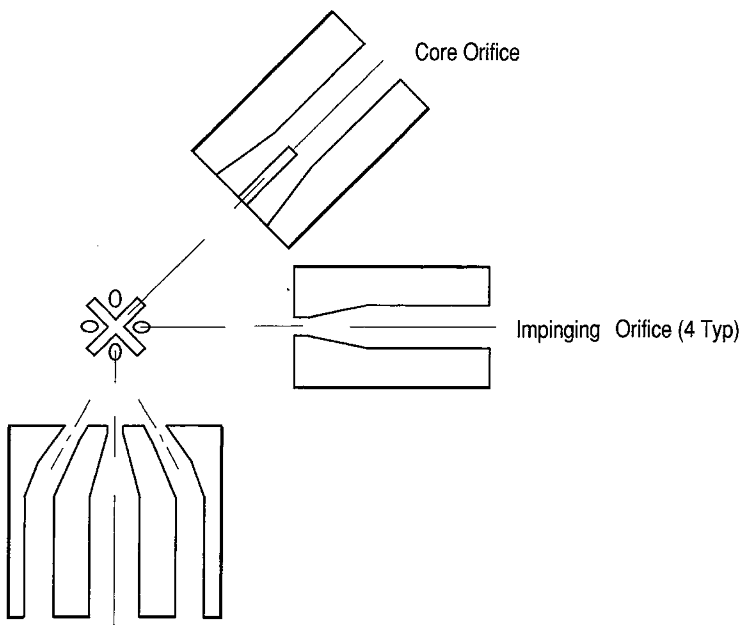


Figure 1. Injector element.

The element in figure 1 is shown looking from the inside of the faceplate toward the chamber. The core orifice starts in a circular shape and transitions to the plus shape close to the face itself. The impinging orifice starts as a wider diameter and is tapered to the final diameter at the face.

The injector faceplate has a diameter of 0.5 in. with a total of 18 individual elements contained within it. The injector design has 2 rings of elements, 12 elements in the outer ring and 6 in the inner ring. Figure 2 shows the layout of the Aerojet faceplate for the subscale rocket design.

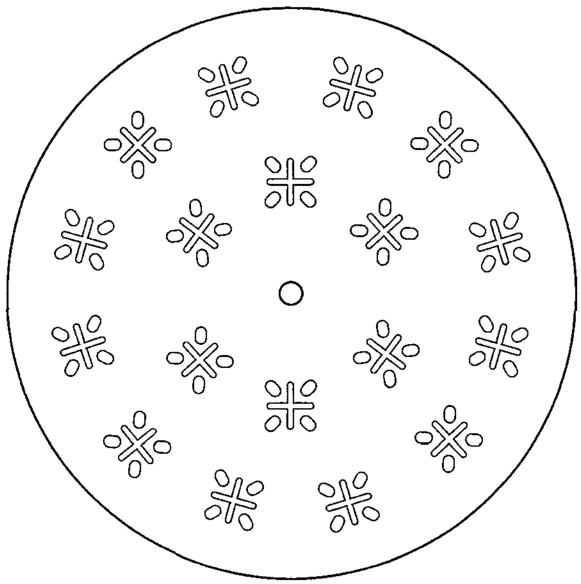


Figure 2. Injector faceplate layout.

B. Nominal Operating Conditions

The design conditions for the Aerojet subscale rocket thruster are given in table 1 below. The conditions are given for both the ejector mode and the all-rocket mode of operation.

Table 1. Design conditions.

Pressure	Ejector Mode	All-Rocket Mode
Chamber Pressure (psia)	2,000.0	1,000.0
Mixture Ratio (-)	7.0	5.0
Flow Rates (lbm/sec)		
- GH_2	0.042	0.027
- GO_2	0.296	0.135
- H_2O (Film Coolant)	0.123	0.060
Injector ΔP (psid)		
- GH_2	230.0	115.0
- GO_2	430.0	215.0

C. Test Article Design and Description

The injector test article is shown in figure 3. The overall height of the test article is 2.25 in. and the maximum diameter is 1.20 in. The top end of the test article is tapered at a 20-degree angle to a diameter of 0.85 in. The 18-element faceplate is centered within the 0.85-in. diameter. The test article is threaded onto a manifold in the test chamber which allows propellants to be fed from the test facility, through the injector module, to the injector face.

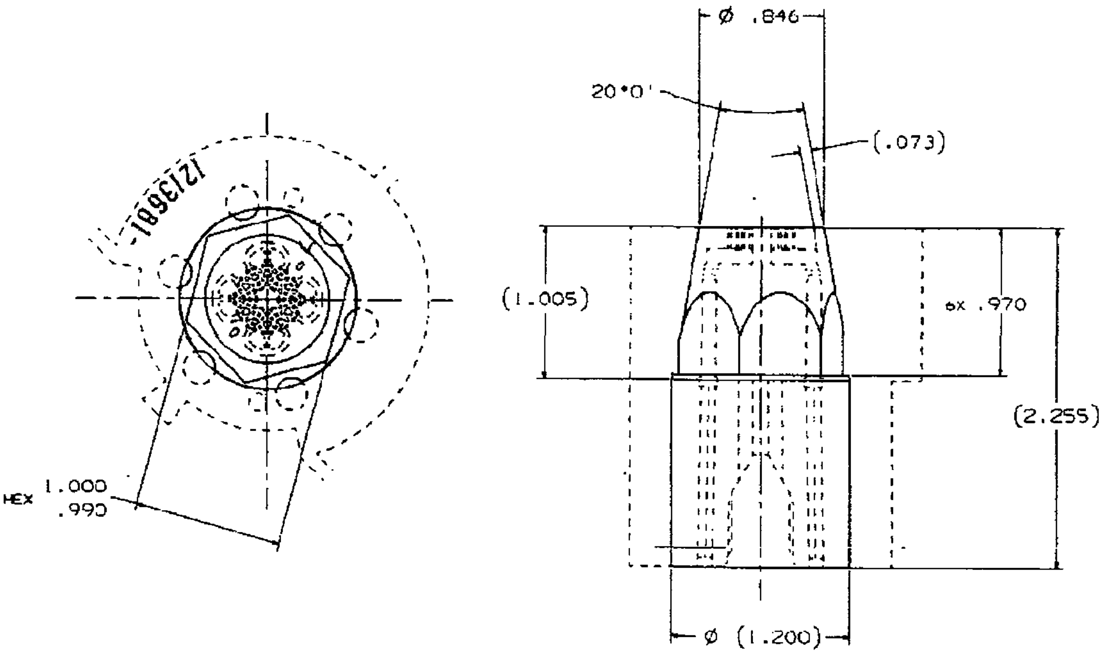


Figure 3. Injector test article.

III. TEST FACILITY

A. Test Facility Description

The injector faceplate testing was conducted at Test Stand 115 in MSFC's east test area. The test facility resources included a digital control system, analog and digital data acquisition systems, and cameras for recording 35 mm, video, and high-speed film.[4] Figure 4 shows a simplified schematic of the test configuration.

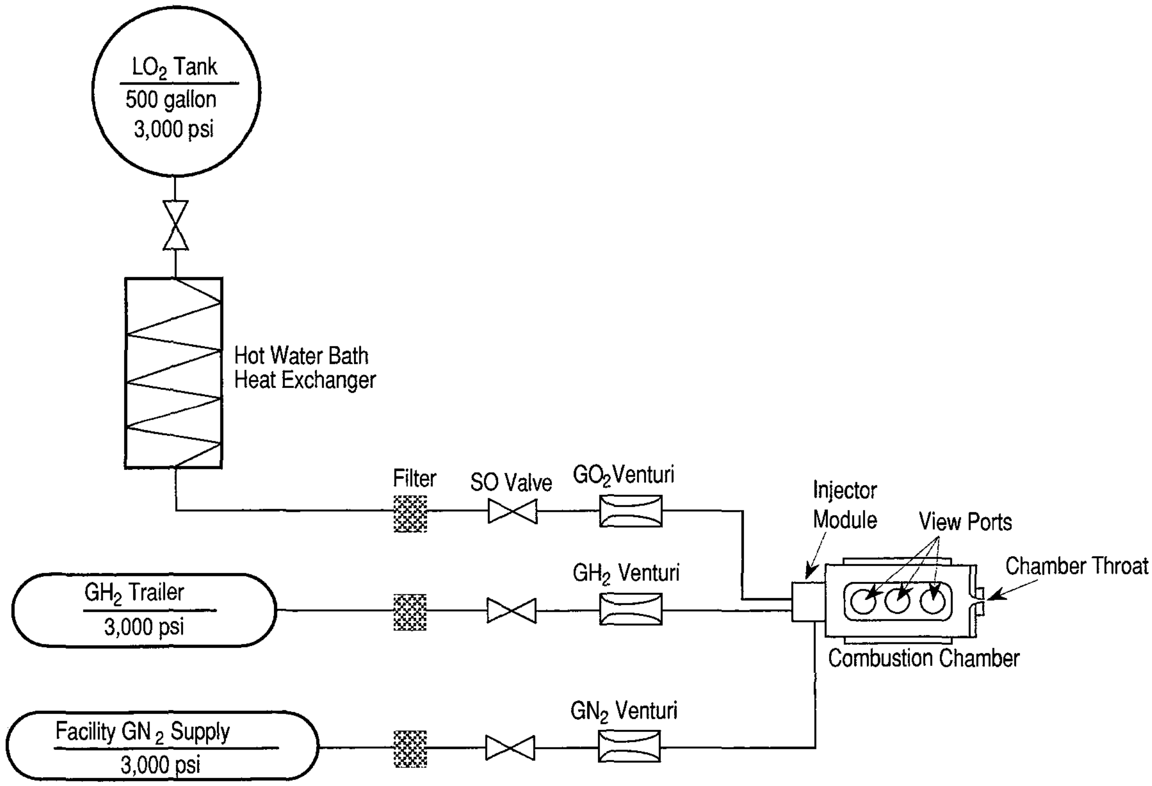


Figure 4. Simplified facility schematic.

As shown in figure 4, there are three main gaseous systems: GO_2, GH_2, and gaseous nitrogen (GN_2). The GO_2 can be supplied in two ways: (1) from a GO_2 trailer with pressure and flow rate controlled by a regulator and venturi or (2) from a liquid oxygen (LO_2) storage tank through a hot water bath heat exchanger to produce GO_2 at or near ambient temperature. The first method is limited by the maximum pressure that can be supplied from a trailer, which is approximately 2,400 psig. For this reason, the second method was used for this test program. The GN_2 is supplied through high-pressure gaseous hydrogen bottles and regulated to the correct pressure. The GN_2 supply is regulated down from a 3,000 psig facility supply line. The GN_2 and GO_2 are supplied to the injector, which is located at one end of the test chamber and to a spark igniter located on the side of the chamber. The GN_2 is used as purge flow before and after a test. GN_2 is also used during a test to establish an annular flow through the chamber, which acts as a thermal barrier and provides a significant portion of the required chamber pressure.

B. Test Chamber Description

The combustion chamber that was used is currently on loan from Aerojet. Figure 5 shows the exterior of the chamber. The combustion chamber has an inner diameter of 3.42 in. and is approximately 6 in. long. Three sets of windows, 1.12 in. in diameter, provide optical access to the combustion chamber at axial distances of 0.50, 2.25, and 4 in. from the injector face. At each axial location, the windows are at four circumferential positions: 0, 150, 180, and 270 degrees.

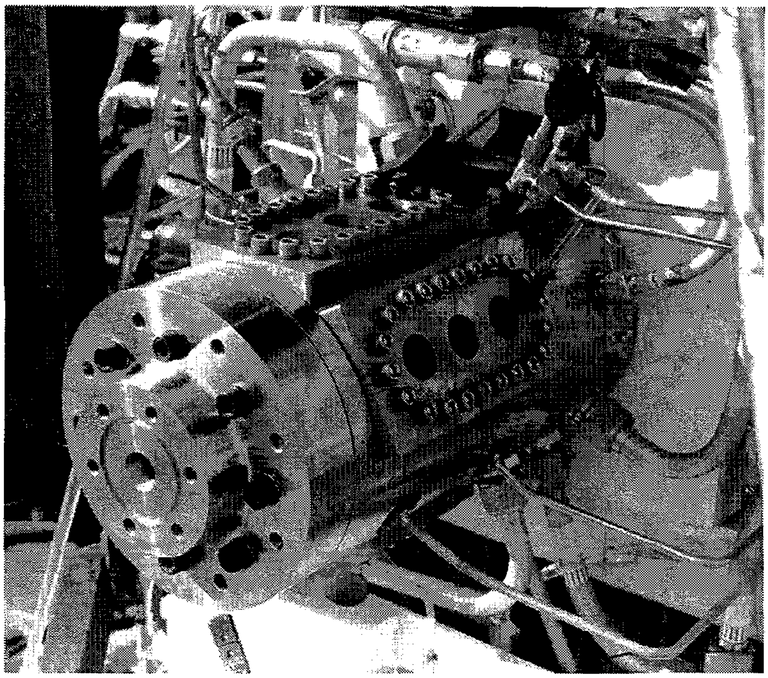


Figure 5. Test chamber.

The chamber is designed to operate at a maximum pressure of 2,000 psia. The entire combustor, including the replaceable throat section, is cooled solely by film cooling from the barrier flow.

The combustion chamber design consists of two separate injectors and a film coolant circuit along the chamber wall. The core injector module is located along the centerline of the chamber and is 1.2 in. in diameter, and designed to accommodate an approximately 0.50-in injector test article. An annular injector is recessed 1 in. from the face of the core module. GN_2 was flowed through this annular injector in this test program. The outer flow circuit, or barrier flow, of the injector allows independent injection of a film coolant. The barrier flow is primarily used to protect the view ports located on the periphery of the chamber and as a film coolant for the throat. This barrier flow was changed from GN_2 to GH_2, after Test No. 13, to provide greater film coolant capacity at the throat for the high Pc tests.

IV. TEST RESULTS

A. Test Matrix and Results

As shown in table 1, the rocket thruster was designed to operate at a maximum Pc of 2,000 psia. A Pc of 2,000 psia is calculated when the GH_2, GO_2, and H_2O flows are present in the chamber. This test program was performed without any water film coolant flow, therefore, the maximum Pc without water was expected to be approximately 1,700 psia. In order to assess the durability of the injector face at the maximum Pc, a series of tests was performed to identify the maximum conditions that could be tested. A series of ignition tests was performed and then the Pc and equivalent injector flow rates were increased until the maximum obtainable conditions were reached. The maximum obtainable conditions were estimated to be approximately 1,600 to 1,700 psia. Table 2 shows the planned test conditions for the 22 total tests that were run.

Table 2. Planned test conditions.

	Test No.	Test Date	Planned Pc (psia)	Planned MR (-)	Planned Duration (sec)
1	P3739701.115	4/1/97	-	-	Ignition Test
2	P3739702.115	4/2/97	-	-	Ignition Test
3	P3739703.115	4/2/97	-	-	Ignition Test
4	P3739704.115	4/3/97	-	-	Ignition Test
5	P3739705.115	4/3/97	-	-	Ignition Test
6	P3739706.115	4/3/97	-	-	Ignition Test
7	P3739707.115	5/8/97	-	-	Ignition Test
8	P3739708.115	5/9/97	500	5.0	6.5
9	P3739709.115	5/9/97	500	7.0	8.5
10	P3739710.115	5/22/97	1,000	7.0	6.5
11	P3739711.115	6/17/97	1,000	7.0	Ignition Test
12	P3739712.115	6/18/97	1,000	7.0	Ignition Test
13	P3739713.115	6/18/97	1,000	7.0	5.5
14	P3739714.115	6/24/97	1,000	7.0	Ignition Test
15	P3739715.115	6/24/97	1,000	7.0	4.5
16	P3739716.115	6/25/97	1,000	7.0	5.5
17	P3739717.115	6/25/97	1,000	5.0	5.5
18	P3739718.115	6/25/97	1,000	5.0	8.5
19	P3739719.115	6/26/97	1,600	7.0	Ignition Test
20	P3739720.115	6/25/97	1,600	7.0	4.5
21	P3739721.115	7/9/97	1,600	7.0	Ignition Test
22	P3739722.115	7/9/97	1,600	7.0	5.5

The test number is a unique identifier that is used to store the digital data files at MSFC and can be used to access data related to each test series. Table 2 also shows the planned Pc, MR, and test duration. The tests denoted by the term “Ignition Test” were approximately 3.5 sec in duration. These tests were terminated just prior to reaching mainstage after the final ignition check was made.

Table 3 below shows the predicted value of Pc and injector propellant ΔP, as compared to the test data for all tests that reached mainstage. The injector ΔP is defined as the difference between the manifold pressure just upstream of the test article and Pc. The ignition tests are not shown due to their transient nature.

Table 3. Predicted Pc and ΔP versus actual.

Test	Predicted Pc (psia)	Actual Pc (psia)	Percent Difference (%)	Predicted ΔP GO_2/GH_2 (psid)	Actual ΔP GO_2/GH_2 (psid)	Percent Difference GO_2/GH_2 (%)
-						
8	810.6	813.6	–0.4	103/77	91/77	11.7/0.0
9	840.4	812.7	3.3	100/40	98/45	2.0/–12.5
10	1,218.0	1,215.8	0.2	266/113	254/104	4.5/8.0
-						
13	1,081.3	1,061.4	1.8	287/125	294/116	–2.4/7.2
-						
15	983.2	949.6	3.4	311/135	320/134	–2.9/0.7
16	1,018.6	1,017.2	0.1	297/132	302/128	–1.7/3.0
17	1,001.1	1,000.1	0.1	257/206	261/203	–1.6/3.5
18	997.6	993.8	0.4	258/205	262/203	–1.6/1.0
-						
21	1,638.6	1,685.3	–2.8	663/308	761/317	–14.8/–2.9
22	1,786.4	1,649.0	7.7	639/292	729/312	–14.1/–6.8

The prediction for Pc was calculated using equation (1):

$$Pc = \frac{C^{*}\dot{m}}{A_t} \quad (1)$$

In equation (1) C^{*} is calculated based on the injector MR and the percentage of nitrogen flow, $\dot{m}$ is the total mass flow rate (core plus annular and barrier flow) into the test chamber, and A_t is the test chamber throat area. This calculation assumes that the flows, injector hot gases, and nitrogen are perfectly mixed.

The prediction for the injector ΔP is obtained once the propellant mass flow rate, specific gravity, and injector flow coefficients are known. The propellant mass flow rate is determined using a sonic venturi flowmeter, and the injector flow coefficients were determined through a series of blowdown tests. Appendix A shows the specific calculations for each hot fire test. Along with calculations for the Pc and injector circuit ΔP, the flow sheets show the venturi data for each leg, core element flow, and nitrogen annular and barrier flow, among other data.

As shown in table 3, both the predicted and actual injector ΔP for GH_2 and GO_2 circuits are higher than the nominal operating conditions shown in table 1. This difference in injector ΔP was due to the unique method used to integrate the test article and the facility in this test program. The integrated strut rocket test article that will be tested at GASL is designed to minimize the pressure drop between the facility interface and the injector, and should result in a lower injector ΔP. The values of ΔP shown in table 1 will be verified during cold flow testing at Aerojet and, eventually, hot fire testing at GASL.

Table 4 below shows an expanded data set that contains averaged data just prior to shutdown.

Table 4. Averaged test data at shutdown.

Test	Pc (psia)	GO_2 ΔP (psid)	GH_2 ΔP (psid)	GO_2 Inlet Temp (R)	GH_2 Inlet Temp (R)	GO_2 Flowrate (lbm/sec)	GH_2 Flowrate (lbm/sec)	MR (-)	Mainstage Duration (sec)	Total Duration (sec)
8	813.6	91	77	529.0	526.2	0.0730	0.0144	5.07	1.86	5.31
9	812.7	98	45	547.8	540.5	0.0723	0.0102	7.09	5.02	8.51
10	1,215.8	254	104	544.4	547.3	0.1502	0.0209	7.19	2.94	5.89
-										
13	1,061.4	294	116	543.2	543.9	0.1492	0.0211	7.07	2.01	5.59
-										
15	949.6	320	134	566.6	562.9	0.1483	0.0206	7.20	1.00	4.50
16	1,017.2	302	128	552.1	549.6	0.1472	0.0210	7.01	1.99	5.35
17	1,000.1	261	203	557.3	559.7	0.1342	0.0266	5.05	1.97	5.38
18	993.8	262	203	555.8	559.9	0.1345	0.0265	5.08	5.00	8.40
-										
21	1,685.3	768	316	550.4	552.2	0.02964	0.0416	7.13	0.99	4.51
22	1,822.2	722	296	551.2	555.2	0.3039	0.0419	7.25	1.30	4.80

In appendix B the instantaneous trace of Pc, injector ΔP, and MR for each mainstage test are shown. As described in the test facility section, the throat section of the test chamber is stainless steel and is cooled only by the nitrogen film cooling from the barrier flow. The throat is approximately 6 in. from the injector face. It was noticed early in the test program that the throat diameter was decreasing during the tests. This continual decrease of the throat diameter caused the Pc to rise throughout the test as indicated by the plots of Pc shown in appendix B. High-speed video and still photographs taken during the tests showed that overheating of the throat was occurring. This was most prominent during Test No. 13 where the throat section was significantly damaged.

The initial concern was that the injector itself was eroding during test and depositing on the throat. After several tests, material analysis of the throat showed that the decrease in throat diameter was due to a depositing of stainless steel onto the throat, not the zirconium copper from the injector face. The exact source of the stainless steel that was being deposited is unclear but is most likely material from the stainless steel chamber. In order to limit the heating of the chamber walls and throat region after Test No. 13, the barrier flow was changed from GN_2 to GH_2 to provide a greater cooling capability.

As shown in the data plots, the Pc, and subsequently, the injector ΔP did not reach a steady-state condition on any test due to throat area variations. The propellant mass flow rates, which were measured using sonic venturi flow meters, reached steady state during main stage of the tests. Equation (2) was used to calculate the flow rate to the injectors:

$$\dot{m} = C_D A P_1 \sqrt{\frac{g_c \gamma}{R T_1} \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{\gamma-1}}} \quad . \tag{2}$$

In equation (2) the discharge coefficient, C_D, was assumed to be 0.98, and the ratio of specific heats, γ, and the gas constant, R, were constant for all tests. The individual flow calculation work sheets shown in appendix A give the values of all parameters used in calculating the mass flow rates. The MR of the injector was calculated by dividing the calculated value of the GO_2 flow rate by GH_2 flow rate. As shown in appendix B, the MR did reach steady state during the tests, although a small oscillation persisted throughout mainstage. This variation in MR was due to small variations in the venturi upstream temperature and pressure. Table 4 shows the relevant data for each mainstage test averaged over approximately 0.2 to 0.5 sec at a representative point in the test.

B. Scanning Electron Microscopy (SEM) Imaging Observations

In order to assess the condition of the injector faceplate after hot fire testing, visual examination was used extensively. Examination was conducted with the unaided eye after each hot-fire test to get a gross indication of the injector condition. In addition, after the 500 and 1,600 psia Pc test series, scanning electron microscopy (SEM) was performed on the injector faceplate by the MSFC Materials Laboratory. The complete set of images is shown in appendix C.

As shown in the SEM images in appendix C, the individual injector elements sustained little damage due to the hot fire testing. The images taken after Test No. 9 show slight oxidation around the element itself and minor erosion around some of the impinging orifices. No burning of the faceplate was observed. The images taken at the end of the program (after Test No. 22) show many of the same results as the previous images. Further oxidation of the faceplate was evident and no further erosion was observed in any of the injector elements.

Contamination was observed in the impinging orifices of some of the elements as shown in appendix C, figures 18, 20, and 22 through 27. The contamination appeared to be in the shape of a flake. The size of the flakes was on the order of the impinging orifice diameter, 0.01 in., or larger. Based on observation, the flakes seem to have originated from inside of the injector, and they became trapped by the decreasing diameter of the impinging orifices.

To determine the source of the contamination, a material analysis of the flakes was performed. The MSFC Materials Laboratory was able to focus the SEM on a contamination flake and determine the chemical composition based on the characteristics of the reflected signal. This chemical analysis revealed that the contamination flakes were stainless steel and not zirconium copper from the face. Examination of the stainless steel test article base did not reveal any obvious erosion but a small unknown amount of material could have been lost and may not be visually detectable. In addition, the facility GO_2 system is comprised mainly of stainless steel. Since the origin of the contamination does not seem to be from the faceplate, this is not a concern for the planned follow-on ART test programs.

V. CONCLUSIONS

The objective of this test program was to qualitatively assess the condition and erosion characteristics of the injector faceplate and element design at or near the design conditions of the thruster. The results of this test program show that the injector faceplate can be successfully operated at a chamber pressure of 1,822 psia and a mixture ratio of 7.25.

A primary concern with the operation of gaseous impinging injector element design is that the resultant combustion in the chamber tends to occur near the injector face. The close proximity of the combustion zone to the injector face generally leads to excessive faceplate heating, resulting in erosion and eventual failure. Active cooling of the injector face is often used to cool the face material. The injector element and faceplate designs discussed in this report do not use any active cooling techniques, but instead use the propellent flowing through the manifold to cool the faceplate. Posttest SEM images shown in appendix C and discussed in section IV confirm only slight faceplate erosion during the testing. These results indicate that the faceplate temperature remained below the melting point of the ZrCu faceplate. Some oxidation was observed on the face and minor erosion can be seen around the oxygen orifices.

In a report by S. Kim,[5] a computational fluid dynamic (CFD) and thermal analysis of this element and faceplate design was performed and validated with test data obtained during a separate test activity. This report shows that the faceplate temperature tends to decrease with increased Pc and MR. This trend may be attributed to the increasing oxygen flow rate through the injector manifold with increasing Pc and MR.

In summary, the injector faceplate was successfully tested 22 times with little or no erosion evident. The maximum chamber pressure and mixture ratio achieved was 1,822 psia and 7.25, respectively. Based on these results, the stated objectives were achieved.

APPENDIX A—FLOW CALCULATION WORKSHEETS

Flow calculation worksheets are shown for Test Nos. 8–10, 13, 15–18, 21, and 22 in tables 5–14.

Table 5. Test No. 8—Flow calculations worksheet.

TEST #	RBCC-08
Pre/Post	Post
Date	5/9/97
Time Slice	5.2 - 5.3

CONSTANTS

Ru=	1544	ft-lbf/lbmol- °R
K1=	222.973	ft/sec
K2=	0.669	
Throat Dia =	0.300	inch
Throat Area=	0.071	sq in

GAS CONSTANTS

Gas	Gamma	Mol. Wt.	f1(gamma)	f2(gamma)
GOX	1.60	32.000	4.333	0.716
GN2	1.45	28.016	5.444	0.693
GH2	1.40	2.018	6.000	0.685

Nom. Ox flow =	0.2960	lb/s
Nom. Fuel flow =	0.0423	lb/s

Core Element

Flow	Venturi #	New?	Vent. Dia. (in)	Vent. Cd	Cd*A (sq in)	Pup (psig)	Tup (°F)	P inlet, max (psia)	Kw	S.G.	P inlet, est. (psia)	Inj. DP	mdot (lb/s)	C* (ft/s)
Main Ox (GOX)	MFL3-B		0.049	*0.9800*	1.848E-03	**1535**	**68**	1240	0.025	0.0828	914	103	0.07295	1264.2
						(P7301)	(T7313)		Factor =	1.7146		13%	24.6%	
									P guess =	914				
									Difference =	*0.0000*				
Main Fuel (GH2)	MO1-B		0.041	*0.9800*	1.294E-03	**1799**	**66**	1451	0.023	0.00509	887	77	0.01437	5257.3
						(P7303)	(T7314)		Factor =	1.6655		9%	34.0%	
									P guess =	887				
									Difference =	*0.0000*				

COMBUSTION CHARACTERISTICS

MR=	5.08	
mdot, tot	0.0873	lb/s
Theo. C*	8077.4	ft/s
Burned Press	309.9	psia
Unburned Press	73.7	psia

Annular Injector

Flow	Venturi #	Vent. Dia. (in)	Vent. Cd	Cd*A (sq in)	Pup (psig)	Tup (°F)	P inlet, max (psia)	Kw	S.G.	P inlet, est. (psia)	C* (ft/s)	mdot (lb/s)	Press. (psia)
Ann. Ox (GN2)	AO1-B	0.044	*0.9800*	1.490E-03	**1116**	**68**	905	0.208	0.0423	811	1396.7	0.039	23.8
					(P7305)	(T7312)							
Ann. Fuel (GN2)	AO3-B	0.089	*0.9800*	6.097E-03	**1101**	**66**	893	0.420	0.0424	814	1394.1	0.157	96.2
					(P7322)	(T7316)							
Barrier (GN2)	MO3-B	0.081	*0.9800*	5.050E-03	**1425**	**65**	1152	2.0	0.0425	811	1392.7	0.168	102.9
					(P7307)	(T7315)							

Annular mdot	0.364	lb/s

Stratified Flow Calcs

Total mdot	0.451	lb/s
Predicted Pressure	532.8	psia
Lower Pressure Limit	*296.6*	*psia*

ODE Calcs

Ox- % GOX =	16.69
Ox- % GN2 =	83.31
Modified MR =	*30.40*

Mixed Flow Calcs

Mixed C* =	4088	ft/sec
Total mdot =	0.451	lb/sec
Predicted Pc =	810.6	psia
Actual Pc =	813.6	psia

J. Cramer *22-Feb-97*

5-3099Test8

Table 6. Test No. 9—Flow calculations worksheet.

TEST #	RBCC-09
Pre/Post	Post
Date	5/9/97
Time Slice	8.4 - 8.5

CONSTANTS

Ru=	1544	ft-lbf/lbmol- °R
K1=	222.973	ft/sec
K2=	0.669	
Throat Dia =	0.283	inch
Throat Area=	0.063	sq in

GAS CONSTANTS

Gas	Gamma	Mol. Wt.	f1(gamma)	f2(gamma)
GOX	1.60	32.000	4.333	0.716
GN2	1.45	28.016	5.444	0.693
GH2	1.40	2.018	6.000	0.685

Nom. Ox flow =	0.2960	lb/s
Nom. Fuel flow =	0.0423	lb/s

Core Element

Flow	Venturi #	New?	Vent. Dia. (in)	Vent. Cd	Cd*A (sq in)	Pup (psig)	Tup (°F)	P inlet, max (psia)	Kw	S.G.	P inlet, est. (psia)	Inj. DP	mdot (lb/s)	C* (ft/s)
Main Ox (GOX)	MFL3-B		0.049	*0.9800*	1.848E-03	**1533**	**76**	1238	0.025	0.0839	940	100	0.07231	1273.7
						(P7301)	(T7313)					12%	24.4%	
Main Fuel (GH2)	MO1-B		0.041	*0.9800*	1.294E-03	**1294**	**85**	1047	0.023	0.00487	881	40	0.01019	5351.4
						(P7303)	(T7314)					5%	24.1%	

Main Ox (GOX):

Factor =	1.7740
P guess =	940
Difference =	*0.0006*

Main Fuel (GH2):

Factor =	1.6618
P guess =	881
Difference =	*0.0009*

COMBUSTION CHARACTERISTICS

MR=	7.10	
mdot, tot	0.0825	lb/s
Theo. C*	7483.8	ft/s
Burned Press	304.8	psia
Unburned Press	72.4	psia

Annular Injector

Flow	Venturi #	Vent. Dia. (in)	Vent. Cd	Cd*A (sq in)	Pup (psig)	Tup (°F)	P inlet, max (psia)	Kw	S.G.	P inlet, est. (psia)	C* (ft/s)	mdot (lb/s)	Press. (psia)
Ann. Ox (GN2)	AO1-B	0.044	*0.9800*	1.490E-03	**974**	**85**	791	0.208	0.0407	841	1419.0	0.033	23.4
					(P7305)	(T7312)							
Ann. Fuel (GN2)	AO3-B	0.089	*0.9800*	6.097E-03	**959**	**84**	779	0.420	0.0408	843	1417.7	0.135	94.4
					(P7322)	(T7316)							
Barrier (GN2)	MO3-B	0.081	*0.9800*	5.050E-03	**1322**	**82**	1069	2.0	0.0409	840	1415.1	0.154	107.3
					(P7307)	(T7315)							

Annular mdot	0.322	lb/s

Stratified Flow Calcs

Total mdot	0.404	lb/s
Predicted Pressure	529.9	psia
Lower Pressure Limit	297.5	psia

ODE Calcs

Ox- % GOX =	18.34
Ox- % GN2 =	81.66
Modified MR =	38.69

Mixed Flow Calcs

Mixed C* =	4209	ft/sec
Total mdot =	0.404	lb/sec
Predicted Pc =	840.4	psia
Actual Pc =	812.7	psia

J. Cramer *22-Feb-97*

5-30998Test9

Table 7. Test No. 10—Flow calculations worksheet.

TEST #	RBCC-10
Pre/Post	Post
Date	5/22/97
Time Slice	5.8 - 6.1

CONSTANTS

Ru=	1544	ft-lbf/lbmol- °R
K1=	222.973	ft/sec
K2=	0.669	
Throat Dia =	0.327	inch
Throat Area=	0.084	sq in

GAS CONSTANTS

Gas	Gamma	Mol. Wt.	f1(gamma)	f2(gamma)
GOX	1.60	32.000	4.333	0.716
GN2	1.45	28.016	5.444	0.693
GH2	1.40	2.018	6.000	0.685

Nom. Ox flow =	0.2960	lb/s
Nom. Fuel flow =	0.0423	lb/s

Core Element

Flow	Venturi #	New?	Vent. Dia. (in)	Vent. Cd	Cd*A (sq in)	Pup (psig)	Tup (°F)	P inlet, max (psia)	Kw	S.G.	P inlet, est. (psia)	Inj. DP	mdot (lb/s)	C* (ft/s)
Main Ox (GOX)	New	y	0.056	*0.9800*	2.414E-03	**2417**	**63**	1945	0.025	0.1357	1484	266	0.15021	1258.2
						(P7301)	(T7313)		Factor =	1.9210		22%	50.7%	
									P guess =	1484				
									Difference =	*0.0000*				
Main Fuel (GH2)	MO1-B		0.041	*0.9800*	1.294E-03	**2683**	**92**	2158	0.023	0.00727	1331	113	0.02087	5385.7
						(P7303)	(T7314)		Factor =	1.7231		9%	49.4%	
									P guess =	*1331*				
									Difference =	*0.0000*				

COMBUSTION CHARACTERISTICS		
MR=	7.20	
mdot, tot	0.1711	lb/s
Theo. C*	7456.3	ft/s
Burned Press	471.7	psia
Unburned Press	111.5	psia

Annular Injector

Flow	Venturi #	Vent. Dia. (in)	Vent. Cd	Cd*A (sq in)	Pup (psig)	Tup (°F)	P inlet, max (psia)	Kw	S.G.	P inlet, est. (psia)	C* (ft/s)	mdot (lb/s)	Press. (psia)
Ann. Ox (GN2)	AO1-B	0.044	*0.9800*	1.490E-03	**1978**	**88**	1594	0.208	0.0590	1220	1422.9	0.067	35.4
					(P7305)	(T7312)							
Ann. Fuel (GN2)	AO3-B	0.089	*0.9800*	6.097E-03	**1964**	**89**	1583	0.420	0.0589	1225	1424.2	0.273	143.6
					(P7322)	(T7316)							
Barrier (GN2)	MO3-B	0.081	*0.9800*	5.050E-03	**2011**	**82**	1621	2.0	0.0597	1218	1415.1	0.233	121.8
					(P7307)	(T7315)							

Annular mdot	0.573	lb/s

Stratified Flow Calcs		
Total mdot	0.744	lb/s
Predicted Pressure	772.5	psia
Lower Pressure Limit	412.3	psia

ODE Calcs	
Ox- % GOX =	20.78
Ox- % GN2 =	79.22
Modified MR =	34.64

Mixed Flow Calcs		
Mixed C* =	4428	ft/sec
Total mdot =	0.744	lb/sec
Predicted Pc =	1218.0	psia
Actual Pc =	1215.8	psia

J. Cramer *22-Feb-97*

5-30989Test10

Table 8. Test No. 13—Flow calculations worksheet.

TEST #	RBCC-13
Pre/Post	Post
Date	6/18/97
Time Slice	5.5 - 5.75

CONSTANTS

Ru=	1544	ft-lbf/lbmol- °R
K1=	222.973	ft/sec
K2=	0.669	
Throat Dia =	0.332	inch
Throat Area=	0.087	sq in

GAS CONSTANTS

Gas	Gamma	Mol. Wt.	f1(gamma)	f2(gamma)
GOX	1.60	32.000	4.333	0.716
GN2	1.45	28.016	5.444	0.693
GH2	1.40	2.018	6.000	0.685

Nom. Ox flow =	0.2960	lb/s
Nom. Fuel flow =	0.0423	lb/s

Core Element

Flow	Venturi #	New?	Vent. Dia. (in)	Vent. Cd	Cd*A (sq in)	Pup (psig)	Tup (°F)	P inlet, max (psia)	Kw	S.G.	P inlet, est. (psia)	Inj. DP	mdot (lb/s)	C* (ft/s)
Main Ox (GOX)	New	y	0.056	*0.9800*	2.414E-03	**2410**	**67**	1940	0.025	0.1242	1368	287	0.14921	1263.0
						(P7301)	(T7313)					27%	50.4%	
Main Fuel (GH2)	MO1-B		0.041	*0.9800*	1.294E-03	**2689**	**85**	2163	0.023	0.00668	1207	125	0.02105	5351.4
						(P7303)	(T7314)					12%	49.8%	

Factor =	1.9516	
P guess =	1368	
Difference =	*0.0000*	

Factor =	1.7213	
P guess =	1207	
Difference =	*0.0000*	

COMBUSTION CHARACTERISTICS

MR=	7.09	
mdot, tot	0.1703	lb/s
Theo. C*	7486.0	ft/s
Burned Press	457.2	psia
Unburned Press	108.0	psia

Annular Injector

Flow	Venturi #	Vent. Dia. (in)	Vent. Cd	Cd*A (sq in)	Pup (psig)	Tup (°F)	P inlet, max (psia)	Kw	S.G.	P inlet, est. (psia)	C* (ft/s)	mdot (lb/s)	Press. (psia)
Ann. Ox (GN2)	AO1-B	0.044	*0.9800*	1.490E-03	**1665**	**89**	1344	0.208	0.0535	1083	1424.2	0.057	28.9
					(P7305)	(T7312)							
Ann. Fuel (GN2)	AO3-B	0.089	*0.9800*	6.097E-03	**1649**	**88**	1331	0.420	0.0536	1087	1422.9	0.230	117.2
					(P7322)	(T7316)							
Barrier (GN2)	MO3-B	0.081	*0.9800*	5.050E-03	**1661**	**85**	1341	2.0	0.0539	1081	1419.0	0.192	97.7
					(P7307)	(T7315)							

Annular mdot	0.478	lb/s

Stratified Flow Calcs

Total mdot	0.648	lb/s
Predicted Pressure	701.1	psia
Lower Pressure Limit	351.8	psia

ODE Calcs

Ox- % GOX =	23.78
Ox- % GN2 =	76.22
Modified MR =	29.80

Mixed Flow Calcs

Mixed C* =	4649	ft/sec
Total mdot =	0.648	lb/sec
Predicted Pc =	1081.3	psia
Actual Pc =	1061.4	psia

J. Cramer *22-Feb-97*

5-30990Test13

Table 9. Test No. 15—Flow calculations worksheet.

TEST #	RBCC-15
Pre/Post	Post
Date	6/24/97
Time Slice	4.25 - 4.5

CONSTANTS

Ru=	1544	ft-lbf/lbmol- °R
K1=	222.973	ft/sec
K2=	0.669	
Throat Dia =	0.350	inch
Throat Area=	*0.096*	*sq in*

GAS CONSTANTS

Gas	Gamma	Mol. Wt.	f1(gamma)	f2(gamma)
GOX	1.60	32.000	4.333	0.716
GN2	1.45	28.016	5.444	0.693
GH2	1.40	2.018	6.000	0.685

Nom. Ox flow =	0.2960	lb/s
Nom. Fuel flow =	0.0423	lb/s

Core Element

Flow	Venturi #	New?	Vent. Dia. (in)	Vent. Cd	Cd*A (sq in)	Pup (psig)	Tup (°F)	P inlet, max (psia)	Kw	S.G.	P inlet, est. (psia)	Inj. DP	mdot (lb/s)	C* (ft/s)
Main Ox (GOX)	New	y	0.056	*0.9800*	2.414E-03	**2442**	**88**	1965	0.025	*0.1130*	1294	311	0.14826	1287.9
						(P7301)	(T7313)		Factor =	1.9309		32%	50.1%	
									P guess =	1294				
									Difference =	*0.0000*				
Main Fuel (GH2)	MFL3-B		0.049	*0.9800*	1.848E-03	**1878**	**109**	1514	0.023	0.00593	1118	135	0.02060	5468.0
						(P7303)	(T7314)		Factor =	1.6683		14%	48.7%	
									P guess =	1118				
									Difference =	*0.0000*				

COMBUSTION CHARACTERISTICS

MR=	7.20	
mdot, tot	0.1689	lb/s
Theo. C*	7456.4	ft/s
Burned Press	406.4	psia
Unburned Press	98.0	psia

Annular Injector

Flow	Venturi #	Vent. Dia. (in)	Vent. Cd	Cd*A (sq in)	Pup (psig)	Tup (°F)	P inlet, max (psia)	Kw	S.G.	P inlet, est. (psia)	C* (ft/s)	mdot (lb/s)	Press. (psia)
Ann. Ox (GN2)	AO1-B	0.044	*0.9800*	1.490E-03	**2115**	**108**	1704	0.208	0.0725	985	1448.7	0.071	33.0
					(P7305)	(T7312)							
Ann. Fuel (GN2)	MO3-B	0.081	*0.9800*	5.050E-03	**2109**	**109**	1699	0.420	0.0724	988	1449.9	0.238	111.5
					(P7322)	(T7316)							

Annular mdot	0.309	lb/s

Barrier

Flow	Venturi #	Vent. Dia. (in)	Vent. Cd	Cd*A (sq in)	Pup (psig)	Tup (°F)	P inlet, max (psia)	Kw	S.G.	P inlet, est. (psia)	C* (ft/s)	mdot (lb/s)	Press. (psia)
Barrier (GH2)	AO3-B	0.089	*0.9800*	6.097E-03	**1872**	**108**	1509	2.0	0.0052	983	5463.2	0.068	119.6
					(P7307)	(T7315)							

Barrier mdot	0.068	lb/s

Stratified Flow Calcs

Total mdot	0.545	lb/s
Predicted Pressure	670.4	psia
Lower Pressure Limit	362.0	psia

ODE Calcs

Ox- % GOX =	32.44
Ox- % GN2 =	67.56
Modified MR =	5.17

Mixed Flow Calcs

Mixed C* =	*5585*	ft/sec
Total mdot =	0.545	lb/sec
Predicted Pc =	983.2	psia
Actual Pc =	949.6	psia

J. Cramer *22-Feb-97*
Modified: *23-Jun-97*

5-30991Test15

Table 10. Test No.16—Flow calculations worksheet.

TEST #	RBCC-16
Pre/Post	Post
Date	6/25/97
Time Slice	5.3 - 5.5

CONSTANTS

Ru=	1544	ft-lbf/lbmol- °R
K1=	222.973	ft/sec
K2=	0.669	
Throat Dia =	0.346	inch
Throat Area=	0.094	sq in

GAS CONSTANTS

Gas	Gamma	Mol. Wt.	f1(gamma)	f2(gamma)
GOX	1.60	32.000	4.333	0.716
GN2	1.45	28.016	5.444	0.693
GH2	1.40	2.018	6.000	0.685

Nom. Ox flow =	0.2960	lb/s
Nom. Fuel flow =	0.0423	lb/s

Core Element

Flow	Venturi #	New?	Vent. Dia. (in)	Vent. Cd	Cd*A (sq in)	Pup (psig)	Tup (°F)	P inlet, max (psia)	Kw	S.G.	P inlet, est. (psia)	Inj. DP	mdot (lb/s)	C* (ft/s)
Main Ox (GOX)	New	y	0.056	*0.9800*	2.414E-03	**2402**	**78**	1933	0.025	0.1169	1315	297	0.14719	1276.1
						(P7301)	(T7313)					29%	49.7%	
Main Fuel (GH2)	MFL3-B		0.049	*0.9800*	1.848E-03	**1880**	**88**	1516	0.023	0.00633	1150	132	0.02101	5366.1
						(P7303)	(T7314)					13%	49.7%	

Factor =	1.9028
P guess =	1315
Difference =	*0.0005*

Factor =	1.6645
P guess =	1150
Difference =	*0.0000*

COMBUSTION CHARACTERISTICS

MR=	7.01	
mdot, tot	0.1682	lb/s
Theo. C*	7508.7	ft/s
Burned Press	417.2	psia
Unburned Press	99.3	psia

Annular Injector

Flow	Venturi #	Vent. Dia. (in)	Vent. Cd	Cd*A (sq in)	Pup (psig)	Tup (°F)	P inlet, max (psia)	Kw	S.G.	P inlet, est. (psia)	C* (ft/s)	mdot (lb/s)	Press. (psia)
Ann. Ox (GN2)	AO1-B	0.044	*0.9800*	1.490E-03	**2173**	**91**	1750	0.208	0.0774	1020	1426.8	0.074	34.7
					(P7305)	(T7312)							
Ann. Fuel (GN2)	MO3-B	0.081	*0.9800*	5.050E-03	**2160**	**92**	1740	0.420	0.0773	1023	1428.1	0.248	116.8
					(P7322)	(T7316)							

Annular mdot	0.321	lb/s

Barrier

Flow	Venturi #	Vent. Dia. (in)	Vent. Cd	Cd*A (sq in)	Pup (psig)	Tup (°F)	P inlet, max (psia)	Kw	S.G.	P inlet, est. (psia)	C* (ft/s)	mdot (lb/s)	Press. (psia)
Barrier (GH2)	AO3-B	0.089	*0.9800*	6.097E-03	**1875**	**93**	1512	2.0	0.0056	1019	5390.6	0.069	122.5
					(P7307)	(T7315)							

Barrier mdot	0.069	lb/s

Stratified Flow Calcs

Total mdot	0.558	lb/s
Predicted Pressure	691.2	psia
Lower Pressure Limit	373.3	psia

ODE Calcs

Ox-% GOX =	31.43
Ox- % GN2 =	68.57
Modified MR =	5.21

Mixed Flow Calcs

Mixed C* =	*5525*	ft/sec
Total mdot =	0.558	lb/sec
Predicted Pc =	1018.6	psia
Actual Pc =	1017.2	psia

J. Cramer *22-Feb-97*
Modified: *23-Jun-97*

5-30992Test16

Table 11. Test No. 17—Flow calculations worksheet.

TEST #	RBCC-17
Pre/Post	Post
Date	6/25/97
Time Slice	5.3 - 5.5

CONSTANTS

Ru=	1544	ft-lbf/lbmol- °R
K1=	222.973	ft/sec
K2=	0.669	
Throat Dia =	0.346	inch
Throat Area=	0.094	sq in

GAS CONSTANTS

Gas	Gamma	Mol. Wt.	f1(gamma)	f2(gamma)
GOX	1.60	32.000	4.333	0.716
GN2	1.45	28.016	5.444	0.693
GH2	1.40	2.018	6.000	0.685

Nom. Ox flow =	0.2960	lb/s
Nom. Fuel flow =	0.0423	lb/s

Core Element

Flow	Venturi #	New?	Vent. Dia. (in)	Vent. Cd	Cd*A (sq in)	Pup (psig)	Tup (°F)	P inlet, max (psia)	Kw	S.G.	P inlet, est. (psia)	Inj. DP	mdot (lb/s)	C* (ft/s)
Main Ox (GOX)	New	y	0.056	*0.9800*	2.414E-03	**2188**	**78**	1762	0.025	0.1119	1258	257	0.13416	1276.1
						(P7301)	(T7313)					26%	45.3%	
Main Fuel (GH2)	MFL3-B		0.049	*0.9800*	1.848E-03	**2413**	**103**	1942	0.023	0.00647	1207	206	0.02656	5439.1
						(P7303)	(T7314)					21%	62.8%	

Main Ox (GOX):

Factor	=	1.7257
P guess	=	1258
Difference	=	*0.0004*

Main Fuel (GH2):

Factor	=	1.6555
P guess	=	1207
Difference	=	*0.0000*

COMBUSTION CHARACTERISTICS

MR=	5.05	
mdot, tot	0.1607	lb/s
Theo. C*	8085.0	ft/s
Burned Press	429.2	psia
Unburned Press	104.3	psia

Annular Injector

Flow	Venturi #	Vent. Dia. (in)	Vent. Cd	Cd*A (sq in)	Pup (psig)	Tup (°F)	P inlet, max (psia)	Kw	S.G.	P inlet, est. (psia)	C* (ft/s)	mdot (lb/s)	Press. (psia)
Ann. Ox (GN2)	AO1-B	0.044	*0.9800*	1.490E-03	**2051**	**104**	1653	0.208	0.0743	1003	1443.5	0.069	32.7
					(P7305)	(T7312)							
Ann. Fuel (GN2)	MO3-B	0.081	*0.9800*	5.050E-03	**2038**	**105**	1642	0.420	0.0742	1005	1444.8	0.231	110.2
					(P7322)	(T7316)							

Annular mdot	0.300	lb/s

Barrier

Flow	Venturi #	Vent. Dia. (in)	Vent. Cd	Cd*A (sq in)	Pup (psig)	Tup (°F)	P inlet, max (psia)	Kw	S.G.	P inlet, est. (psia)	C* (ft/s)	mdot (lb/s)	Press. (psia)
Barrier (GH2)	AO3-B	0.089	*0.9800*	6.097E-03	**2408**	**101**	1938	2.0	0.0054	1001	5429.4	0.088	157.1
					(P7307)	(T7315)							

Barrier mdot	0.088	lb/s

Stratified Flow Calcs

Total mdot	0.548	lb/s
Predicted Pressure	729.3	psia
Lower Pressure Limit	404.3	psia

ODE Calcs

Ox- % GOX =	30.92
Ox- % GN2 =	69.08
Modified MR =	3.80

Mixed Flow Calcs

Mixed C* =	*5531*	ft/sec
Total mdot =	0.548	lb/sec
Predicted Pc =	1001.1	psia
Actual Pc =	1000.1	psia

J. Cramer *22-Feb-97*
Modified: *23-Jun-97*

5-30993Test17

Table 12. Test No. 18—Flow calculations worksheet.

TEST #	RBCC-18
Pre/Post	Post
Date	6/25/97
Time Slice	8.4 - 8.6

CONSTANTS

Ru=	1544	ft-lbf/lbmol- °R
K1=	222.973	ft/sec
K2=	0.669	
Throat Dia =	0.347	inch
Throat Area=	0.095	sq in

GAS CONSTANTS

Gas	Gamma	Mol. Wt.	f1(gamma)	f2(gamma)
GOX	1.60	32.000	4.333	0.716
GN2	1.45	28.016	5.444	0.693
GH2	1.40	2.018	6.000	0.685

Nom. Ox flow =	0.2960	lb/s
Nom. Fuel flow =	0.0423	lb/s

Core Element

Flow	Venturi #	New?	Vent. Dia. (in)	Vent. Cd	Cd*A (sq in)	Pup (psig)	Tup (°F)	P inlet, max (psia)	Kw	S.G.	P inlet, est. (psia)	Inj. DP	mdot (lb/s)	C* (ft/s)
Main Ox (GOX)	New	y	0.056	*0.9800*	2.414E-03	**2187**	**75**	1761	0.025	0.1122	1255	258	0.13447	1272.5
						(P7301)	(T7313)					26%	45.4%	
Main Fuel (GH2)	MFL3-B		0.049	*0.9800*	1.848E-03	**2404**	**101**	1935	0.023	0.00647	1203	205	0.02651	5429.4
						(P7303)	(T7314)					21%	62.7%	

Main Ox (GOX)		
Factor =	1.7320	
P guess =	1255	
Difference =	*0.0000*	

Main Fuel (GH2)		
Factor =	1.6597	
P guess =	1203	
Difference =	*0.0000*	

COMBUSTION CHARACTERISTICS

MR=	5.07	
mdot, tot	0.1610	lb/s
Theo. C*	8078.2	ft/s
Burned Press	427.1	psia
Unburned Press	103.5	psia

Annular Injector

Flow	Venturi #	Vent. Dia. (in)	Vent. Cd	Cd*A (sq in)	Pup (psig)	Tup (°F)	P inlet, max (psia)	Kw	S.G.	P inlet, est. (psia)	C* (ft/s)	mdot (lb/s)	Press. (psia)
Ann. Ox (GN2)	AO1-B	0.044	*0.9800*	1.490E-03	**2052**	**97**	1653	0.208	0.0750	999	1434.6	0.069	32.6
					(P7305)	(T7312)							
Ann. Fuel (GN2)	MO3-B	0.081	*0.9800*	5.050E-03	**2037**	**100**	1641	0.420	0.0746	1002	1438.4	0.232	109.6
					(P7322)	(T7316)							

Annular mdot	0.301	lb/s

Barrier

Flow	Venturi #	Vent. Dia. (in)	Vent. Cd	Cd*A (sq in)	Pup (psig)	Tup (°F)	P inlet, max (psia)	Kw	S.G.	P inlet, est. (psia)	C* (ft/s)	mdot (lb/s)	Press. (psia)
Barrier (GH2)	AO3-B	0.089	*0.9800*	6.097E-03	**2400**	**98**	1932	2.0	0.0054	998	5414.9	0.088	155.7
					(P7307)	(T7315)							

Barrier mdot	0.088	lb/s

Stratified Flow Calcs

Total mdot	0.550	lb/s
Predicted Pressure	724.9	psia
Lower Pressure Limit	401.3	psia

ODE Calcs

Ox- % GOX =	30.88
Ox- % GN2 =	69.12
Modified MR =	3.82

Mixed Flow Calcs

Mixed C* =	*5528*	ft/sec
Total mdot =	0.550	lb/sec
Predicted Pc =	997.6	psia
Actual Pc =	993.8	psia

J. Cramer *22-Feb-97*
Modified: *23-Jun-97*

5-30994Test18

Table 13. Test No. 21—Flow calculations worksheet.

CONSTANTS

TEST #	RBCC-21
Pre/Post	Post
Date	7/9/97
Time Slice	4.4 - 4.55

Ru=	1544	ft-lbf/lbmol- °R
K1=	222.973	ft/sec
K2=	0.669	
Throat Dia =	0.346	inch
Throat Area=	0.094	sq in

GAS CONSTANTS

Gas	Gamma	Mol. Wt.	f1(gamma)	f2(gamma)
GOX	1.60	32.000	4.333	0.716
GN2	1.45	28.016	5.444	0.693
GH2	1.40	2.018	6.000	0.685

Nom. Ox flow =	0.2960	lb/s
Nom. Fuel flow =	0.0423	lb/s

Core Element

Flow	Venturi #	New?	Vent. Dia. (in)	Vent. Cd	Cd*A (sq in)	Pup (psig)	Tup (°F)	P inlet, max (psia)	Kw	S.G.	P inlet, est. (psia)	Inj. DP	mdot (lb/s)	C* (ft/s)
Main Ox (GOX)	MO3-A		0.073	*0.9800*	4.102E-03	**2798** (P7301)	**59** (T7313)	1406	0.025	0.2121	2301	663	0.29639	1253.4
									Factor =	1.9559		40%	100.1%	
									P guess =	*2301*				
									Difference =	*-0.0001*				
Main Fuel (GH2)	New	y	0.056	*0.9800*	2.414E-03	**2868** (P7303)	**91** (T7314)	2306	0.023	0.01065	1946	308	0.04164	5380.8
									Factor =	1.6541		19%	98.5%	
									P guess =	1946				
									Difference =	*0.0000*				

COMBUSTION CHARACTERISTICS

MR=	7.12	
mdot, tot	0.3380	lb/s
Theo. C*	7478.0	ft/s
Burned Press	834.9	psia
Unburned Press	196.7	psia

Annular Injector

Flow	Venturi #	Vent. Dia. (in)	Vent. Cd	Cd*A (sq in)	Pup (psig)	Tup (°F)	P inlet, max (psia)	Kw	S.G.	P inlet, est. (psia)	C* (ft/s)	mdot (lb/s)	Press. (psia)
Ann. Ox (GN2)	AO1-B	0.044	*0.9800*	1.490E-03	**2204** (P7305)	**90** (T7312)	1775	0.208	0.1248	1640	1425.5	0.075	35.2
Ann. Fuel (GN2)	MO3-B	0.081	*0.9800*	5.050E-03	**2190** (P7322)	**92** (T7316)	1764	0.420	0.1243	1642	1428.1	0.251	118.4

Annular mdot	0.326	lb/s

Barrier

Barrier (GH2)	AO3-B	0.089	*0.9800*	6.097E-03	**2887** (P7307)	**92** (T7315)	2321	2.0	0.0090	1639	5385.7	0.106	188.2

Barrier mdot	0.106	lb/s

Stratified Flow Calcs

Total mdot	0.770	lb/s
Predicted Pressure	1176.6	psia
Lower Pressure Limit	538.4	psia

ODE Calcs

Ox-% GOX =	47.64
Ox- % GN2 =	52.36
Modified MR =	4.22

Mixed Flow Calcs

Mixed C* =	*6447*	ft/sec
Total mdot =	0.770	lb/sec
Predicted Pc =	1638.6	psia
Actual Pc =	1685.3	psia

J. Cramer *22-Feb-97*
Modified: *23-Jun-97*

5-30995Test21

Table 14. Test No. 22—Flow calculations worksheet.

TEST #	RBCC-22
Pre/Post	Post
Date	7/9/97
Time Slice	3.48 - 3.52

CONSTANTS

Ru=	1544	ft-lbf/lbmol- °R
K1=	222.973	ft/sec
K2=	0.669	
Throat Dia =	0.335	inch
Throat Area=	0.088	sq in

GAS CONSTANTS

Gas	Gamma	Mol. Wt.	f1(gamma)	f2(gamma)
GOX	1.60	32.000	4.333	0.716
GN2	1.45	28.016	5.444	0.693
GH2	1.40	2.018	6.000	0.685

Nom. Ox flow =	0.2960	lb/s
Nom. Fuel flow =	0.0423	lb/s

Core Element

Flow	Venturi #	New?	Vent. Dia. (in)	Vent. Cd	Cd*A (sq in)	Pup (psig)	Tup (°F)	P inlet, max (psia)	Kw	S.G.	P inlet, est. (psia)	Inj. DP	mdot (lb/s)	C* (ft/s)
Main Ox (GOX)	MO3-A		0.073	*0.9800*	4.102E-03	**2822**	**42**	1418	0.025	0.2311	2426	639	0.30394	1232.7
						(P7301)	(T7313)					36%	102.7%	
Main Fuel (GH2)	New	y	0.056	*0.9800*	2.414E-03	**2888**	**93**	2322	0.023	0.01134	2079	292	0.04185	5390.6
						(P7303)	(T7314)					16%	99.0%	

Main Ox (GOX):

Factor =	1.8989
P guess =	2426
Difference =	*0.0000*

Main Fuel (GH2):

Factor =	1.6270
P guess =	2079
Difference =	*0.0000*

COMBUSTION CHARACTERISTICS

MR=	7.26	
mdot, tot	0.3458	lb/s
Theo. C*	7439.1	ft/s
Burned Press	906.3	psia
Unburned Press	211.5	psia

Annular Injector

Flow	Venturi #	Vent. Dia. (in)	Vent. Cd	Cd*A (sq in)	Pup (psig)	Tup (°F)	P inlet, max (psia)	Kw	S.G.	P inlet, est. (psia)	C* (ft/s)	mdot (lb/s)	Press. (psia)
Ann. Ox (GN2)	AO1-B	0.044	*0.9800*	1.490E-03	**2278**	**93**	1834	0.208	0.1353	1787	1429.4	0.077	38.8
					(P7305)	(T7312)							
Ann. Fuel (GN2)	MO3-B	0.081	*0.9800*	5.050E-03	**2259**	**94**	1819	0.420	0.1350	1789	1430.7	0.258	130.3
					(P7322)	(T7316)							

Annular mdot	0.335	lb/s

Barrier

Flow	Venturi #	Vent. Dia. (in)	Vent. Cd	Cd*A (sq in)	Pup (psig)	Tup (°F)	P inlet, max (psia)	Kw	S.G.	P inlet, est. (psia)	C* (ft/s)	mdot (lb/s)	Press. (psia)
Barrier (GH2)	AO3-B	0.089	*0.9800*	6.097E-03	**2908**	**95**	2338	2.0	0.0097	1787	5400.3	0.106	202.2
					(P7307)	(T7315)							

Barrier mdot	0.106	lb/s

Stratified Flow Calcs

Total mdot	0.787	lb/s
Predicted Pressure	1277.5	psia
Lower Pressure Limit	582.7	psia

ODE Calcs

Ox- % GOX =	47.54
Ox- % GN2 =	52.46
Modified MR =	4.32

Mixed Flow Calcs

Mixed C* =	*6439*	ft/sec
Total mdot =	0.787	lb/sec
Predicted Pc =	1786.4	psia
Actual Pc =	1649	psia

J. Cramer *22-Feb-97*
Modified: *23-Jun-97*

5-30996Test22

APPENDIX B—DATA PLOTS

Data plots for Test Nos. 8–10, 13, 15–18, 21, and 22 are shown in figures 6–15.

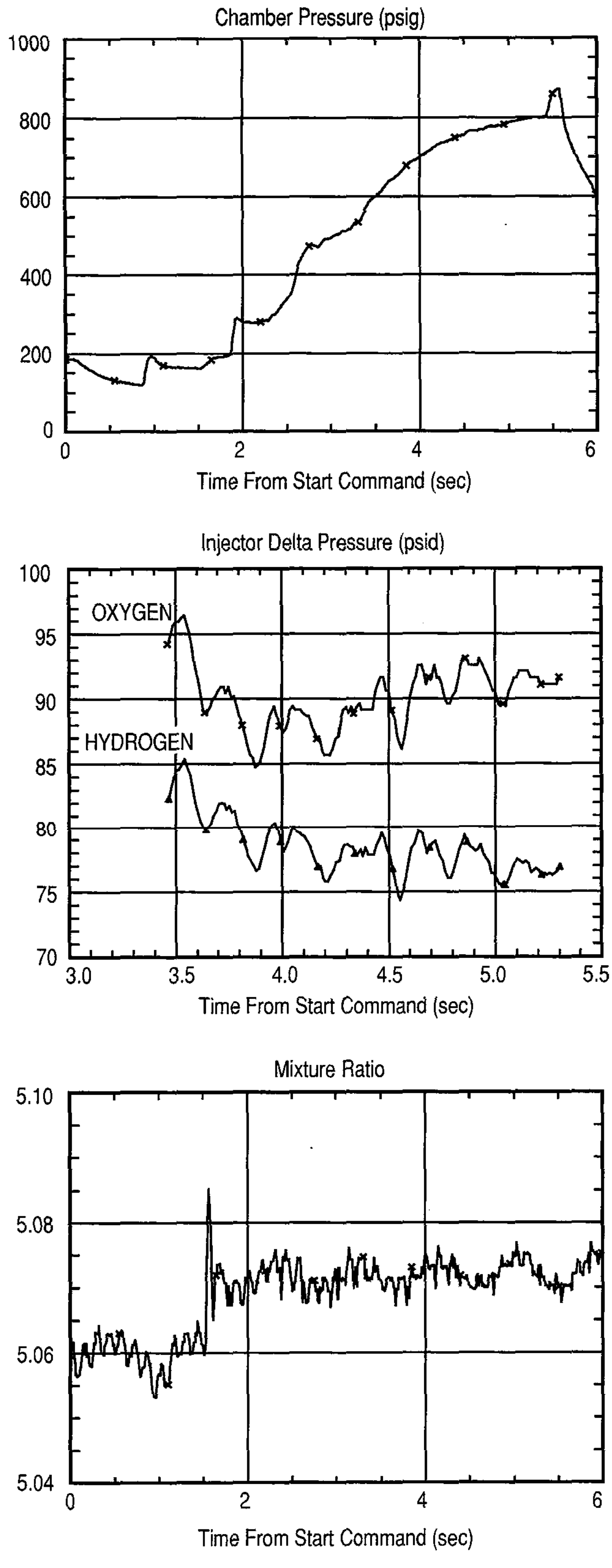


Figure 6. Test No. 8—chamber pressure, injector ΔP, and mixture ratio versus time.

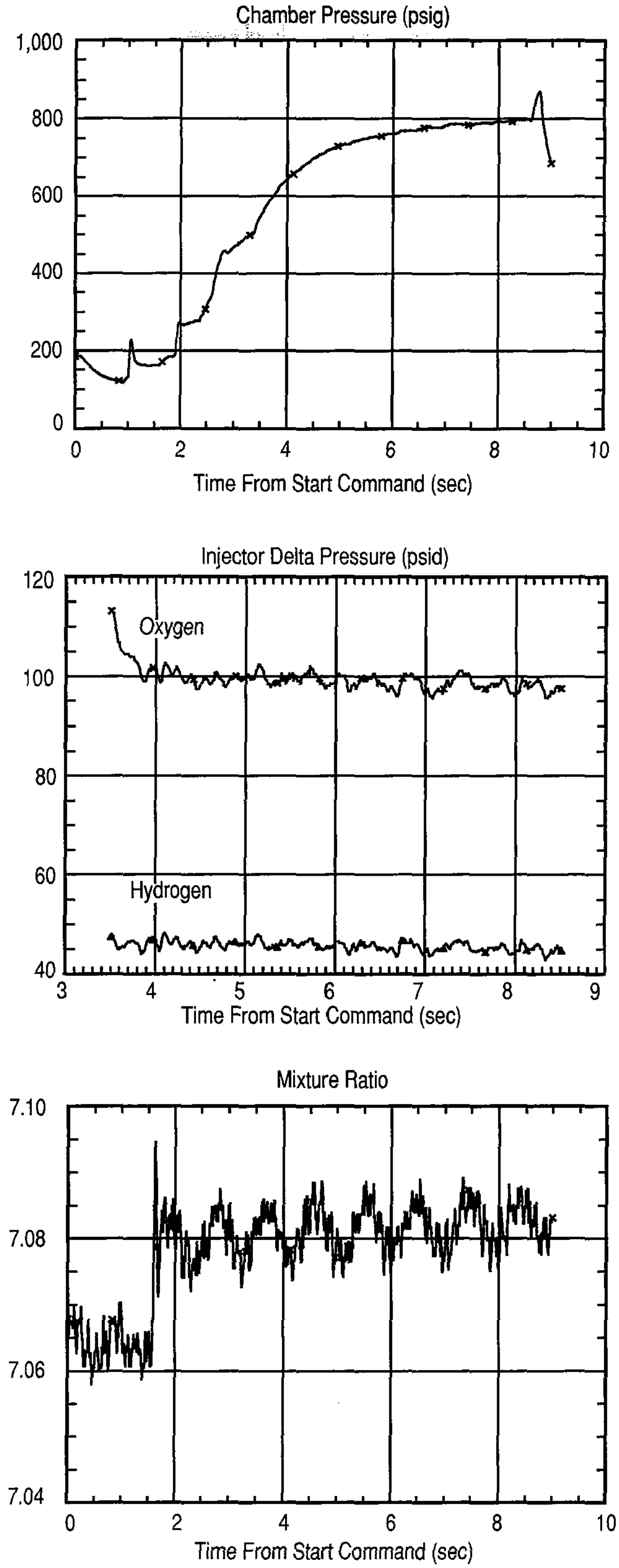


Figure 7. Test No. 9—chamber pressure, injector ΔP, and mixture ratio versus time.

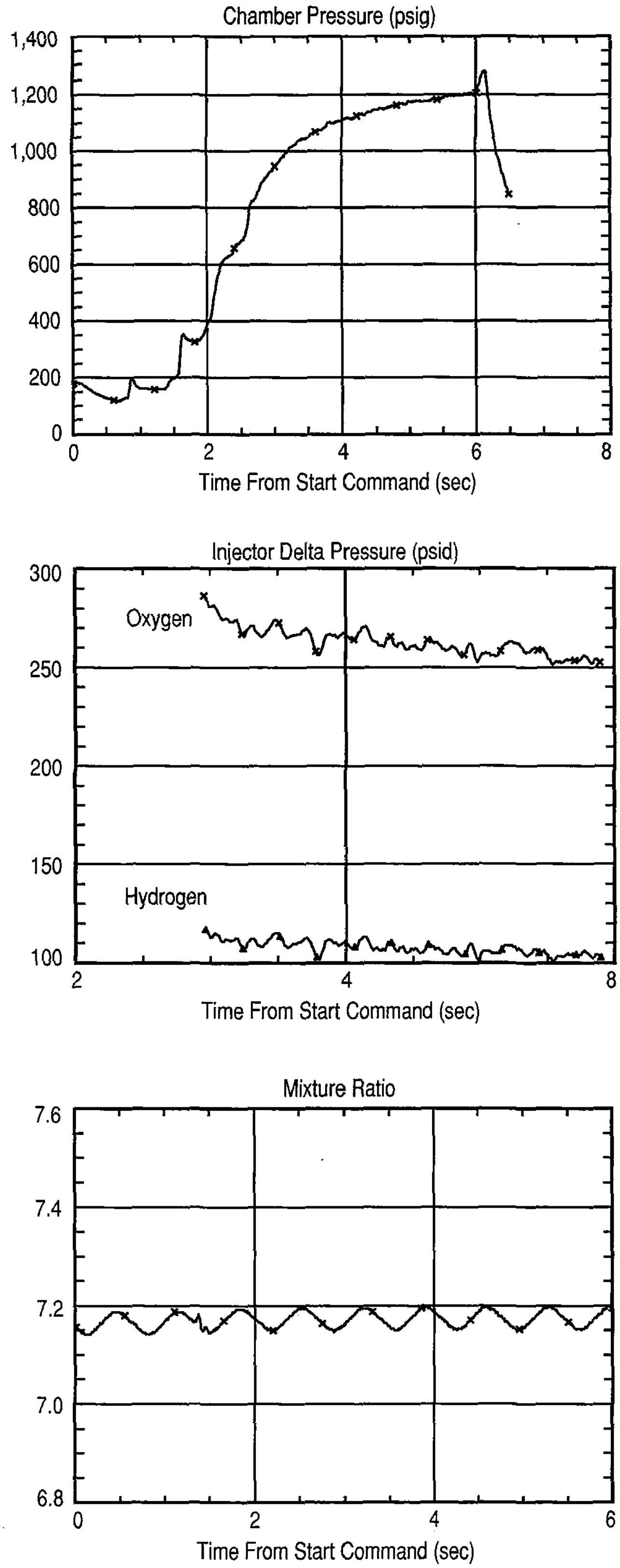


Figure 8. Test No. 10—chamber pressure, injector ΔP, and mixture ratio versus time.

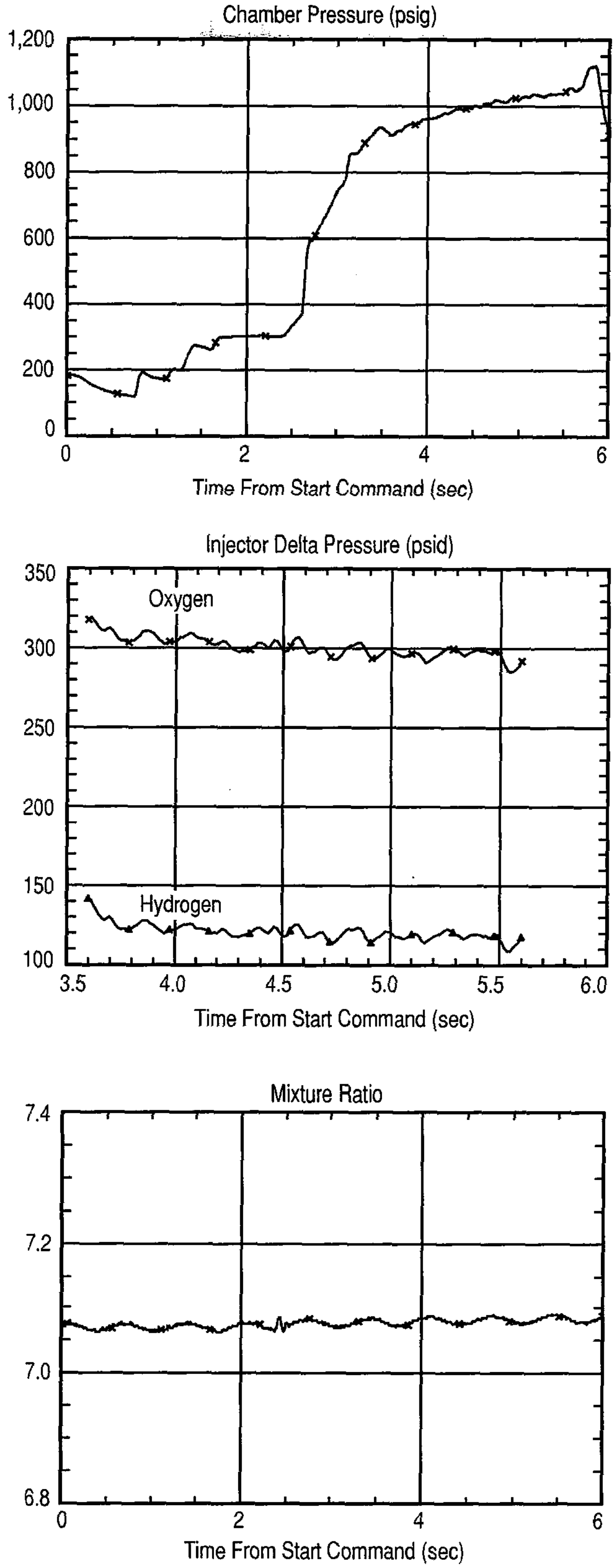


Figure 9. Test No. 13—chamber pressure, injector ΔP, and mixture ratio versus time.

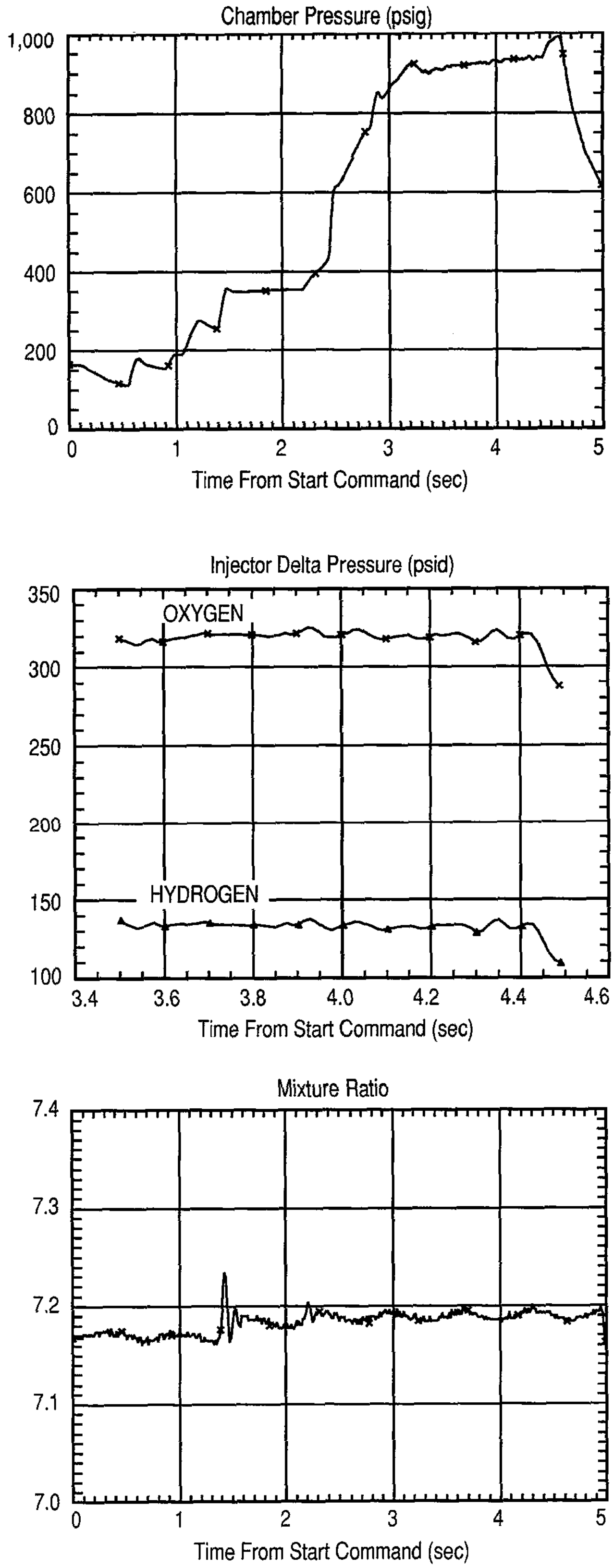


Figure 10. Test No. 15—chamber pressure, injector ΔP, and mixture ratio versus time.

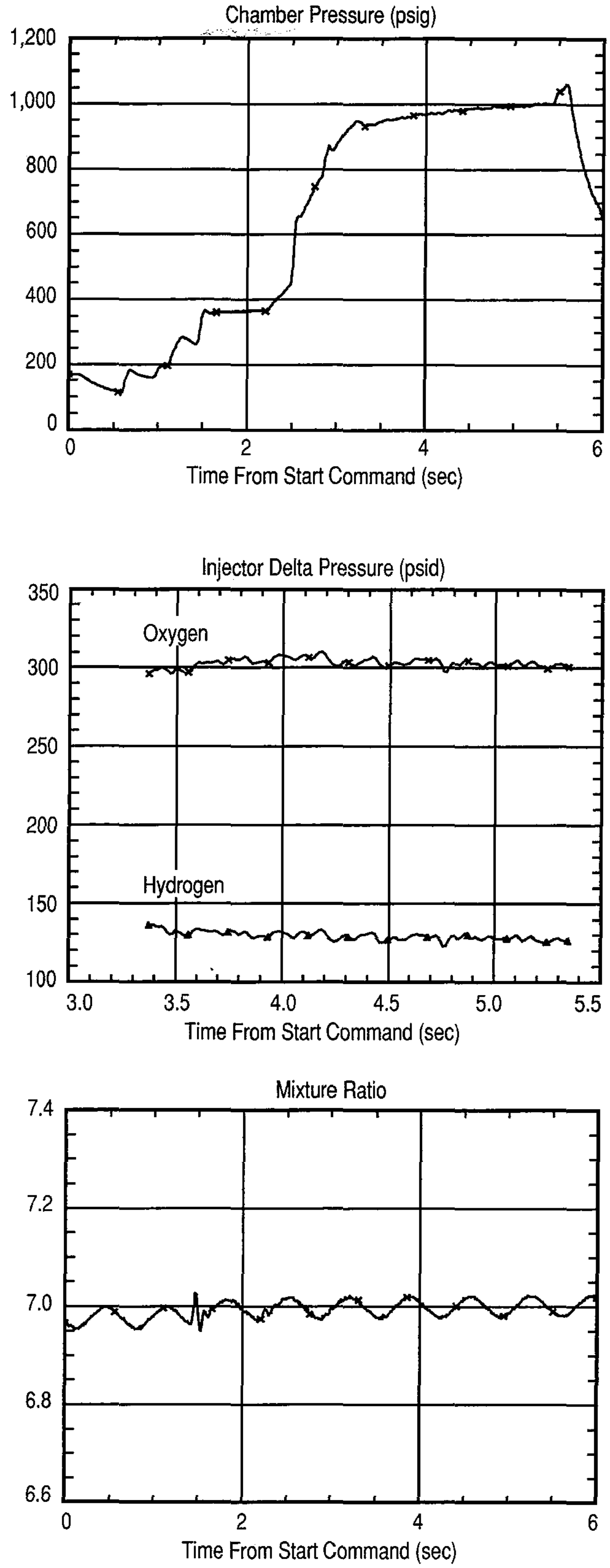


Figure 11. Test No. 16—chamber pressure, injector ΔP, and mixture ratio versus time.

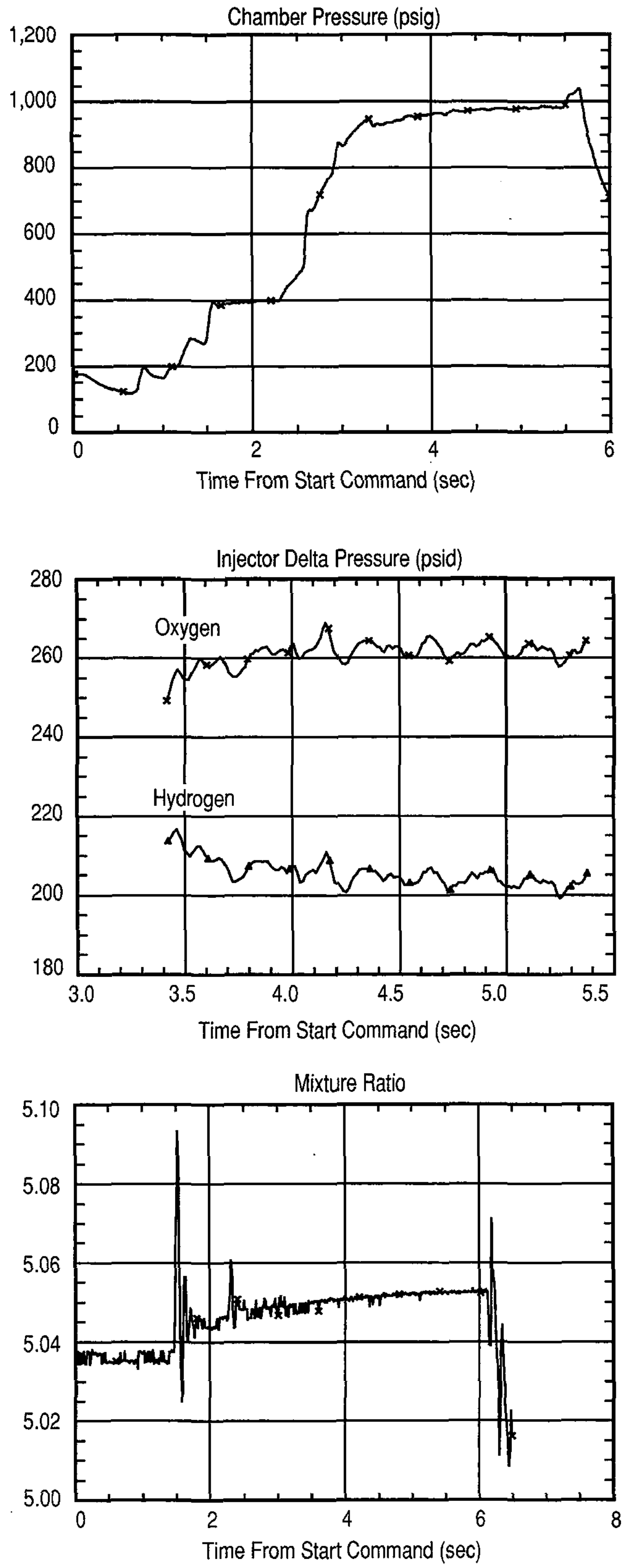


Figure 12. Test No. 17—chamber pressure, injector ΔP, and mixture ratio versus time.

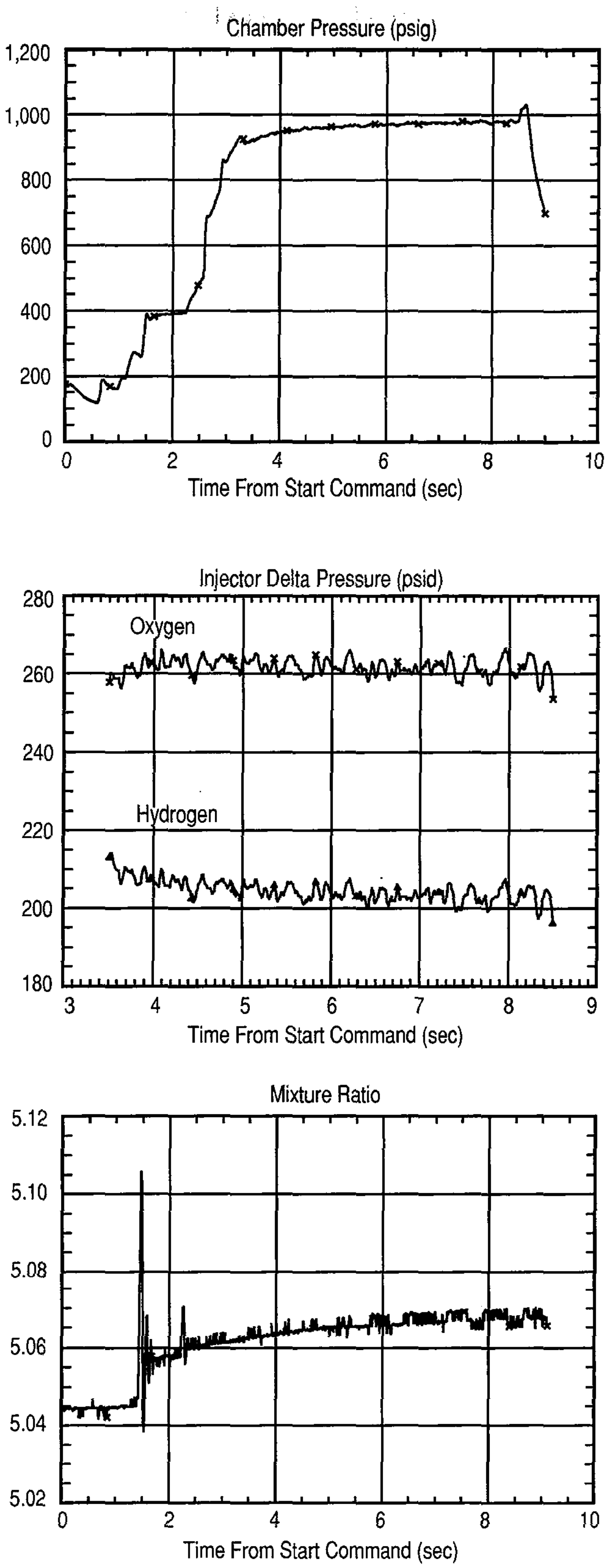


Figure 13. Test No. 18—chamber pressure, injector ΔP, and mixture ratio versus time.

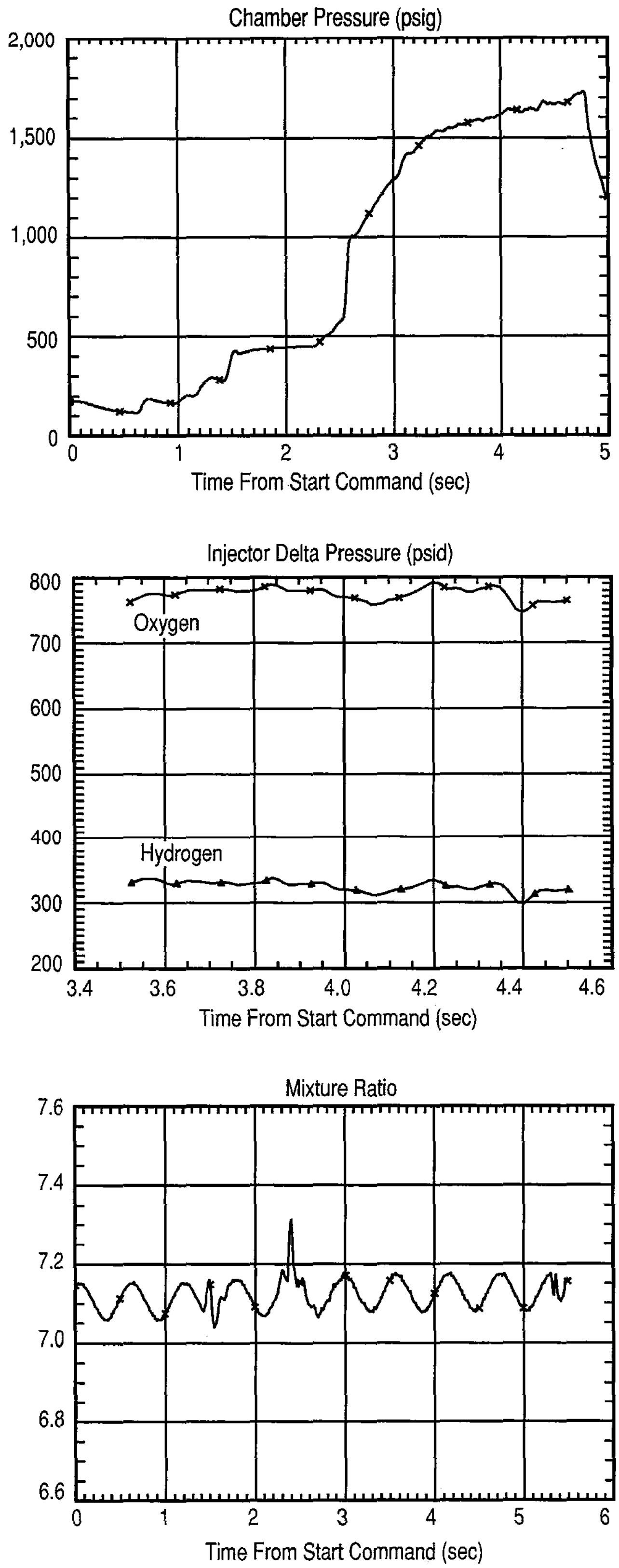


Figure 14. Test No. 21—chamber pressure, injector ΔP, and mixture ratio versus time.

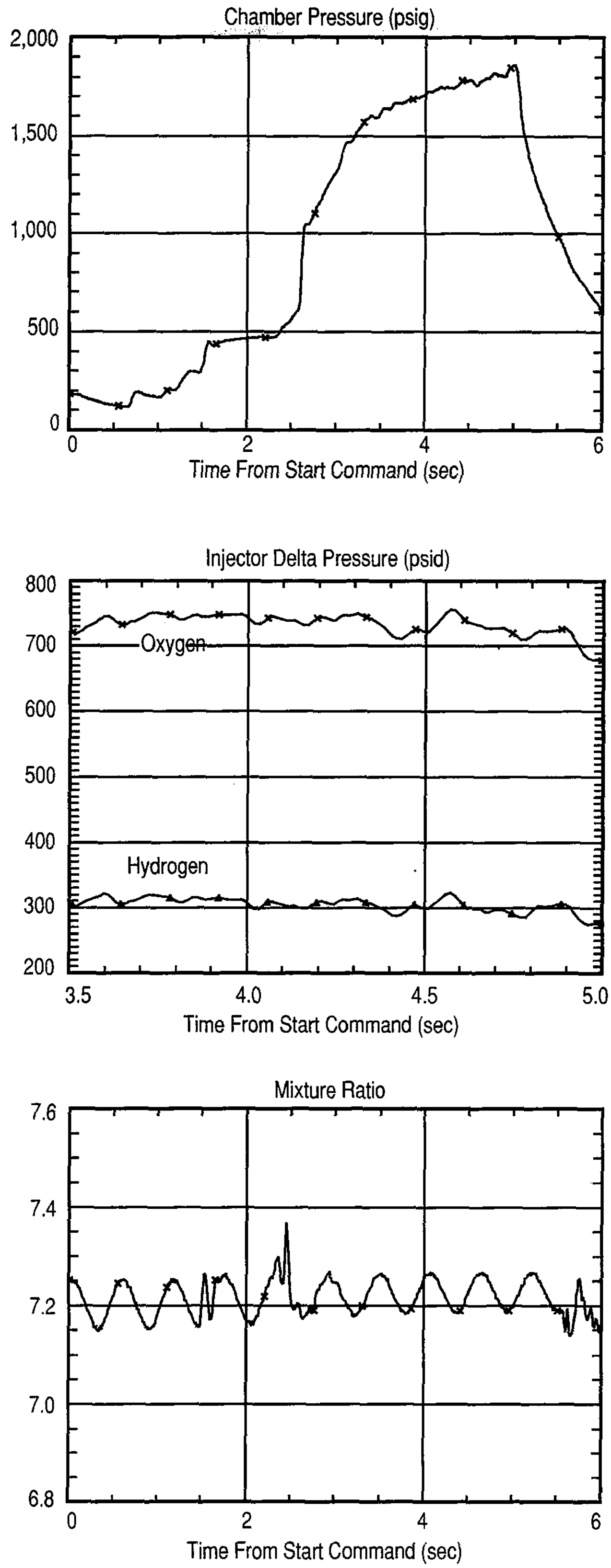


Figure 15. Test No. 22—chamber pressure, injector ΔP, and mixture ratio versus time.

APPENDIX C—SEM IMAGES

An SEM utilizes a focused beam of electrons to illuminate the surface of a sample. The incident electron beam interacts with the sample to produce secondary electron and x-ray signals which are monitored with specific detectors. These signals provide topographical information about surface features which can be magnified up to × 300,000. Chemical information can also be derived from the x-ray signals.

In order to identify the individual elements, they are numbered as shown in figure 16. Figure 16 is shown without the water film cooling slots. The images that follow were taken with the MSFC SEM at a magnification of × 40.

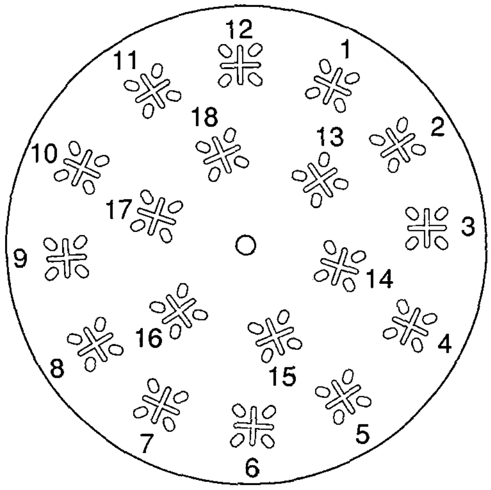
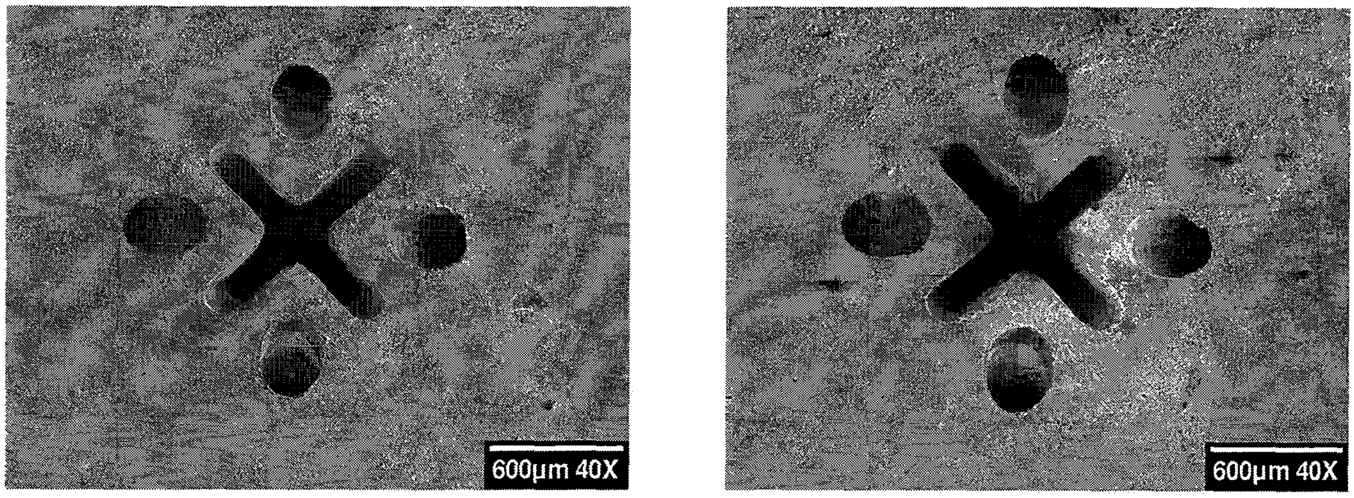


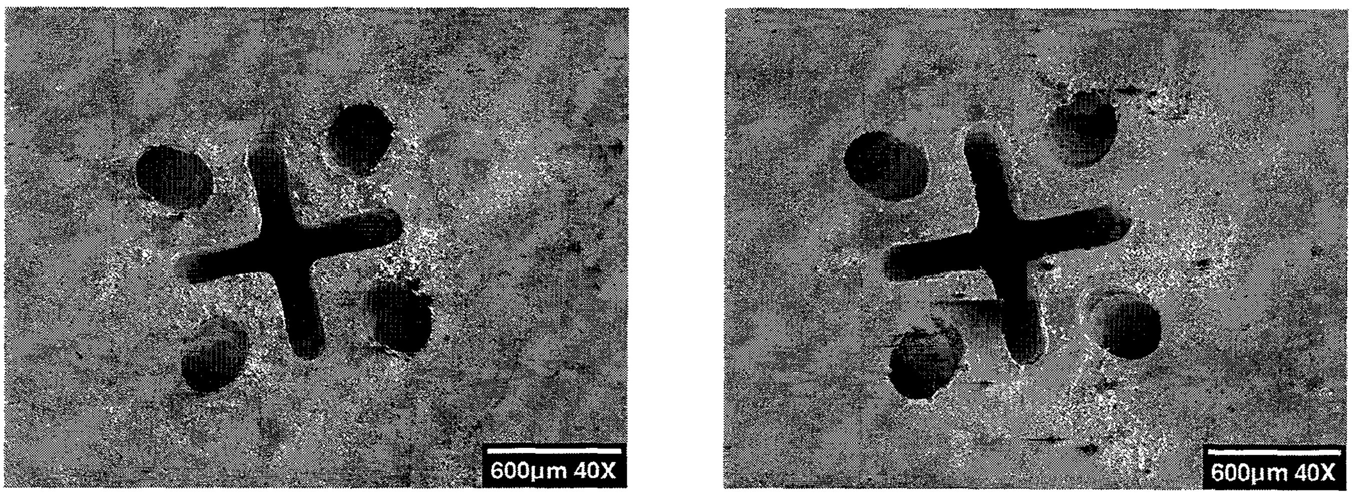
Figure 16. Injector element layout.

The conditions of elements 1–18 after Test No. 9 and Test No. 22 are shown in figures 17–34.



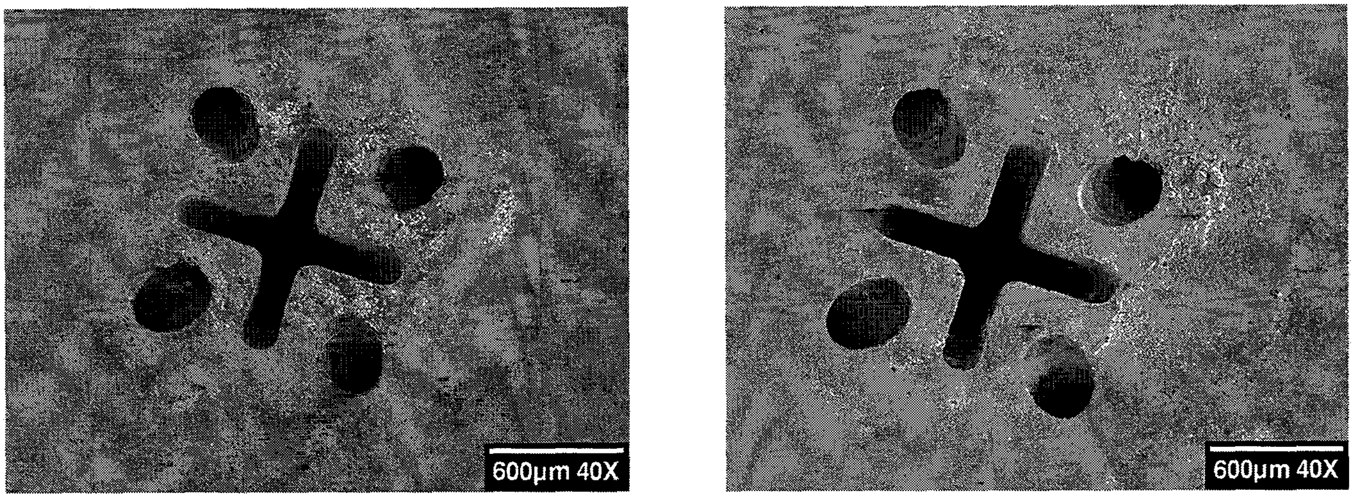
(a) (b)

Figure 17. Element No. 1: (a) condition after Test No. 9, and (b) condition after Test No. 22.



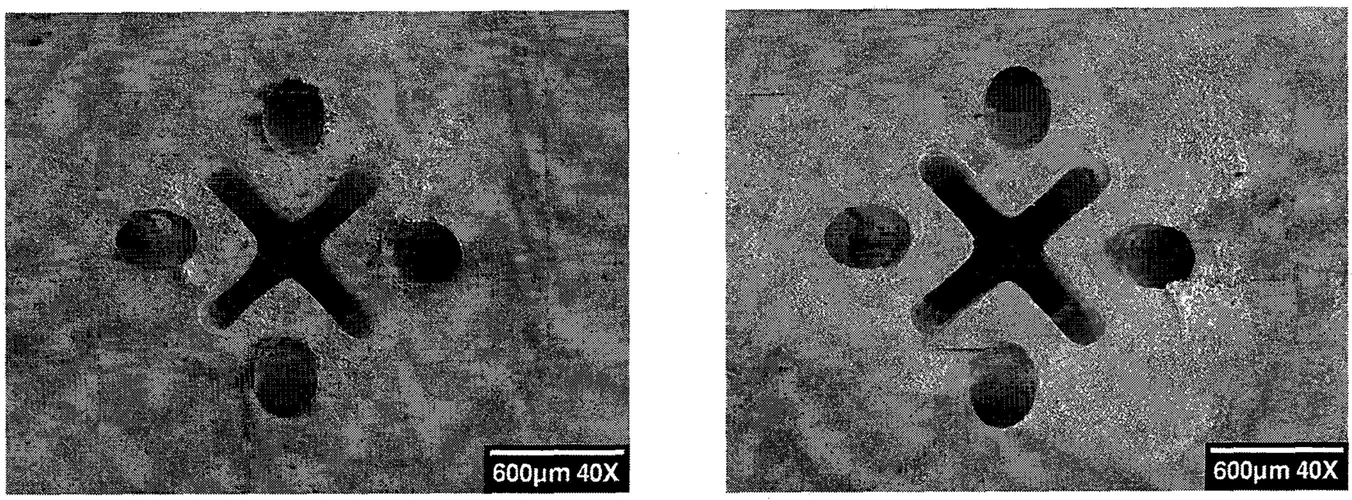
(a) (b)

Figure 18. Element No. 2: (a) condition after Test No. 9, and (b) condition after Test No. 22.



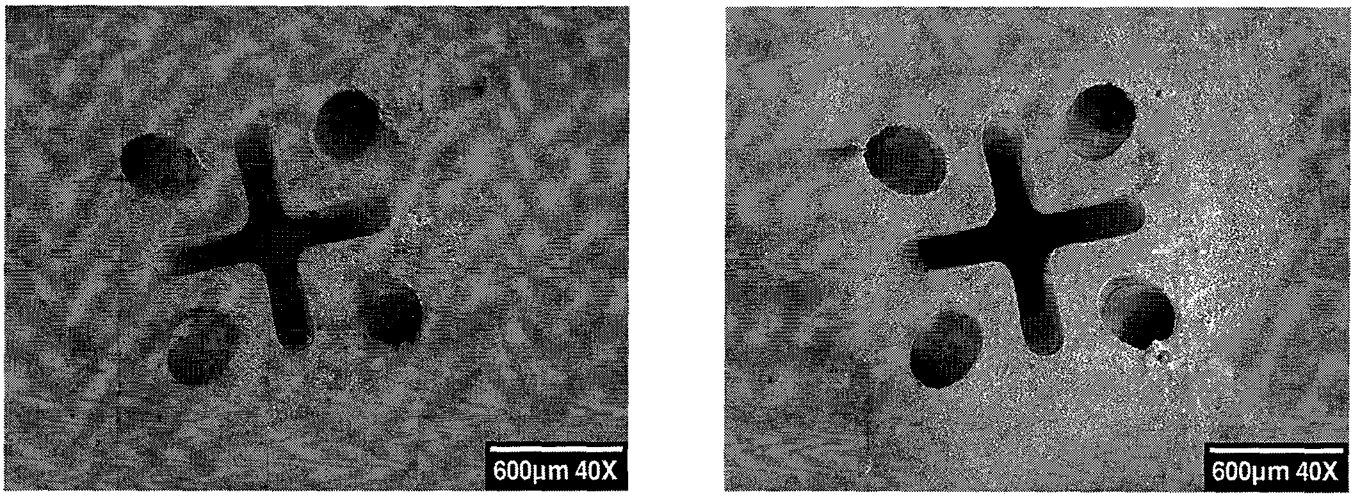
(a) (b)

Figure 19. Element No. 3: (a) condition after Test No. 9, and (b) condition after Test No. 22.



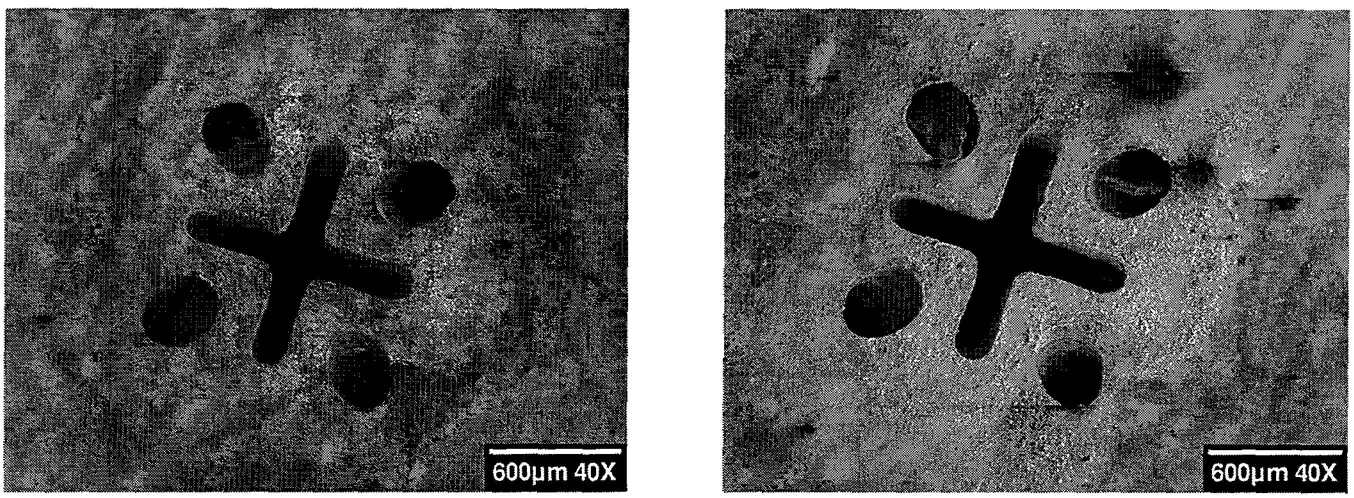
(a) (b)

Figure 20. Element No. 4: (a) condition after Test No. 9, and (b) condition after Test No. 22.



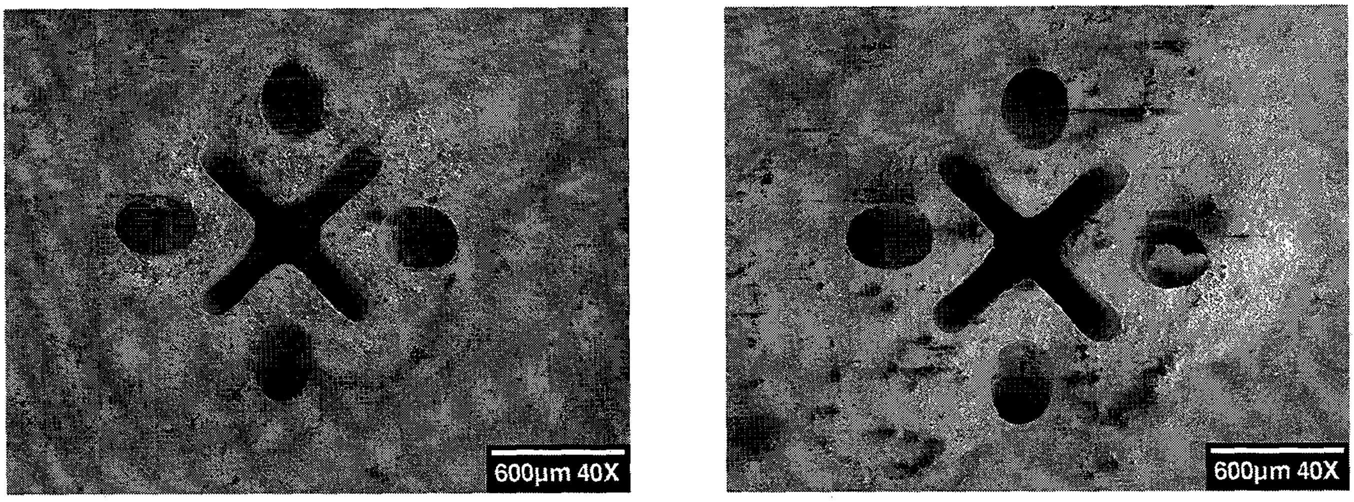
(a) (b)

Figure 21. Element No. 5: (a) condition after Test No. 9, and (b) condition after Test No. 22.



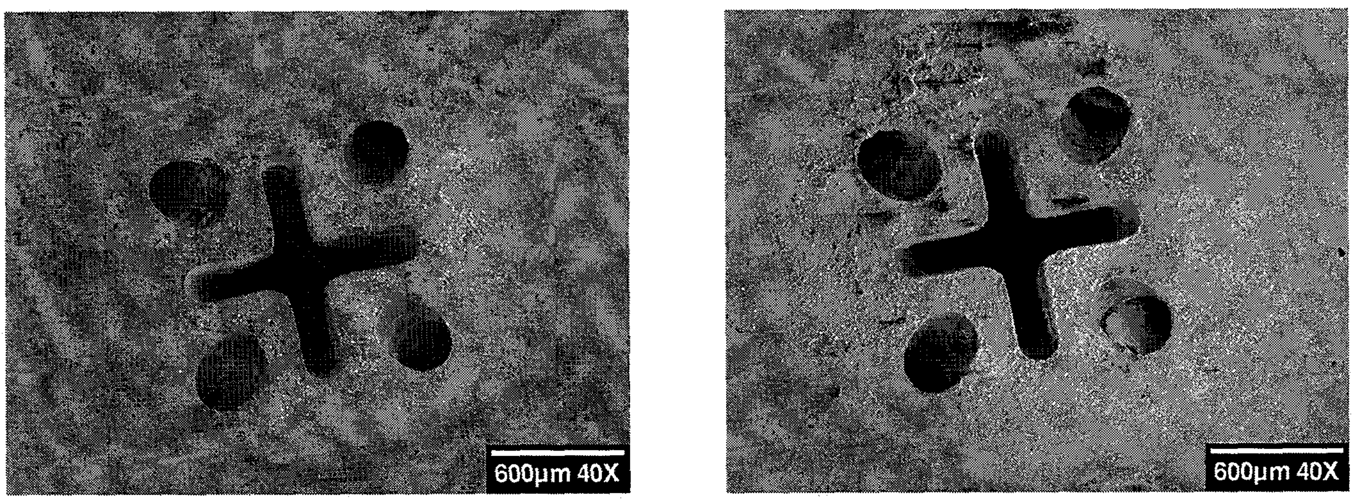
(a) (b)

Figure 22. Element No. 6: (a) condition after Test No. 9, and (b) condition after Test No. 22.



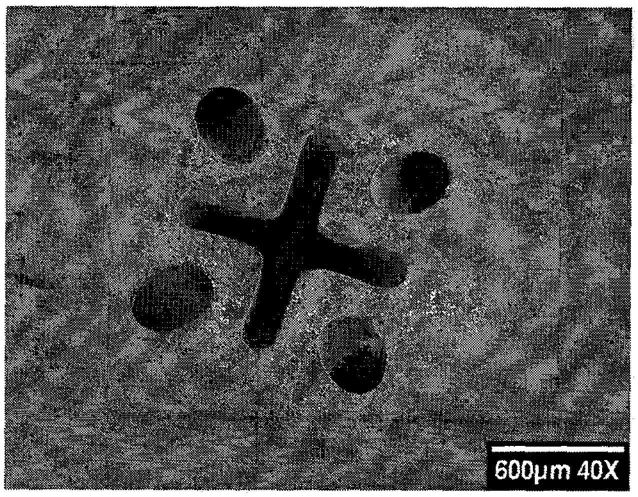
(a) (b)

Figure 23. Element No. 7: (a) condition after Test No. 9, and (b) condition after Test No. 22.

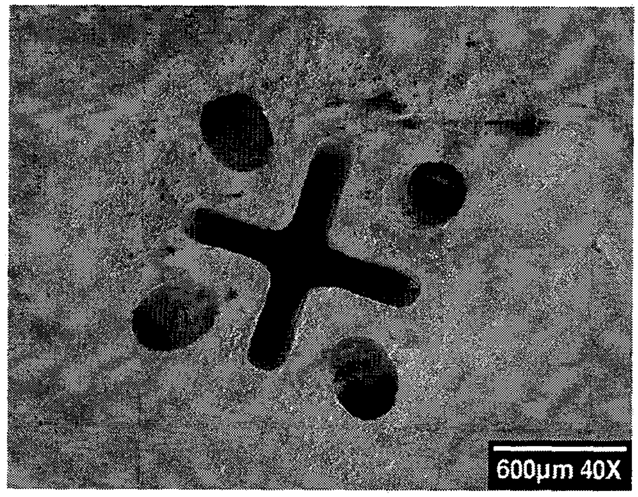


(a) (b)

Figure 24. Element No. 8: (a) condition after Test No. 9, and (b) condition after Test No. 22.

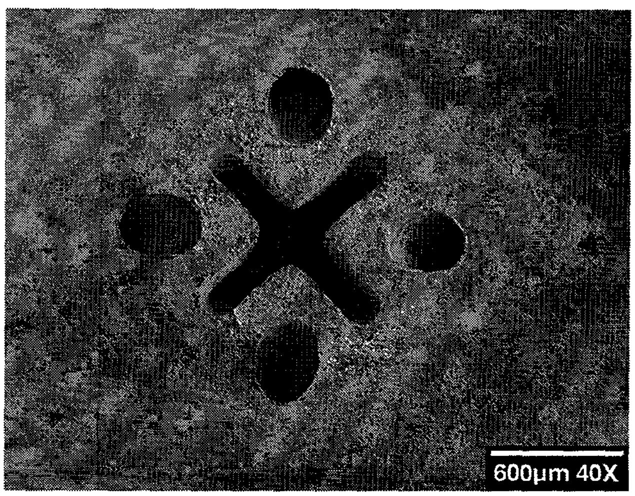


(a)

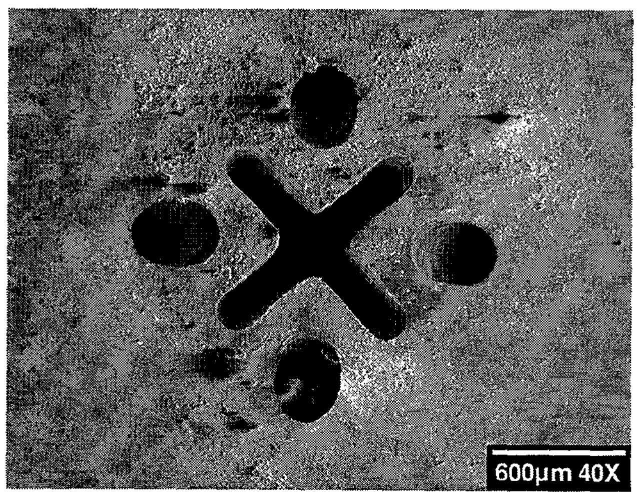


(b)

Figure 25. Element No. 9: (a) condition after Test No. 9, and (b) condition after Test No. 22.

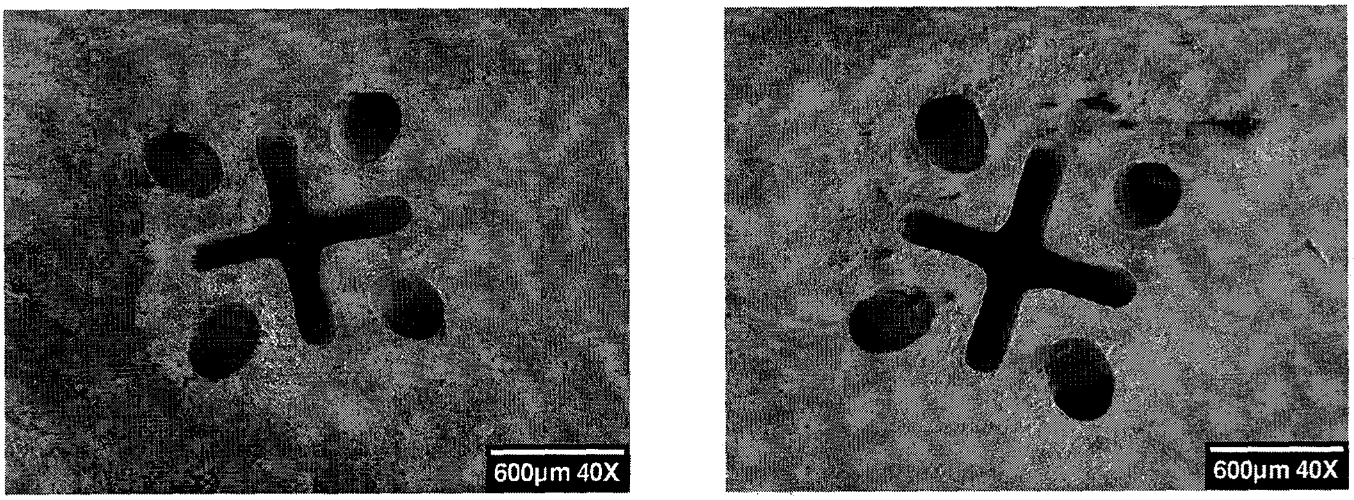


(a)



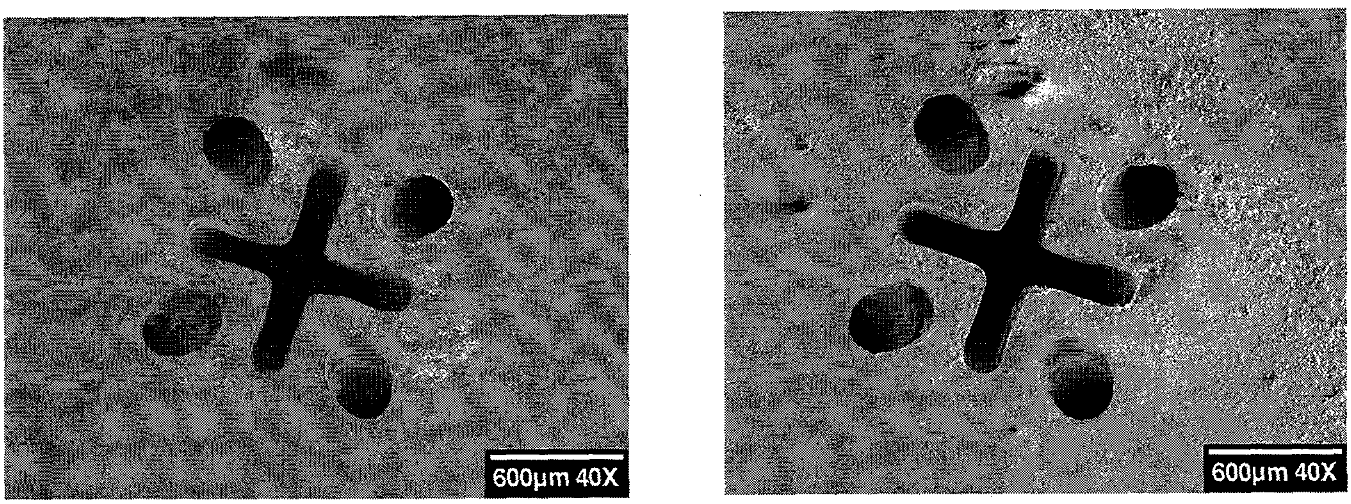
(b)

Figure 26. Element No. 10: (a) condition after Test No. 9, and (b) condition after Test No. 22.



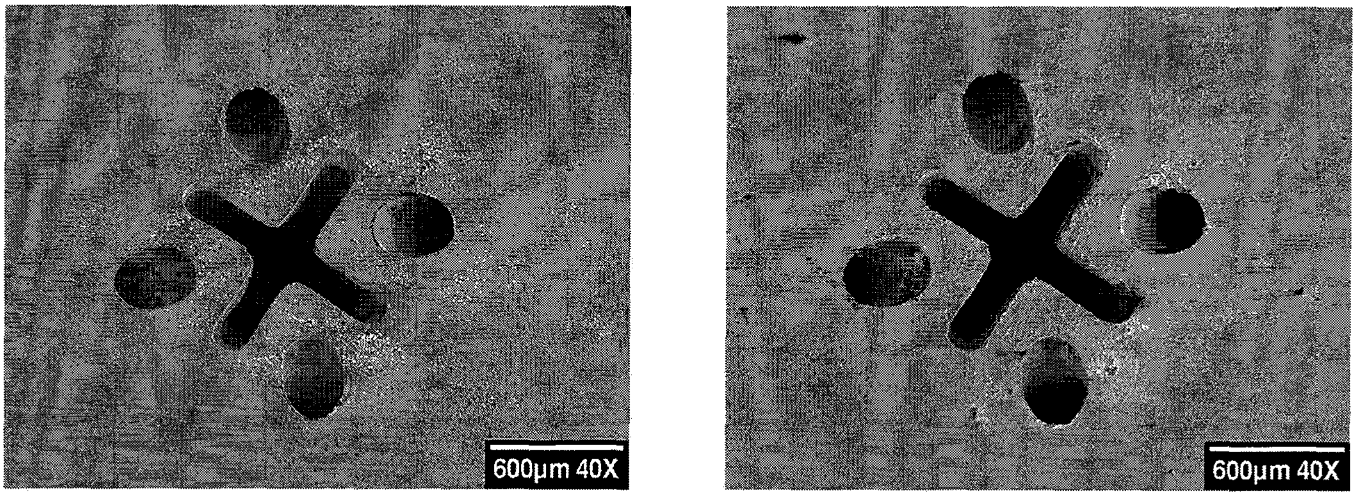
(a) (b)

Figure 27. Element No. 11: (a) condition after Test No. 9, and (b) condition after Test No. 22.



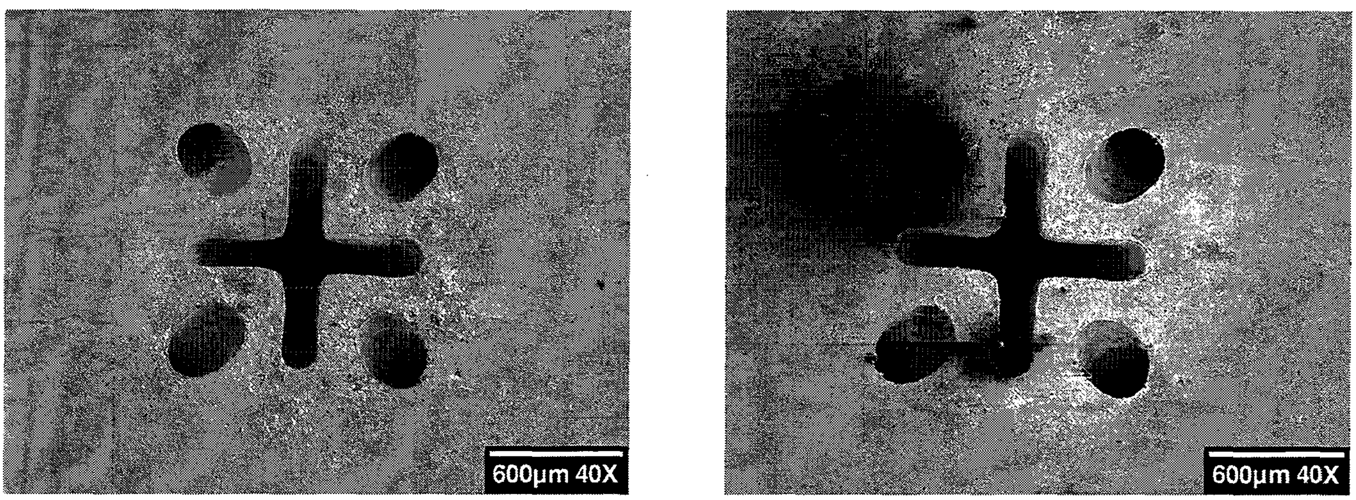
(a) (b)

Figure 28. Element 12: (a) condition after Test No. 9, and (b) condition after Test No. 22.



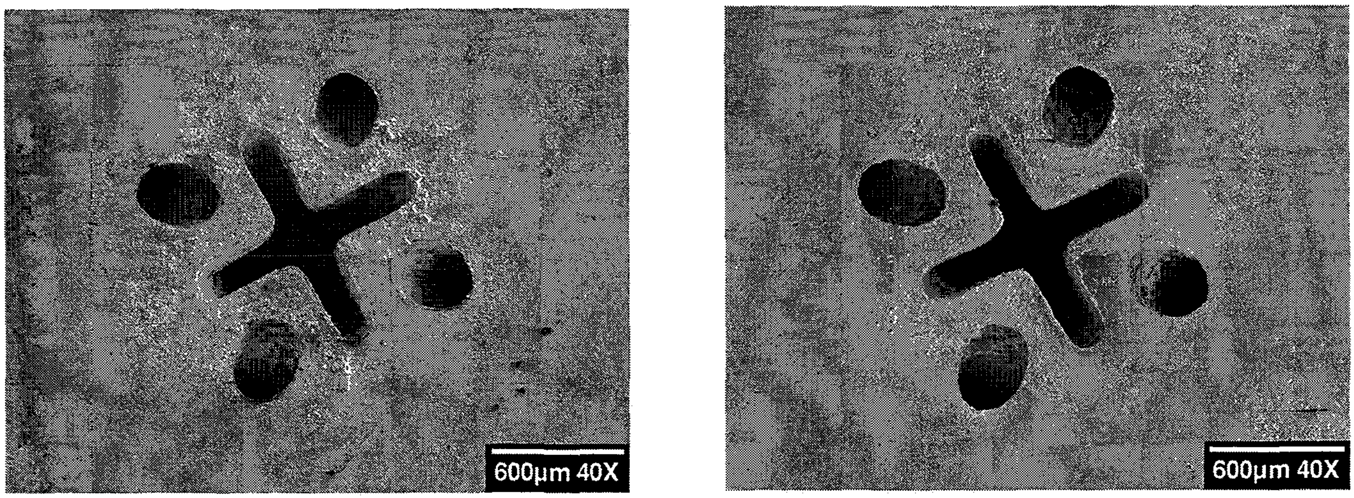
(a) (b)

Figure 29. Element No. 13: (a) condition after Test No. 9, and (b) condition after Test No. 22.



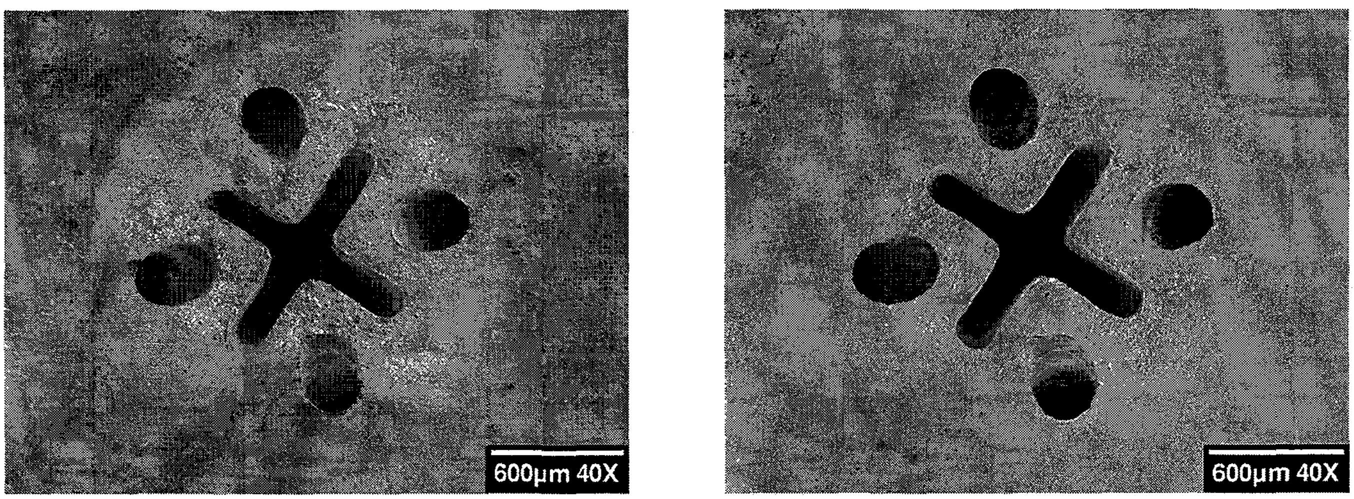
(a) (b)

Figure 30. Element No. 14: (a) condition after Test No. 9, and (b) condition after Test No. 22.



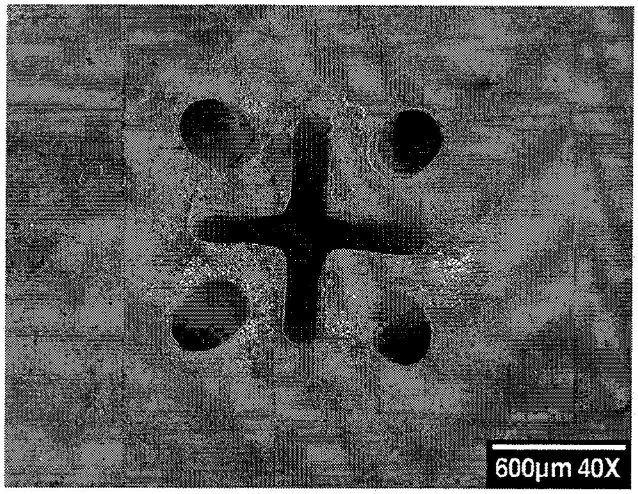
(a) (b)

Figure 31. Element 15: (a) condition after Test No. 9, and (b) condition after Test No. 22.

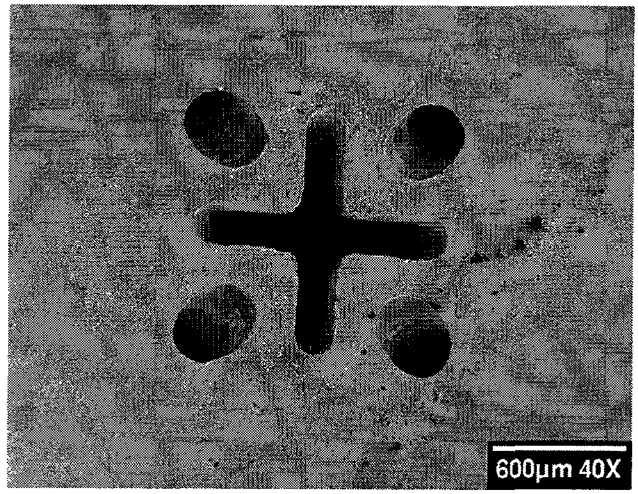


(a) (b)

Figure 32. Element 16: (a) condition after Test No. 9, and (b) condition after Test No. 22.

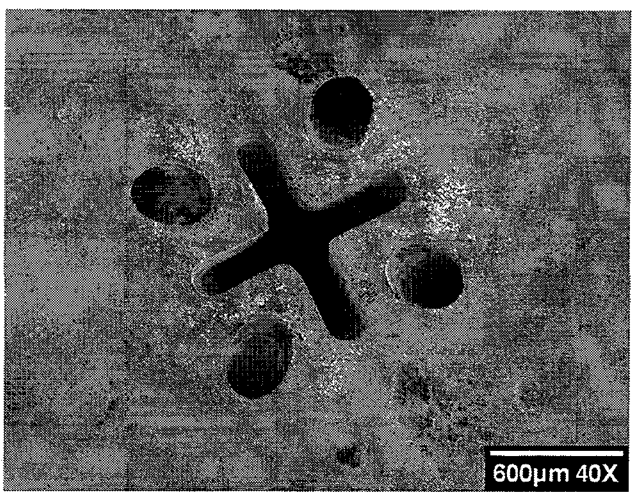


(a)

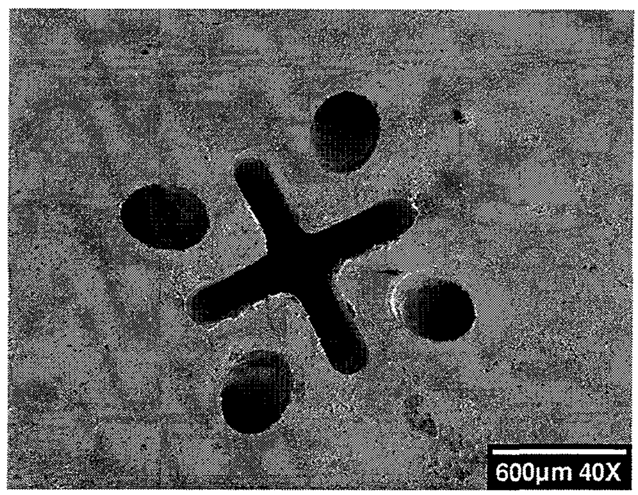


(b)

Figure 33. Element No. 17: (a) condition after Test No. 9, and (b) condition after Test No. 22.



(a)



(b)

Figure 34. Element No. 18: (a) condition after Test No. 9, and (b) condition after Test No. 22.

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M.M. Fazah and J.M. Cramer

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Marshall Space Flight Center, Alabama 35812

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13. ABSTRACT *(Maximum 200 words)*

To satisfy RBCC rocket thruster requirements of high performance and a minimum amount of free hydrogen at plume boundary, a new impinging injector element using gaseous hydrogen and gaseous oxygen as the propellants has been designed. Analysis has shown that this injector design has potential to provide a high specific impulse (Isp) while minimizing the amount of free hydrogen that is available to be burned with incoming secondary flow. Past studies and test programs have shown that gas/gas-impinging elements typically result in high injector face temperatures due to combustion occurring close to the face. Since this design is new, there is no hot fire experience with this element. Objectives of this test program were to gain experience and hot fire test data on this new rocket thruster element design and injector faceplate pattern.

Twenty-two hot fire tests were run with maximum mixture ratio (MR) and chamber pressure (Pc) obtained at 7.25 and 1,822 psia, respectively. Posttest scanning microscope (SEM) images show only slight faceplate erosion during testing. This injector element design performed well and can be operated at design conditions: (1) Pc of 2,000 psia and MR of 7.0 and (2) Pc of 1,000 psia and MR of 5.0.

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rocket-based combine cycle, RBCC, Pentad plus injector element, injector element layout

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APPROVAL

THRUSTER INJECTOR FACEPLATE TESTING IN SUPPORT OF THE AEROJET ROCKET-BASED COMBINED CYCLE (RBCC) CONCEPT

M.M. Fazah and J.M. Cramer

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

H.V. McCONNAUGHEY
DIRECTOR, PROPULSION LABORATORY