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Comprehensive Review of Liquid-Propellant Combustion Instabilities in F-1 Engines

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Nomenclature

c^* = characteristic velocity
D = propellant orifice diameter
$I.A.$ = propellant impingement half-angle
I_{sp} = specific impulse
p = mean chamber pressure
p' = pressure perturbation about the mean
V = nominal propellant injection velocity
w = propellant weight flow rate
Δp = propellant pressure drop across injector face
η_{c^*} = characteristic velocity efficiency
τ = damp time

Introduction

UNDERSTANDING and predicting high-frequency combustion instabilities in liquid-propellant rocket engines continues to pose significant challenges due to the highly complex and nonlinear nature of turbulent combustion processes. This type of instability is considered to be the most destructive, and is usually characterized by well-defined frequencies and mode shapes corresponding to the acoustic modes of the chamber. Traditional strategies used to eliminate combustion instabilities have been to increase the damping of the system and/or reduce coupling between unsteady combustion responses and periodic flow oscillations. While often effective, these methods usually suffer deficiencies associated with a lack of knowledge concerning fundamental mechanisms and the coupling dynamics leading to combustion instabilities. Difficulties in assessing the impact of various processes arises from the presence of many diverse phenomena such as the hydrodynamics of injection, spray formation processes, transport characteristics of individual droplets, turbulent multiphase flow conditions, and chemical phenomena in a turbulent environment. Multiple strongly coupled processes with a wide disparity in time and length scales exist in close proximity to one another. Although advances in the field have been made, the largest and most reliable source of information to date applicable to the design of improved combustion devices is the store of experimental data from full-scale engine tests. Consequently, the motivation behind the present work was to gain further insight into the mechanisms associated with combustion instability by providing a detailed, concise account and analyses of the design attributes which led to dynamic stability in F-1 developmental injectors. Objectives were 1) to preserve the experience gained through development of the F-1 engine; 2) to merge full-scale test results with corresponding theories and experiments; and 3) to analyze the effect of proposed solutions.

To facilitate analysis, all available full-scale component and engine test data have been combined into a single data base. This compilation provides a complete genealogy of F-1 developmental injector design configurations, and contains all available measured and observed test results. Table 1 lists the injector design parameters and test results acquired. The complete data base is available as an appendix to a separate technical report prepared by the authors.[1] These data have been assembled from a variety of sources.[2–6] Reference 2 is a chronological tabulation of full-scale injector component test results recorded at the test site. This document lists the injectors tested along with the date, chamber pressure, thrust, run time, mixture ratio, bomb size, and damp times, as well as observations made during various tests. Reference 3 contains a set of 16 reports (four volumes of four reports each) which present a somewhat chronological account of the methodology leading to a dynamically stable injector design. Full-scale engine and component test results are discussed throughout this set of reports. Reference 4 provides a broad overview of the problems and solutions encountered with combustion instability in the F-1 engine. Finally, Refs. 5 and 6 are weekly

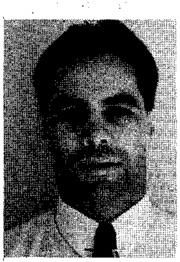

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Table 1 F-1 injector design parameters and test results included in the data base

Injector parameters	Test data
Injector unit number	Test number
Design type number	Test stand
Injection pattern	Engine number
Basic design	Mixture ratio
Total injection areas[a]	Mean chamber pressure
Injection element type[a]	Fuel injection temperature
Impingement angles[b]	Nominal injection velocities[a]
Orifice diameters[b]	Nominal mass flow rates[a]
Orifice spacing	Nominal injection pressure drop[a]
Ring thickness[a]	Thrust
Ring groove depth[a]	Specific impulse
Baffle configuration	Characteristic velocity efficiency
No. of compartments	Stability characteristics
Length	Mode of instability
Coolant	Frequency[c]
Type	Amplitude[c]
Area	
Method	Stability rating
Base width	Bomb size
No. of passage dams	Damp time
Outer fuel ring	Self-triggered (Y/N)
Orifice diameter	Resurging (Y/N)
Impingement angle	Buzzing (Y/N)
Percent of maximum passage flow	General observations
Wall gap	
Miscellaneous modifications	
General remarks	

[a]For both fuel and oxidizer. [b]For both unconfined elements and elements adjacent to radial baffles. [c]Chamber, fuel side, and oxidizer side.

status reports and the minutes of meetings held to discuss combustion instability in the F-1 engine. These documents provide insight into the reasoning behind various design modifications.

The next section outlines the basic design features and operating characteristics of the F-1 engine, with emphasis on the injector and thrust chamber configurations. A brief historical profile is then presented which puts the development process into perspective, followed by detailed injector genealogy which highlights modifications leading to dynamic stability. Concurrent discussion focuses on the conditions required for optimum combustion dynamics in terms of fundamental processes such as atomization, vaporization, and turbulent mixing. Various experimental and theoretical treatments are considered and discussed in the context of full-scale test results. In closing, appropriate conclusions which highlight key observations are presented.

Design Features of the F-1 Engine

The F-1 engine is a fixed-thrust, pump-fed, liquid-propellant rocket engine which utilizes the LOX/RP-1 propellant combination and operates on a gas-generator power cycle. Figure 1 is a photograph which displays key external features. Table 2 lists the basic operating conditions, along with performance specifications, feed system particulars, thrust chamber geometry, major components, and operational systems. This engine operates at a chamber pressure of 7757 kPa (1125 psia), and an oxygen to fuel (O/F) mixture ratio of 2.4. The flight-qualified configuration yields a specific impulse of 265.4 s while producing a characteristic velocity efficiency of 93.8%. Thrust levels in excess of 6672 kN (1,500,000 lbf) are generated at sea level. The assembled engine is contained within an envelope 6.1-m (20-ft) long by 3.7 m (12 ft) in diameter, and weighs approximately 82.7 kN (18,600 lbf) dry. Major components include a two-piece thrust chamber assembly, turbopump assembly, gas generator, and heat exchanger. The thrust chamber assembly includes the injector, fuel and oxidizer manifolds, an oxidizer dome, and gimbal assemblies.

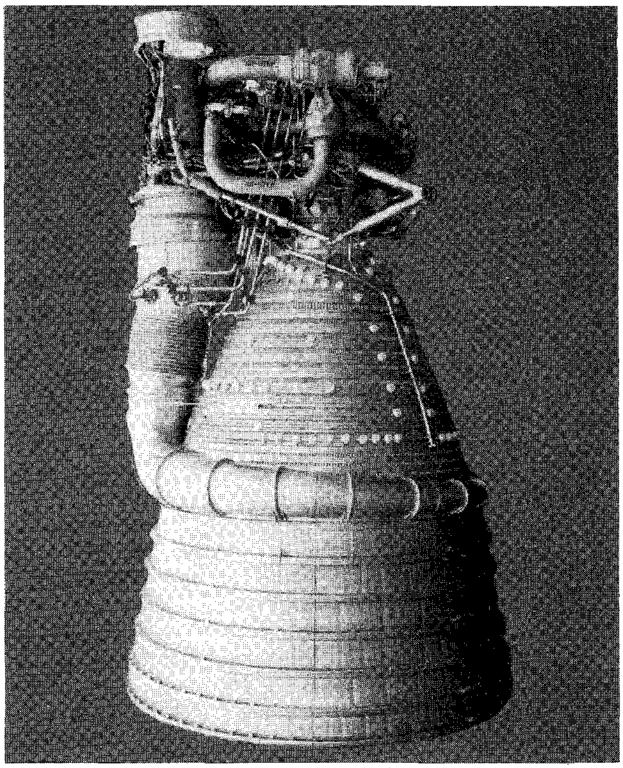


Fig. 1 Key external features of the F-1 engine.

Additionally, a furnace-brazed, tubular wall, regeneratively cooled combustion chamber/nozzle is used to a 10:1 expansion, together with a turbine exhaust gas-cooled nozzle extension which further expands gases to 16:1. The turbopump assembly consists of two centrifugal pumps (one fuel, one oxidizer) and a two-stage impulse turbine mounted on a common shaft which generates 40 MW (53,000 hp) at 5500 rpm. Nominal pump flow rates are 984 l/s (15,600 gal/min) of fuel

Table 2 F-1 engine operating conditions and performance specifications

Operating conditions				
	Engine[a]		Chamber	
Mass flow rate, kg/s, lbm/s				
Fuel	797	1,756	742	1,636
Oxidizer	1,808	3,986	1,784	3,933
Mixture ratio	2.27	2.27	2.40	2.40
Pressure, kPa, lbf/in.^{2}				
Injector face	7,757	1,125	7,757	1,125
Throat (stagnation)	6,757	980	6,757	980
Nozzle exit (16:1)	4,000	5.8	4,000	5.8
Temperature, K, °F				
Combustion area	3,572	5,970	3,572	5,970
Throat (static)	3,215	5,328	3,215	5,328
Exhaust gases (static)	1,566	2,359	1,566	2,359
Performance specifications				
	Engine		Chamber	
Thrust, kN, lbf				
Sea level	6,770	1,522,000	6,770	1,522,000
3657.6 m (120,000 ft)	7,775	1,522,000	7,775	1,748,000
Specific impulse, s				
Sea level	265.4	265.4	273.5	273.5
3657.6 m (120,000 ft)	304.8	304.8	314.0	314.0
Characteristic velocity, m/s, ft/s				
Injector face/nozzle throat	1,902/1,660	6,241/5,446	1,902/1,660	6,241/5,446
Efficiency, %	94.32	94.32	94.32	94.32
Feed system specifications				
	Fuel side		Oxidizer side	
Injection temperatures, K, °F	311	100	97	−285
Pressure drops, kPa, lbf/in.^{2}				
Injector	641	93	2,100	305
Fuel manifold/oxidizer dome	2,450	355	340	50
Main propellant valves	680	99	680	98
Control orifice	910	132	N/A	N/A
High-pressure ducts	440	64	110	16
Turbopump				
Mass flow rate, kg/s, lbm/s	796	1,754	1,804	3,978
Inlet temperature, K, °F	290	60	90	−298
Inlet density, kg/m^3, lbf/ft^3	808	50.6	1,143	71.38
Inlet pressure, kPa, lbf/in.^{2}	310	45	450	65
Discharge pressure, kPa, lbf/in.^{2}	13,000	1,856	11,000	1,600
Developed head, m, in.	1,575	5,168	944	3,097

[a]0.91 kg/s (2 lbm/s) fuel allotted to gimbal actuator, 1.8 kg/s (4 lbm/s) oxidizer diverted to heat exchanger.

at 12.9 MPa (1870 psia) and 1577 l/s (25,000 gal/min) of oxidizer at 11.0 MPa (1600 psia). The gas generator provides turbine drive gas, while the heat exchanger provides liquid oxygen (LOX) tank pressurization to maintain an acceptable net-positive-suction-head at the LOX pump inlet. Detailed engine specifications can be found in Refs. 1, 7, and 8.

Components relevant to discussion are the injector assembly, fuel and oxidizer manifolds, oxidizer dome, and combustion chamber-injector interface. Figure 2 illustrates key features of the injector assembly and combustion chamber. The injector assembly incorporates the typical alternating fuel and oxidizer ring groove design, 112 cm in diameter, extending 20 cm back from the face. Installed, the wall-to-wall face diameter is 100 cm. Fuel is funneled through 32 radial feed passages and is supplied to the ring grooves through a series of axial holes drilled into the passages. Radial feed passages are fed from a fuel manifold which is welded to the upper end of the combustion chamber. The LOX dome assembly distributes oxidizer to the axial feed holes and is fed by the oxidizer manifold. Oxidizer ring grooves are supplied by a series of axial holes drilled into the oxidizer dome cavity. Both fuel and oxidizer manifolds incorporate two flanges 180-deg apart for mounting the main fuel and oxidizer valves. The fuel manifold also provides the interface for the combustion chamber wall cooling tubes, with the tube transition located at the throat (3:1 expansion ratio). Tubes between the injector and the 3:1 expansion ratio have been designated as primary tubes, while tubes extending from the throat to the 10:1 expansion ratio have been designated as secondary tubes. Two secondary tubes are spliced into each primary tube. Primary tubes consist of 89 supply tubes and 89 return tubes. Seventy percent of the incoming fuel is used for combustion chamber cooling. The remaining 30% enters directly into the injector manifold and is mixed with return coolant fuel.

Historical Profile

Development of the F-1 engine system spanned the period from the mid-1950s to the early 1970s to satisfy heavy-lift requirements of the Apollo program. A cluster of five F-1 engines powered the first stage of the Saturn V launch vehicle. During the period between the inception of F-1 development and October 1962, several failures resulting from combustion instabilities highlighted the fact that this problem was not sufficiently understood. To circumvent these difficulties, and to enhance the level of fundamental knowledge in the area of combustion instabilities, a combustion stability Ad-Hoc Committee was formed in July 1962, followed by the initiation

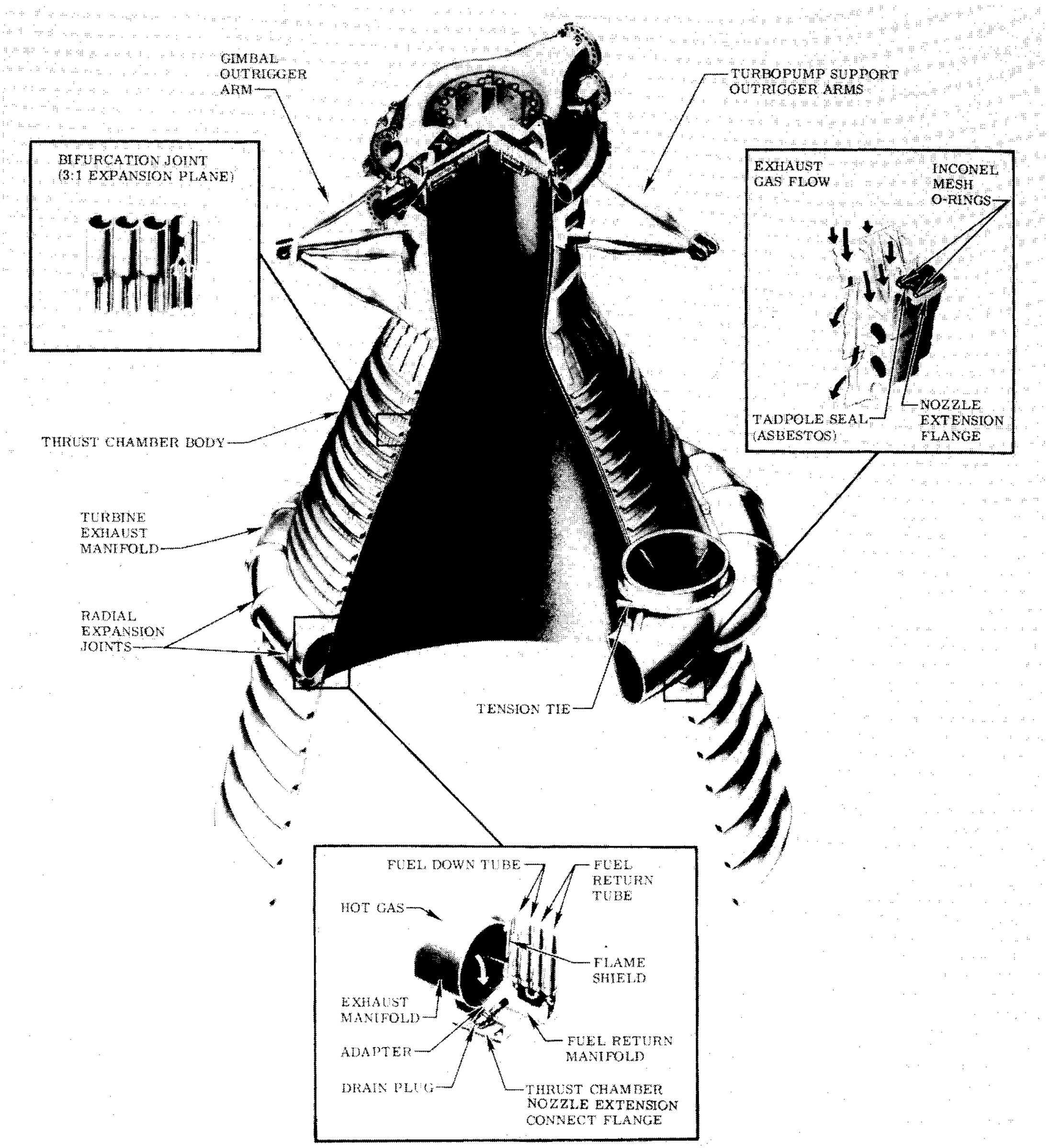


Fig. 2 Key features of the F-1 engine combustion chamber and injector body.

of the "Project First" program in October 1962. Project First was established as an all-out effort to solve the combustion stability problems encountered in the F-1 engine. This program spanned the period from October 1962 to September 1966, at which time the F-1 engine received complete qualification for manned missions. The two principal objectives of the program were to develop a dynamically stable F-1 engine within the development schedule, and to determine what design and operational parameters were fundamental to the development of dynamically stable liquid-propellant rocket engines. As a result, several basic and applied research programs were initiated in support of the development process.

Of approximately 3200 full-scale tests performed during development of the F-1 engine, about 2000 were conducted during Project First. Fourteen basic injection patterns in combination with fifteen baffle configurations were tested at full scale during periods leading up to preliminary flight rating tests (PFRT), flight rating tests (FRT), and flight qualification tests.[3,4] Table 3 lists the injection patterns investigated, with the corresponding baffle configuration given in Fig. 3. Over 90% of the tests conducted during Project First focused on the 5U and modified 5U patterns fitted with a 13-compartment by 7.62-cm baffle. This combination ultimately evolved into the flight qualification configuration, thus, these injectors are the focal point of the analysis which follows. In the ensuing discussion, various injector designs are referred to in terms of the unit and type numbers originally designated by Rocketdyne. Unit numbers correspond to a particular piece of hardware. Type numbers identify a particular design configuration. This information is retained in the interest of preserving injector genealogy.

Research Programs in Support of Injector Development

Two large-scale research programs which produced significant results during Project First were a two-dimensional thrust chamber program which was initiated to evaluate concepts related to F-1 combustion characteristics and H-1 testing in support of F-1 development. The two-dimensional thrust chamber program initially made use of a low pressure chamber low-pressure, two-dimensional engine (LP2D) capable of producing up to 500 psia.[9-11] This chamber had previously been used for modeling the Atlas MA-5, H-1, and Thor-Jupiter S-3D type booster engines, and was best suited for investigating basic theories. Visual approximation of combustion dynamics was also made through use of transparent chamber walls. Exact modeling of F-1 combustion was not possible with the LP2D. By June 1963, a high-pressure, two-dimensional engine system (HP2D), which was essentially a radial

Table 3 Injector patterns investigated during the F-1 Project First program

	Baffle			Injection element		
Injector pattern	(a)	(b)	(c)	Fuel	Oxidizer	No. tests
1) Modified 5U	—	—		Doublet	Doublet	4
	b	4	7.62	Doublet	Doublet	5
	c	9	7.62	Doublet	Doublet	2
	e	13	7.62	Doublet	Doublet	20
	f	13	7.62	Doublet	Doublet	1307
	f	13	15.2	Doublet	Doublet	1
	g	21	7.62	Doublet	Doublet	4
	k	53	7.62	Doublet	Doublet	1
2) 5U	—	—		Doublet	Triplet	19
	a	3	7.62	Doublet	Triplet	35
	e	13	7.62	Doublet	Triplet	350
	e	13	15.2	Doublet	Triplet	1
	e	13	25.4	Doublet	Triplet	1
	f	13	7.62	Doublet	Triplet	101
3) Radially aligned	f	13	7.62	Doublet	Doublet	19
	g	21	7.62	Doublet	Doublet	1
	i	25	7.62	Doublet	Doublet	33
	i	25	7.62	Doublet	Triplet	7
4) Double-row cluster	e	13	7.62	Doublet	Triplet	5
	e	13	7.62	Showerhead	Triplet	2
	i	25	7.62	Doublet	Triplet	9
5) Single-row fuel, double-row LOX	e	13	7.62	Doublet	Triplet	4
6) H-1	f	13	7.62	Doublet	Triplet	4
7) Reverse 5U	e	13	7.62	Doublet	Triplet	2
8) Rotated fan	d	11	7.62	Doublet	Doublet	2
9) Spray nozzle	f	13	7.62	Nozzle	Nozzle	2
10) Double-row fuel, single-row LOX	f	13	7.62	Doublet	Doublet	13
	l	81	7.62	Doublet	Triplet	1
11) Splash ring	—	—		Showerhead	Triplet	2
12) Shielded stream	—	—		Doublet	Triplet	1
13) O-F-O Triplet	—	—		—	—	1
14) Coaxial	h	21	7.62	—	—	17

(a) Baffle pattern key; (b) number of baffle compartments; and (c) baffle length, cm.

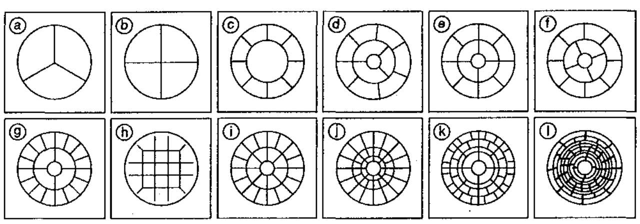


Fig. 3 Baffle patterns investigated during the F-1 Project First program.

slice of the F-1 chamber, was developed. A complete description of the operational details of the HP2D is given by Arbit.[12] This system produced chamber pressures on the order of 7500 kPa (1100 psia) and was used so that processes such as spray fan formation, atomization, and mixing characteristics at chamber pressures comparable to that of the F-1 engine could be better understood. H-1 testing in support of F-1 development was established with the objective of modeling certain F-1 operational conditions.[13,14] Significant contributions included verification that large fuel orifices and/or a "high" O/F velocity ratio was beneficial for dynamic stability, and that the outer zone of an injector was sensitive in terms of wave amplification. Other test series demonstrated that fuel film coolant on the order of 3–4% was all that was necessary to provide adequate cooling of the chamber walls. A limited investigation of propellant additives such as potassium tert-butoxide and ethylene dibromide showed no appreciable effect on either stability or performance. Finally, the need for baffles was emphasized through an attempt to show improved damping characteristics on flatface injectors with high O/F velocity ratio. Dynamic stability was never exhibited unless baffles were in place.

Stability Rating and Performance Calculations

The technique used to rate the dynamic stability characteristics was ultimately based on detonation of 13.5-grain, side-mounted powder charges enclosed in a 15-cm-long ablative case. Detonation typically occurred within 1 s after mainstage was reached, and produced initial pressure perturbations which were approximately 100% of the mean chamber pressure.

Performance calculations were based on characteristic velocity values based on theoretical frozen equilibrium values. A throat area of 6206 cm^2 (962 $in.^2$) and ratio of injector-end to nozzle entrance stagnation pressure of 1.145 were assumed.

Initial Development Efforts

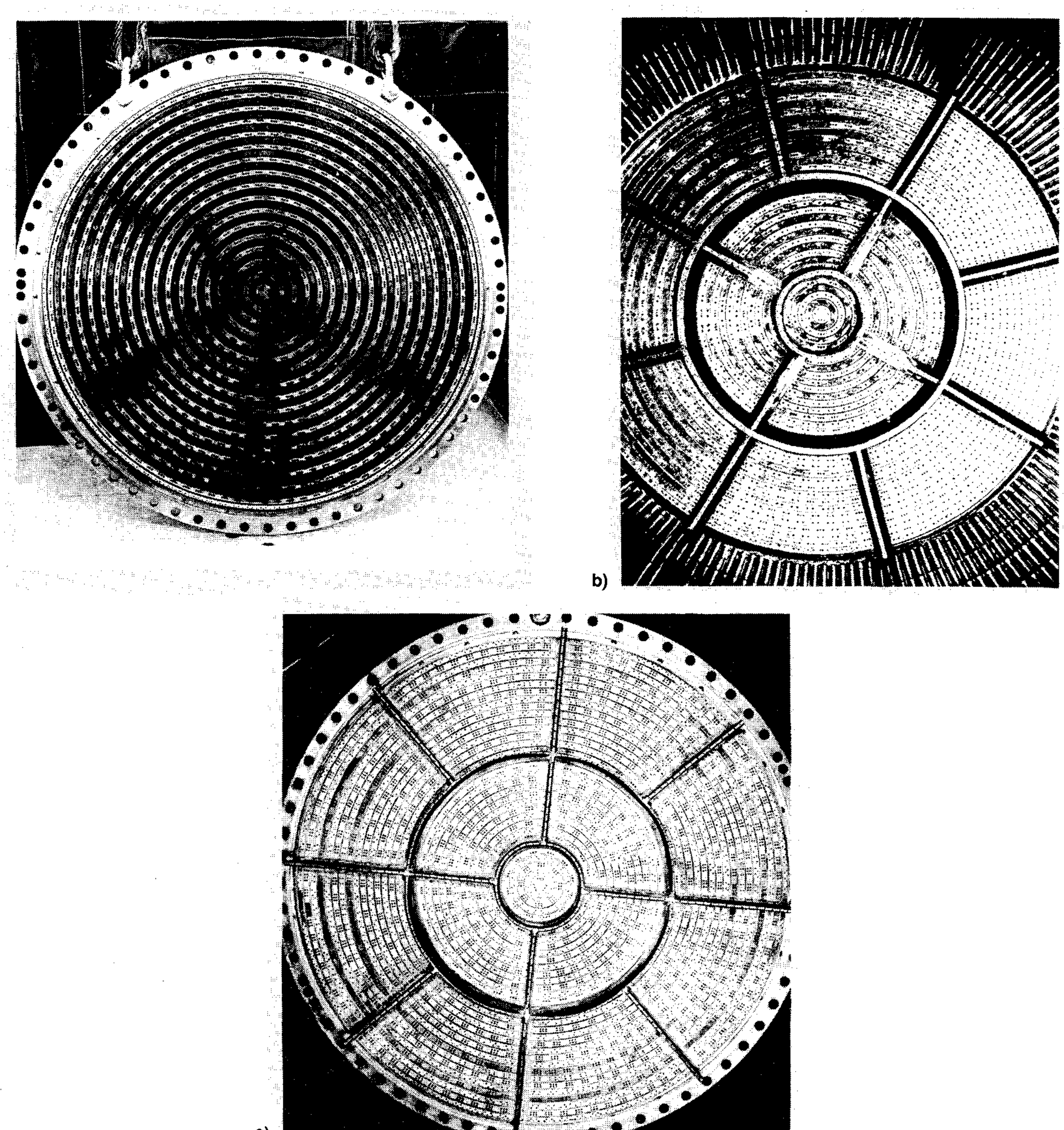
Harrje and Reardon[15] present a historical survey which clearly depicts the maturity of research on liquid-rocket combustion instability during the period prior to 1960 through 1972. During the 1950s, basic research in this area was in its infancy. Most prior experimental research was based on previous engine development programs, focusing on such bulk geometrical features of the combustion chamber as characteristic length and contraction ratio. Because of this, the F-1 combustion chamber and nozzle geometry were derived with a high degree of confidence in terms of performance. Consequently, design of a dynamically stable F-1 engine focused on modifications to the injector assembly.

Early injector designs were based on previous experience with the E-1 engine[16] at thrust levels up to 1334 kN (300,000 lbf). Orifice diameters were essentially uniform across the injector face, and the impingement plane of fuel and oxidizer elements were uniplanar. Forty-four injector tests with full-scale hardware at 4448 kN (1,000,000 lbf) thrust were conducted from January 1959 to May 1960, using rough, heavy duty hardware which was cheap and easy to work with.[17] This marked the first wave of problems concerning combustion instability. Twenty tests resulted in spontaneous combustion instabilities with amplitudes well in excess of 100% of the mean chamber pressure. Face burning occurred in all cases, creating erosion patterns which indicated the presence of significant radial fluid motion. Succeeding injector designs were based on H-1 injectors which were being developed concurrently with the F-1 engine. H-1 injectors had exhibited more favorable results in terms of stability during component tests.

Commencement of Project First

At the onset of Project First, all existing injector designs were evaluated to determine which configurations displayed the most promising characteristics in terms of both stability and performance. As a result, three injectors were selected to serve as the baseline for on-going research and development. These units were designated the 1) 5U-"flatface" (unit R005, type 4852E); 2) the 5U-"baffled" (unit 076, type 4866E); and 3) the double-row cluster (unit 067, type 4838) injectors. Photographs of these three injectors are presented in Fig. 4. Comparison of relevant design attributes can be found in Table 4. Each was designed using the typical ring groove type arrangement with matched pairs of fuel doublet and oxidizer triplet injection elements. Element orifice spacing, ring thickness, ring groove depth, and injector body hydraulics were all identical. Additionally, the orifice elements of all three units were designed with an impingement half-angle of 20 deg for both fuel and oxidizer injection elements. The 5U-flatface and 5U-baffled injectors were identical in design, with the exception of those modifications required to accommodate the baffle. Unlike the 5U pattern, the double-row cluster pattern incorporated a double row of both fuel and oxidizer elements on matched ring pairs.

All three of the injector configurations described above exhibited spontaneous instabilities that occurred and persisted until cutoff of the propellant flow. Figure 5 is representative



a) b) c)

Fig. 4 Baseline injectors: a) 5U-flatface (unit 005, type 4852); b) 5U-baffled (unit 076, type 4866); and c) double-row cluster (unit 067, type 4838).

Table 4 Design attributes of the initial baseline injectors

	(a)	(b)	(c)
Injector pattern[a]	2	2	4
Fuel element type	Doublet	Doublet	Doublet
Impingement half-angle, deg	20	20	20
Orifice diameter, mm	3.66	4.04	2.79
Orifice spacing, mm	10.6	10.6	10.6
Oxidizer element type	Triplet	Triplet	Triplet
Impingement half-angle, deg	20	20	20
Orifice diameter, mm	4.04	4.32	3.28
Orifice spacing, mm	10.6	10.6	10.6
Baffle pattern[a]	——	*e*	*e*
Number of compartments	——	13	13
Length, cm	——	7.62	7.62
Nominal injection conditions			
Fuel injection velocity, m/s	51.0	46.2	49.9
Fuel-side pressure drop, kPa	N/A	N/A	N/A
Oxidizer injection velocity, m/s	46.2	49.1	47.0
Oxidizer-side pressure drop, kPa	N/A	N/A	N/A
Fraction of fuel used as film coolant, %	10.7	9.6	6.2
Fraction of total outer fuel ring flow, %	100	100	100
Stability characteristics			
Mode of instability	$1T^{b}$	$1T^{b}$	$1T^{b}$
Frequency of oscillation, Hz	538	460	454
Amplitude, % p_{Chamber}	150	65	400
Stability rating			
Number of tests	15	39	7
Average damp time, ms	∞	∞	∞
Performance			
Characteristic velocity efficiency, %	94.6	93.1	N/A
Specific impulse, s	243.2	252.4	N/A

[a]Keyed numbers and letters correspond to those found in Table 3.
[b]First tangential mode.
(a) 5U-Flatface injector (unit 005, type 4852); (b) 5U-baffled injector (unit 076, type 4866); and (c) double-row cluster injector (unit 067, type 4838).

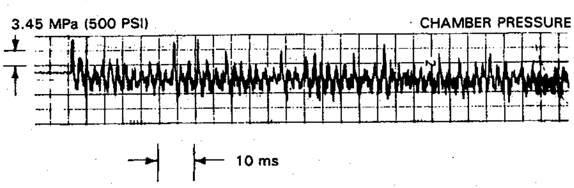


Fig. 5 Typical pressure-time trace exhibited during operation of injector units 005, 076, and 067.

of typical pressure traces observed during operation of these injectors. First-tangential spinning oscillations were the principal mode encountered when unstable combustion was initiated. A detailed description of this type of oscillation is provided by Clayton.[18] Frequencies of approximately 540 Hz were observed for the 5U-flatface injector, and frequencies of approximately 440 Hz were observed for the 5U-baffled injector. The 5U-flatface injector typically exhibited amplitudes on the order of 150% of the mean chamber pressure. In all cases, the oscillation amplitudes of the 5U-baffled injector were lowered to a point where significant engine damage was less likely to occur. Compared to the 5U-flatface injector, the incidence of self-triggered instability was higher on the baffled version. The double-row cluster injector exhibited a chamber frequency in the vicinity of 450 Hz; however, oscillation amplitudes on the order of 400% of the mean chamber pressure were observed.

Of the three baseline candidates described, the 5U pattern exhibited more favorable characteristics when compared to the double-row cluster. Consideration of 5U-baffled vs 5U-flatface injectors indicated that a tradeoff existed between engine reliability; which was brought about through decreased oscillation amplitude afforded by the baffle, and incidence of self-triggering; which occurred less frequently on the flatface version. One additional consideration, as demonstrated by the works of Levine and Bambanek,[19] and Reardon,[20] was that the combustion process was strongly affected by transverse velocity components associated with transverse modes of oscillation. This effect was especially noticeable near the injector face where large temperature gradients existed. Introduction of radial baffles into this region was known to effectively reduce the magnitude of transverse oscillations, since each baffle surface became an acoustic velocity node. Questions remained regarding the pattern and length, since effective suppression of transverse flow depended on the baffle blade length, the blade spacing, and the wave pattern of the mode induced in the unbaffled portion of the chamber.[21] The above assessments led to the pursuit of an injector design incorporating baffles, with emphasis placed on the 5U pattern.

Development of the PFRT Injector

The PFRT injector configuration evolved from the results of full-scale component tests conducted from October 1962 to June 1963. Objectives during this period were to identify and eliminate mechanisms responsible for self-triggered oscillations. Tests were also conducted to determine the effect of various injector element orifice modifications on dynamic stability. Initial investigations focused on the possibility that injection coupling acted as a driver for spontaneous oscillations in the combustion chamber. This led to a series of feed-system modifications in an effort to eliminate low-frequency acoustic paths and minimize unsteady motions in the feed system. These modifications resulted in a significant reduction in the incidence of self-triggered combustion instability. Subsequent investigations focused on the displacement sensitivity of impinging jets. Several series of tests demonstrated that increased fuel-droplet size, coupled with increased relative velocity between gaseous oxygen (GOX) and fuel-droplets (obtained by reducing the nominal fuel-injection velocity), had a significant favorable impact on dynamic stability. This combination had the net effect of moving the combustion zone downstream away from the sensitive region near the injector face. After establishing trends related to the above concepts, a broad range of tests were conducted to investigate the effect of various injector patterns and chamber geometry modifications on stability and performance.

Hydraulic Modifications

The potential for hydraulic flip in F-1 injector orifices, and the impact of the Klystron® effect on stability, remained conjectural during the PFRT stage. The term "hydraulic flip" characterizes the variation in pressure drop between two stable points across an injector orifice. The Klystron effect is attributed to intrinsic hydrodynamic instability within an issuing jet, and induced by axial variations in fluid particle acceleration. Experimental observations[22–24] had shown that sinusoidal flow variations could form in the combustion chamber as a result of the hydraulic flip phenomena or through the Klystron effect. Heidmann et al.[25] had demonstrated close correspondence between natural combustion fluctuations observed in thrust chambers to spray oscillations exhibited by impinging jets. Disturbances produced by these phenomena were observed to propagate through pockets of unburned propellant and grow into steep-fronted waves. Either condition is aggravated by pressure oscillations in the feed system. Thus, early attempts to eliminate self-triggered instabilities focused on injector body hydraulics.

General Electric's experience[26] with project Hermes had shown that a properly designed ASME orifice did not show any flip characteristics, while a chamfered orifice had very poor flip characteristics. Therefore, as a precaution, ASME orifices were incorporated into the PFRT configuration to eliminate the possibility of this phenomenon. Ito[27] and Wright[28] have since determined the effect of orifice length-to-diameter ratio, manifold cross velocity, and pressure drop on the discharge coefficient of a typical orifice. Lack of definitive data regarding the Klystron effect left few options open aside from injector body impedance modifications. These modifications consisted of dams in the LOX torus, flow diverters on the back-side of the injector (LOX dome baffles), fuel port isolation tabs, fuel port inserts, and dams within the fuel and oxidizer ring grooves. The combination of these devices was designated hydraulic modification kit 1. To eliminate flashback, which had caused severe injector face burning in previous cases, a series of flame arresters were installed in the fuel ring grooves. This modification, combined with the components used in hydraulic modification kit 1, was designated hydraulic modification kit 2. Figure 6 illustrates hydraulic modification kits 1 and 2, respectively.

Tests were conducted to evaluate the effect of each component depicted in Fig. 6. 5U-Flatface injectors identical to

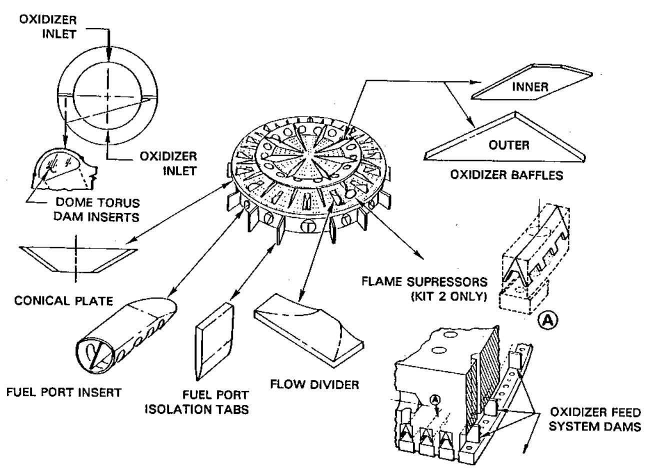


Fig. 6 Hydraulic modification kits 1 and 2.

unit R005 (units 079 and X004), and 5U-baffled injectors identical to unit 076 (units 075, 074, and X002) were used. Combined, these devices had a pronouncedly favorable effect on the incidence of self-triggered instability observed with 5U-flatface injectors, and were favorable to a somewhat lesser extent on 5U-baffled injectors. None of these modifications produced a tendency toward dynamic stability. However, they did appear to reduce chamber pressure oscillation amplitudes in 5U-baffled injectors with frequencies spread over a broader range. Later in the development process, the achievement of markedly improved dynamic stability characteristics exhibited by injectors and subsequent redesign of the LOX dome allowed removal of all the hydraulic modifications described above along with the ASME orifices.

Impinging Jet Displacement Sensitivity

The first significant trends toward dynamic stability were achieved with F-1 developmental injectors by displacing the combustion zone downstream away from the injector face. Work conducted at Princeton[29] had shown that effects due to the relative position of the fuel and oxidizer fans (referred to as displacement sensitivity) provided the proper conditions for maintenance of a spinning mode. This displacement sensitivity only appeared if the major combustion zone was relatively close to the injector face, where oxidizer vapor existed in a sufficient degree of angular nonuniformity. If the combustion zone was moved to a region downstream where the oxidizer vapor concentration was essentially uniform, the effect of displacement decayed to a level incapable of supporting instability. Further experiments performed by Crocco et al.,[30–32] using a model scale rocket motor, demonstrated the importance of the axial energy release pattern on transverse modes of instabilities. Increasing the fuel injector orifice diameters while maintaining constant mass flow rates and oxidizer orifice diameter, produced a delay in the fuel vaporization rate which caused the combustion zone to move downstream to a less sensitive region. This modification decreased the fuel side pressure drop which in turn reduced the nominal fuel injection velocity. Lower fuel injection velocity resulted in an increase in the mean fuel droplet diameter. The overall result produced a consistent attenuating effect on instabilities and a substantially reduced occurrence of the tangential mode, with oxidizer to fuel velocity ratios of 3:1 producing the most marked influence toward stability. Tangential modes had been observed to produce maximum unsteady pressure amplitudes near the injector face.[33,34] It was concluded that the displacement sensitivity of the fuel and oxidizer fans was greatest when the combustion zone was close to the injector face, and that this condition supported the tangential mode.

Initial investigations into the displacement sensitivity of impinging jets with full-scale F-1 injectors focused on the 5U-baffled injector unit 076. This unit originally operated at an O/F velocity ratio of approximately 1:1. Fuel orifices were enlarged in two steps from 4.04 to 7.14 mm, then to 8.89 mm while holding mass flow constant. This produced a corresponding change in fuel-injection velocity from 46.2 (151.5) to 16.0 m/s (52.5 ft/s), then to 11.2 m/s (36.7 ft/s). Damp times associated with a 13.5-grain bomb-induced instability, in respective order, were 420 ± 368 ms and 200 ± 150 ms. In comparison with the initial baseline units, this injector configuration exhibited a marked change in combustion characteristics. Prior to these modifications, no tendency towards self-stabilization at design point conditions was observed. The favorable results achieved with the 5U-baffled configuration resulted in evaluation of similar modifications with a 5U-flatface injector (unit X004). This unit was identical to the baseline unit R005, except that the fuel orifices were enlarged from 3.66 to 7.14 mm, which increased the O/F velocity ratio from 0.91 to 2.15. For this configuration, however, no tendency toward dynamic stability was observed. This was one of many unsuccessful attempts to achieve dynamic stability without the aid of baffles.

The improvement in stability attributes achieved with 5U-baffled injectors was accompanied by a loss in performance and the occurrence of low-frequency, steep-fronted, high-amplitude waves classified as "resurging." The resurging phenomenon was observed during every bomb test of a system with enlarged fuel orifices. Figure 7 shows a typical pressure trace of the resurge phenomena observed during tests with unit 076. Inspection of these oscillations suggests that the erratic damp times exhibited in the above tests can be attributed to retriggering of the initial perturbation following significant damping. Maximum power in the range of 120–160 Hz was generally observed. It was not uncommon for these oscillations to be spontaneously extinguished. This phenomenon was further studied during the FRT development period.

While the beneficial effect of enlarged fuel orifices in terms of dynamic stability had apparently been proven, it was unclear whether the benefit could be attributed to enlarged stream diameters, or the resultant reduction in the nominal fuel-injection velocity. Abbe et al.[35] conducted tests which isolated the effect of propellant mass flow, injection velocity, and pressure drop on stability. Results indicated that larger orifice sizes resulted in improved stability, with the influence of both fuel and oxidizer orifice diameter changes combined being greater than either individually. In general, fuel droplet size distributions were observed to control the rate of LOX/hydrocarbon combustion.[36] Axial distribution of fuel droplets in a uniform GOX environment were observed to minimize acoustic coupling by moving the flame zone away from the sensitive region near the injector face.[37] Fuel droplet size, and the relative velocity between fuel droplets and GOX, were found to have a significant effect on this distribution. Furthermore, diameters of orifices play an important role in determining spray-fan characteristics and drop sizes. Larger drop sizes tended to reduce propellant vaporization rates, which is a stabilizing influence.

Investigation of Divergent Rings

Simultaneous efforts during this period focused on boundary effects which promoted wave amplification. Prior to F-1 development, combustion instability in the E-1 engine[16] was overcome through the use of a divergent ring placed around the perimeter of the injector face. Divergent profiles were used to attenuate oscillations induced by reflection of high-amplitude pressure waves by eliminating the corner region produced at the injector face and chamber wall interface. This concept was effectively tested on a 5U pattern (unit R007) identical to the baseline 5U unit R005, with the exception of a three-compartment radial baffle. Twenty-five tests were conducted using divergent rings extending 12.45-cm up the chamber wall, and 13.06-, 10.41-, and 7.770-cm over the injector face (types 5810, 5810X, and 5832/5866X, respectively). In each case, 13.5-grain bomb-induced perturbations were damped in less than 20 ms; however, characteristic velocity efficiency and specific impulse were reduced to 89% and 239.10 s, respectively. Two additional tests conducted using a 12.45 by 10.41-cm divergent ring without baffles (type 5820) exhibited self-sustained instabilities. This was another case which suggested the need for baffles to achieve dynamic stability.

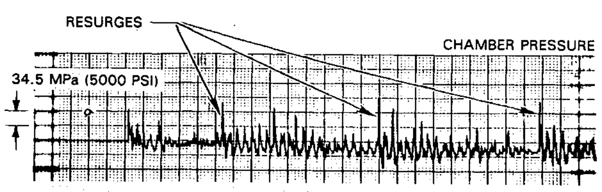


Fig. 7 Pressure trace exhibiting the resurge phenomena observed during bomb-induced perturbations of injector unit 076 with enlarged fuel orifices.

Selection of the PFRT Configuration

Final selection of the PFRT injector configuration was made in June 1963. The 5U pattern had clearly exhibited the most favorable combustion characteristics. 5U-flatface injectors exhibited a specific impulse of 261 s at sea level (1 s above requirements), while that of the 5U-baffled version was 252 s due to fuel baffle cooling requirements. No self-triggered instabilities had been experienced with either configuration fitted with hydraulic modification kits 1 or 2, and face burning behind the injector rings had been eliminated. Flatface injectors appeared to be the most promising in terms of performance; on the other hand, baffled injectors offered a higher degree of reliability at the expense of performance. Both designs exhibited first tangential spinning oscillations when perturbed by a 13.5-grain bomb. Previous tests with injector units X004 and R007 suggested the need for baffles to prevent sustained instabilities in the transverse mode. Since the prime concern at this point in development was attainment of a dynamically stable injector, and since the 5U-baffled injector offered a higher degree of reliability in terms of engine damage, this pattern was selected as the PFRT design.

Before final determination of the fuel injector orifice diameter size was made, an additional series of tests were conducted to re-evaluate the effects of enlarged fuel orifices on the dynamic stability characteristics of a 5U-baffled injector fitted with all other PFRT components (unit X007). This unit incorporated a 13-compartment by 7.62-cm baffle configuration similar to unit 076, except that the inner radial baffles were offset with respect to the outer radial baffles. Fuel-injection orifices were enlarged from 4.22 to 5.79 mm, resulting in a corresponding reduction in velocity from 46.3 (152) to 23.1 m/s (75.7 ft/s). Oxidizer injection orifices were fixed at 4.70 mm, which yielded a nominal injection velocity of 46 m/s (150 ft/s). Mixture ratio and mean chamber pressure were maintained at the design point conditions of 2.4 and 7757 kPa (1125 psia), respectively. Results yielded a distinct change in combustion characteristics. Average recovery times of 183 ms, with respective minimum and maximum values of 10 and 530 ms, were now observed in comparison to a prior condition which exhibited no dynamic stability characteristics. Fuel orifice diameters of 5.79 mm were selected along with oxidizer orifice diameters of 4.70 mm. No attempt was made at this point to determine the optimum injection velocities.

Figure 8 is a photograph of the PFRT injector (unit F1002, type 5828V) with key design specifications listed in Table 5. This injector was identical to unit X007. Ring orifice elements consisted of fuel doublet and oxidizer triplets, each with im-

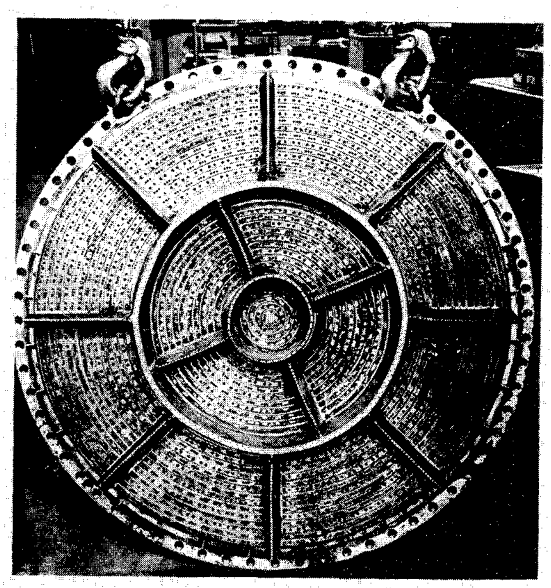


Fig. 8 PFRT injector configuration.

Table 5 PFRT injector specifications

Injector pattern	
Fuel element type	Doublet
Impingement half-angle, deg	20
Orifice diameter, mm	5.79
Orifice spacing, mm	10.6
Oxidizer element type	Triplet
Impingement half-angle, deg	20
Orifice diameter, mm	4.70
Orifice spacing, mm	10.6
Nominal injection conditions	
Fuel injection velocity, m/s	23.2
Fuel-side pressure drop, kPa	1975
Oxidizer injection velocity, m/s	46.6
Oxidizer-side pressure drop, kPa	2424
Fraction of fuel used as film coolant, %	10.9
Fraction of total outer fuel ring flow, %	100
Stability rating	
Number of tests	5
Average damp time, ms	108
Performance	
Characteristic velocity efficiency, %	91.5
Specific impulse, s	256.5

pingement angles of 20 deg. The injector body was fitted with hydraulic modification kit 2 to eliminate the incidence of self-triggering. Both the radial and circumferential baffle blades were dump cooled with fuel. This unit exhibited an average c^* efficiency of 91.5% and an average specific impulse of 256.5 s, in comparison to 93% and 252 s exhibited by the baseline 5U-baffled injector (unit 076). Fuel and oxidizer pressure drop at rated flow conditions were 1975 kPa (286.5 psi) and 2424 kPa (351.5 psi), respectively. No incidence of self-triggered instability was encountered in 11,040 s of testing. Additionally, self-damping characteristics were not consistently exhibited by this unit when subjected to a 13.5-grain bomb. First tangential resurging oscillations, identical to those observed on unit 076, were predominant.

Development of the FRT Injector

FRT injectors evolved from the results of full-scale component tests conducted from June 1963 to January 1965. During this period, injector modifications yielded significant improvement in dynamic stability characteristics in addition to improved efficiency and performance. Analysis of combustion-zone dynamics included determination of the LOX vapor environment most favorable for fuel droplet vaporization and combustion. These studies led to the concept of biplanar impingement followed by investigations regarding the optimum propellant injection velocity ratio. Attempts were also made to differentiate between the effects of fuel-injection velocity, fuel orifice size, and fuel differential pressure drop. Incidence of resurging was reduced by significantly decreasing the percentage of fuel used as chamber-wall film coolant.

Variations in LOX-injection velocity produced conflicting trends between stability and performance. Analysis of test results indicated that the circumferential LOX velocity components had a dominating effect on stability, whereas the axial components affected performance. This prompted a series of tests to determine the optimum velocity and impingement angle for oxidizer injection elements. Improvement in both stability and performance were realized; however, a low-amplitude 500-Hz first tangential oscillation designated "buzz" appeared. To counteract this problem while maintaining stability and performance, the LOX dome and injector body hydraulics were reinvestigated in terms of the effect of each on buzzing. While some trends were noted, the problem of buzzing carried into the period leading to the flight qualification injector. Concurrent studies focused on the effects of "near-wall" injection element modifications and the resurging phenomena on transverse oscillations. Near-wall injection element modifications involved canting fuel and LOX fans away from radial baffles to alter the mixture ratio near confining surfaces. The effect of increased wall-gap between the chamber wall and adjacent injector orifices was also investigated.

Physical Trends

Trends exhibited by the PFRT configuration exhibited two distinct phenomena: the appearance of a 500-Hz acoustic mode, and the presence of a resurging "mode" which induced erratic repetition and severity of pressure oscillations. The 500-Hz mode was characterized by a first tangential oscillation consistently spinning in one direction. Tests conducted with the LP2D apparatus by Levine and co-workers[38,39] using like-on-like doublet elements similar to those in the F-1, suggested the spray field produced by the PFRT configuration was stratified.[40,41] The mixture ratio gradients produced by this condition promote mixture ratio oscillations in the vicinity of vaporizing droplets, inducing burning rate oscillations which could couple with the acoustic field.[42,43] Upstream jet-impingement and fan-intersection attributes were known to have a marked effect on this sequence of processes.[44] On the other hand, Heidmann and Foster[45] had demonstrated that spray distributions with larger mean droplet diameters existed with decreasing impingement angle.

In an attempt to gain further insight into resultant trends produced over a range of injector orifice sizes, local mixture ratio and mass distribution of a single 5U element pair (i.e., one fuel doublet, and one oxidizer triplet),[46,47] and droplet distributions studies were conducted using single element doublets identical to those used in the PFRT configuration.[48] Detailed results of these test series are given in Ref. 1. Local mixture ratio and mass distributions measurements of a plane 30.5 cm from the injector face indicated that the momentum of impinging fans caused the principal portions of both the fuel and oxidizer flows to be driven apart at design point conditions. The relatively greater amount of oxidizer, coupled with higher momentum, produced a zone into which virtually no fuel penetrated. The fuel fan appeared to be split such that fuel was displaced to either side of the oxidizer and forced directly away from the point of impingement. Lowering the nominal mixture ratio 5% below the design point value produced the same general pattern, with reduced penetration into the fuel. This caused the oxidizer-rich zone to drop off more sharply at the fan impingement point, producing a slightly broader zone of uniformity. A nominal mixture ratio 10% above the design point value reversed the situation. This change produced a highly nonuniform mixture-ratio distribution. Enlarging the fuel orifices, while maintaining the design point mixture ratio, produced greatly increased zones of high oxidizer concentration. Extremely high concentrations of oxidizer were observed directly below the fuel fan, and the fuel side mass peak was displaced further away from the point of impingement. The foregoing conditions were exaggerated with increased fuel orifice diameter. Results of droplet size studies produced by a single doublet element with orifice diameters of 4.039, 5.791, 7.142, and 9.347 mm are presented in Table 6. Mass flow rate was held constant throughout. Size ranges between 155–494 μm are displayed. Droplet size was observed to increase with the orifice size in a monotonic fashion. This was true for both centerline spray measurements, and at 10 deg off the centerline.

Biplanar Impingement

The above results suggested that the benefit demonstrated in terms of stability by enlarging the fuel element orifices could be further enhanced by decreasing the fuel element impingement half-angle such that biplanar impingement existed between the fuel and oxidizer, with the fuel impingement plane displaced downstream of the oxidizer impingement plane. The goal was to increase the axial combustion distribution of the propellants, while providing a fuel-lean condition. This

Table 6 Droplet distributions produced by single-element doublets with an impingement half-angle of 20 deg, 43.2-cm downstream

Orifice diameters, mm	Injection velocity, m/s	Centerline, μ		10-Deg off center, μ	
		D_{10}	D_{32}	D_{10}	D_{32}
4.039	45.7	155	214	197	245
5.791	22.9	237	298	258	320
7.142	15.2	329	742	348	500
9.347	9.14	494	826	412	836

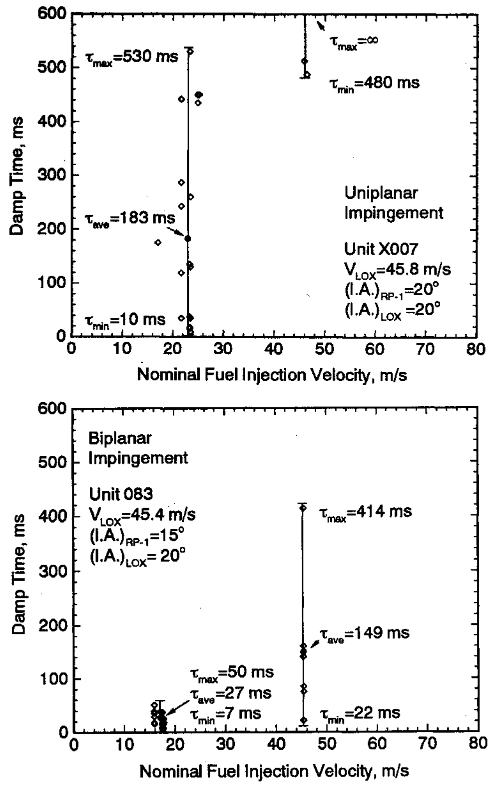


Fig. 9 Damping characteristics exhibited by uniplanar (unit X007) and biplanar (unit 083) impingement injectors.

concept was first tested on unit 083, which was a 5U-baffled configuration identical to the PFRT injector (unit X007), with the exception that the impingement half-angle of the fuel elements was changed from 20 to 15 deg. A series of tests was conducted at nominal fuel-injection velocities of 16.8 (55.0) and 46.3 m/s (152 ft/s). Figure 9 illustrates the favorable effect of this modification on damping characteristics. A nominal fuel-injection velocity of 16.8 m/s (55.0 ft/s) yielded average damp times which were reduced from 183 to 27 ms, with corresponding minimum and maximum values of 7 and 50 ms, respectively. At a nominal fuel-injection velocity of 46.3 m/s (152 ft/s), an average damp time of 149 ms was observed, with corresponding minimum and maximum values of 22 and 414 ms, respectively. The latter result was significant since no tendency toward dynamic stability had been observed at fuel-injection velocities in this range prior to these tests (i.e., unit X007). These results prompted a similar series of tests on a 5U-flatface pattern using unit X004 to determine if the same combination of design attributes was sufficient to render dynamic stability in the absence of a baffle. Attainment of dynamic stability on a flatface injector would minimize design complications and performance losses associated with baffle cooling. Unfortunately, the unbaffled injector failed to damp when perturbed by a 13.5-grain bomb, demonstrating once again the need for baffles to achieve dynamic stability.

Effect of LOX Injection Velocity

After establishing the favorable effect of biplanar impingement, a series of tests was conducted to determine the influence of the nominal LOX-injection velocity on stability. Changes in LOX-injection velocity were made through modifications to injector element orifice diameters. Injector unit 083 was used in the initial test series. As described in the last section, this was a 5U-baffled configuration identical to the PFRT injector, except that the fuel and LOX impingement half-angles were fixed at 15 and 20 deg, respectively. The nominal fuel-injection velocity was fixed at 16.5 m/s (54.1 ft/s). Extrapolation of test results conducted at LOX-injection velocities of 42.4 (139) and 51.5 m/s (170 ft/s) indicated that velocities beyond 61.0 m/s (200 ft/s) would produce combustion characteristics capable of consistently recovering from bomb-induced disturbances in less than 10 ms. To verify this observation, the LOX triplets of a 5U injector identical to unit 083 were converted to doublets so that the desired injection velocities could be achieved (unit 082). Injectors with this altered pattern were designated "modified 5U" configurations. Tests were conducted at the same fuel-injection velocity, with LOX-injection velocities of 42.5 (139) and 68.5 m/s (225 ft/s). Results at the higher velocity ($V_{LOX}/V_{RP\text{-}1}$ = 4.15) resulted in the damping of six 13.5-grain bomb-induced perturbations in 14 ms or less. Figure 10 illustrates the combined outcome of tests conducted with units 082 and 083. Instabilities at the higher velocity exhibited reduced angular frequency in the spinning mode, with a predominant frequency of 400 Hz rather than the typical 500 Hz characteristic of the PFRT configuration.

Two undesirable effects were observed as a result of the LOX orifice modifications. Favorable damping characteristics were accompanied by a decrease in performance and a LOX side pressure drop on the order of 5102 kPa (740 psi). The reduction in performance was associated with excessive spreading and displacement of the combustion zone away from the injector face due to high axial LOX velocity, suggesting that both axial and circumferential LOX stream velocity components had a distinct effect on stability and performance. Axial stream velocity altered the combustion distribution and affected performance. Circumferential stream velocity affected stability through interaction with adjacent elements. The effect of each component was evaluated by changing the LOX impingement half-angles on unit 082 from 20 to 28.3 deg, and enlarging the LOX orifice diameters from

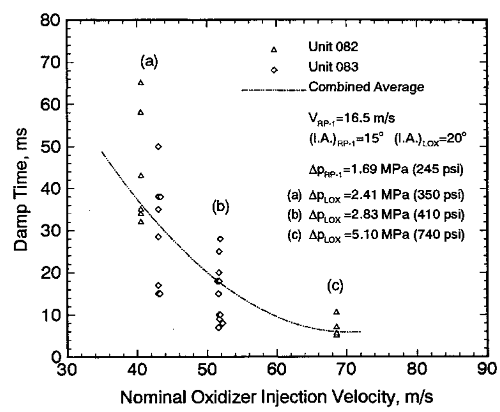


Fig. 10 Damp time vs oxidizer injection velocity for tests conducted with injector units 082 and 083.

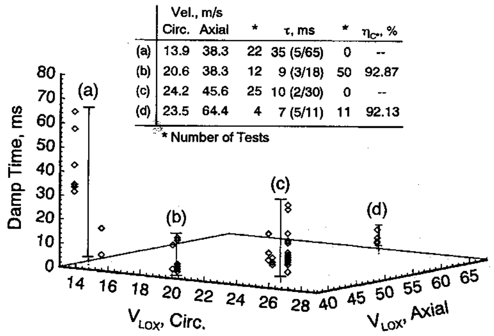


Fig. 11 Effect of oxidizer axial and circumferential injection velocities on damping characteristics and performance; unit 082, $V_{RP\text{-}1}$ = 17.1 m/s, $(I.A.)_{RP\text{-}1}$ = 15 deg.

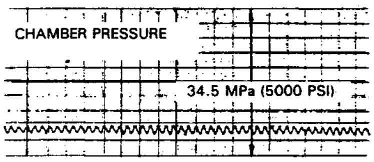


Fig. 12 Pressure trace exhibiting typical buzzing observed during the FRT and flight qualification development periods.

4.70 to 5.31 mm. Comparison of results are given in Fig. 11, which presents a plot of the recovery time required to damp a 13.5-grain bomb-induced perturbation vs nominal LOX circumferential and axial velocities. Four sets of data were acquired. Also included is a table which summarizes average, minimum, and maximum damp times for the four data sets. Available values of characteristic velocity are also given. All tests were conducted at a nominal fuel-injection velocity of 17.1 m/s (56.1 ft/s) and a fuel element impingement angle of 15 deg. Results suggest that minimum damp times were achieved at a circumferential velocity near 20 m/s (66 ft/s). Further decrease in damp time was observed when the axial velocity component was increased from 38.3 (126) to 64.4 m/s (211 ft/s) data sets (b) to (d). Comparison of these two data sets indicates a slight decrease in the average characteristic velocity efficiency at higher axial velocities accompanied by an increase in data scatter. None of the injectors tested with increased circumferential velocity experienced extensive resurging; however, low-amplitude, self-induced sinusoidal 500-Hz oscillations termed buzz appeared as a result of these modifications. Figure 12 exhibits a typical chamber pressure trace of the buzz phenomenon. Investigations of this condition are discussed subsequently.

Effect of Injector Body Pressure Drop

The effect of fuel-side pressure drop on stability was evaluated using injector units 081, 083, and X021. Units 081 and 083, which incorporated fuel and LOX orifice diameters of 7.14 and 4.62 mm, respectively, produced corresponding injection velocities of 17.7 (57.7) and 43.1 m/s (142 ft/s). Fuel and LOX impingement half-angles of both units were fixed at 15 and 20 deg. A secondary fuel ring located behind the injection ring set of unit 083 was the only difference between these two injectors. The secondary ring produced a fuel-side pressure of 1689 kPa (245 psi) in contrast to 931 kPa (135 psi) exhibited by unit 081. A series of nine bomb tests conducted on each injector resulted in average recovery times of 40 ms for unit 083 and 108 ms for unit 081. This suggested that high-pressure drop enhanced dynamic stability characteristics. Further tests were conducted on unit X021 with a secondary fuel ring set to determine if the double fuel ring was sufficient in itself to cause an injector with small fuel orifices to be dynamically stable. This injector was a 5U-baffled configuration identical to unit 076, with fuel and LOX impingement half-angles of 20 deg. Fuel and LOX orifice diameters of 4.04 and 4.70 mm, respectively, were used, producing injection velocities of 48.8 (160) and 43.0 m/s (141 ft/s). Neither of two tests conducted recovered from a 13.5-grain bomb-induced perturbation. It was concluded that both high fuel-side pressure drop and large fuel orifices with biplanar impingement were required to promote dynamic stability.

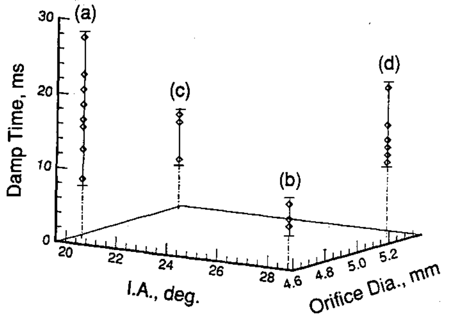
Efforts to reduce the pressure drop associated with LOX-side hydraulic losses led to evaluation of the LOX dome assembly. Two independent calculations had shown that approximately 80% of an 883 kPa (128 psi) overall dome head loss occurred in the inlet assemblies. Pressure fluctuations observed at frequencies of 350 Hz, with amplitudes of 2068 (300) to 3447 kPa (500 psi), had also been noted in the dome during tests. Minimization of these effects was desirable. Earlier in the development program, Priem[49] had made calculations which, when corrected for the effect of the vena contracta and curvature of passages, indicated effective velocities of 32.9 m/s (108 ft/s) in the two lines feeding the LOX torus, 43.0 m/s (141 ft/s) in the torus, and 76.2 m/s (250 ft/s) in the passage between the torus and dome. To reduce both hydraulic losses and oscillation amplitudes, velocities in the dome assembly were decreased by enlarging the passage area by a factor of 2 at the entrance, and a factor of 3 at the exit. The new design eliminated all abrupt turns and increased the area in the direction of flow. Flow conditions at the intersection of the inlet and torus manifold were also improved, reducing the hydraulic head such that LOX dome pressure oscillation amplitudes were less than 689 kPa (100 psi). Test results displayed a reduction in total LOX-side pressure drop of 586 kPa (85 psi).

Near-Wall Modifications

After establishing general trends and design conditions favorable in terms of stability, attention focused on confined regions within the proximity of the injector-face, baffle, and chamber-wall interfaces. Conditions near the wall serve to shape the waveform and modify amplitude and period of rotation. Deflection of the interlapped propellant sprays produced both increased mixing rate, and increased bulk density in these areas. Clayton[50] also noted that separation effects in the main flow further modified the actual near-wall spray distribution of propellants. These phenomenon produced conditions for generation of high-amplitude pressure waves.

Initial investigations of near-wall effects focused on regions adjacent to the radial baffle blades of the PFRT injector (unit F1002). Four test series incorporating (a) symmetrical (unmodified), (b) canted, (c) overlapped, and (d) both canted and overlapped oxidizer doublets, were conducted with this unit to determine the effect of various oxidizer spray pattern modifications on damping. Canting of LOX fans was achieved by increasing the impingement half-angle of the wall-side element orifices from 20 to 28.2 deg. Overlapping was achieved by redrilling the wall-side orifices out from 4.70 to 5.31 mm. Results are found in Fig. 13 along with a diagram which illustrates the various modifications. In all tests, effects due to resurging were neglected. Tests conducted with symmetrical impingement yielded an average recovery time of 16 ms when perturbed by a 13.5-grain bomb. Three tests employing canted fans only resulted in an average recovery time of 6 ms, while four tests employing overlapped doublets with no canting resulted in an average recovery time of 10 ms. Tests employing both overlapped doublets and canted fans resulted in an average recovery time of 14 ms. An additional series of tests entailed elimination of the LOX doublets adjacent to the radial baffles. These tests resulted in an average recovery time of 132 ms. Overall, results demonstrated that modification of the local degree of reaction adjacent to radial baffles produced a favorable effect in terms of damping, and suggested that canting of the spray fans produced the most favorable results.

Further tests to evaluate the effects of near-wall modifications were conducted using modified 5U configurations.



	I.A., deg.	Dia., mm	τ_{AVE}, ms	Spray Fan Characteristic
(a)	20.0	4.70	16	Symmetrical
(b)	28.2	4.70	6	Canted
(c)	20.0	5.31	10	Overlapped
(d)	28.2	5.31	14	Canted & Overlapped

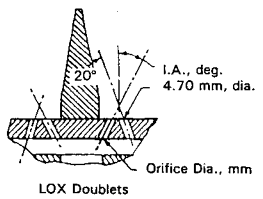


Fig. 13 Effect of near-wall modifications on stability characteristics of PFRT unit F1002.

Collective results are summarized in Ref. 1 along with relevant operating conditions. Tests conducted with unit 056 again demonstrated the advantage of canting adjacent LOX fans away from radial baffles. Increasing the impingement half-angle of the adjacent orifice from 20 to 28.2 deg resulted in a reduction of the average recovery time from 24 to 9.8 ms after perturbing the system with a 13.5-grain bomb. This modification was incorporated into the FRT injector design and was the one factor most responsible for the excellent stability characteristic of the FRT configuration. Further investigation into the effect of overlapping of adjacent LOX element orifices demonstrated a trend of increasing recovery times with increasing orifice diameter. Nonetheless, an overlapping LOX orifice diameter of 6.35 mm on all elements adjacent to radial baffles was selected for the FRT configuration. A final series of tests conducted to determine the effect of fuel element orifice modifications adjacent to radial baffles demonstrated no clear advantage.

The favorable stability characteristics gained by means of near-wall modifications adjacent to radial baffles, coupled with early successes with chamber wall divergence concepts, suggested that the interface between the injector face and chamber wall was exceedingly sensitive to pressure perturbations. Absence of propellants and subsequent decrease in reaction in this region were found to promote attenuation of sustaining waves. These observations prompted initiation of a study to determine the advantages of increased spacing between the chamber wall and the outermost fuel doublets (termed "wall-gap"). Initial tests were conducted using a PFRT injector (unit 090). This configuration was a baffled 5U type similar in design to unit X007. Five tests conducted with the standard 18.1-mm wall-gap recovered in an average time of 165 ms when perturbed by a 13.5-grain bomb. In comparison, three tests conducted with a wall-gap of 90.5 mm resulted in an average recovery time of 7 ms. Wall-gap was varied by eliminating the element orifices of outer LOX/fuel ring pairs. In general, improved stability characteristics were accompanied by a significant decrease in performance. This fact averted incorporation of this modification into the FRT configuration. A final test series was conducted with a 5U-flatface pattern similar to unit 090 (unit X038). Although improvement in stability was noted, it was not sufficient to eliminate the bomb-induced perturbations. A tangential mode with 700-Hz oscillations persisted until cutoff. Amplitudes were moderate and decreased with increasing wall-gap.

Resurging Phenomenon

Concurrently, a substantial effort to understand the resurging problem was undertaken. All injector designs at this point in development exhibited a decaying 500-Hz oscillation following each pressure surge, which often completely decayed before the next surge appeared. This indicated that the high-frequency type instability no longer constituted the main problem in the F-1. Resurging was not strictly periodic; however, the majority of its spectral power was concentrated in the 100- to 140-Hz region. Levine[51] suggested that this phenomenon was driven by the rapid consumption of propellants in a localized region of the combustion chamber due to "exploding" of droplets burning at pressures above critical values. One cause of this was attributed to the Klystron effect discussed earlier.[52] The second cause was attributed to excess film coolant being projected into the combustion zone. Each of the above two effects would result in a distinct increase in local combustion rate and, as a consequence, chamber pressure.

While the Klystron effect appears to be of some consequence, excess film coolant emerged as a dominant factor causing resurging. Bomb-induced pressure waves, amplified by propagation through the combustion zone, appear to have produced a severe disturbance on the film coolant liquid layer. This caused pockets of fuel to be projected into the combustion zone. The surge itself temporarily altered the local injection conditions of the fuel film which propagated downstream at a particular characteristic film velocity. Under suitable conditions, the process was sustained by the projection of another set of fuel pockets due to wave propagation in the film. In comparison with the Klystron effect, this mechanism explained the eccentricity, and also the fact that sometimes after a few surges the phenomenon was spontaneously extinguished.

A test program using injector units 081 and 082 to determine the effects of reduced film coolant on frequency of resurging, compatibility, and performance demonstrated a significant reduction in the incidence of resurging. An increase in performance attributed to reduced fuel film coolant was also observed. These trends suggested the presence of an optimum film thickness which would maximize performance, minimize resurging, and provide adequate cooling. Additional tests conducted on unit 081 eliminated baffle dump coolant as a potential source of fuel pockets. Assessment of the gathered data resulted in a reduction in film coolant from 10.9 to 4.6% in the FRT injector and, in turn, an increase in characteristic velocity from 91.5 to 93.7%.

Buzzing Phenomenon

Of equal interest was consideration of the 500-Hz buzz problem first observed on injector unit 082. This phenomenon was characterized by a low-amplitude sinusoidal pressure oscillation which was rarely amplified and was seldom destructive. In most cases the oscillations were spontaneous and in a phase corresponding to the first tangential mode. When present in combustors with less favorable damping characteristics, buzzing would trigger steep-fronted transverse acoustic modes. Initial tests to investigate buzz instabilities began with unit 082. LOX axial feed-hole splitters were used to eliminate cross velocities in the LOX ring grooves. Tests conducted with splitters in each set of feed holes were successful in reducing the amplitude of the 500-Hz buzz; however, they did not completely eliminate it. Eight tests conducted with splitters in the outer ring exhibited no appreciable buzz. Upon removal of the splitters, buzzing was again encountered. Similar tests conducted on unit 081 to determine the effect of splitters in the oxidizer ring grooves showed no evidence of buzzing. Various combinations of "baffle dams" were also considered to eliminate hydraulic surging in the fuel system. (Baffle dams were used to isolate sets of dump coolant orifices so that they were fed by fuel from selected ring groove channels.) As a result of these tests, the FRT configuration was fitted with 270 splitters in the oxidizer axial feed passages, 32 baffle dams placed in the outer circumferential baffle, and 8 baffle dams placed in the inner circumferential baffles. Ad-

Table 7 Effect of reduced flow to the outer fuel ring on stability and performance

Outer ring fuel flow, %	No. tests	η_{C^*}	No. tests	Damp time, ms
50	5	90.1	1	48
60	40	90.5	33	35
70	373	92.3	195	46
80	4	92.0	1	45
90	—	—	—	—
100	9	91.1	5	51

Nominal values: fuel: V = 17.1 m/s, diameter = 7.14 mm, $I.A.$ = 15 deg; LOX: V = 40.5 m/s, diameter = 6.15 mm, $I.A.$ = 20 deg.

ditional tests indicated that the tendency to buzz increased with increasing LOX impingement angle, was greatest with LOX doublets compared to LOX triplets, and decreased with canting of LOX fans away from radial baffles.

Selection of the FRT Configuration

By the end of June 1964, the basic design features of an FRT injector which would exhibit single-cycle damping had been validated on the test stands. The final design evolved from units 092 and 056 (type 5867J), which were modified 5U configurations similar to unit 082. Four series of tests were conducted to investigate the repeatability of observed results. Fuel- and oxidizer-injection velocities were fixed at 17.0 (55.6) and 42.3 m/s (139 ft/s), respectively, with impingement half-angles of 15 and 20 deg. Wall coolant was reduced to 4.6%. Stability was greatly improved by canting all adjacent LOX elements away from the radial baffles. Characteristic damping times before canting were approximately 60 ms; however, with canting they were less than 13 ms. This was the single factor most responsible for the excellent stability of FRT type injectors as opposed PFRT injectors.

Installation of static and dynamic pressure taps across the face of unit 056 indicated the presence of a decreasing pressure gradient in the radial direction. Pressure differences of 207 kPa (30 psi) were observed between the center and the chamber wall. Additionally, low-pressure drop on the fuel side was observed from the center of the injector to the outer circumferential baffle. Because of the intricate geometry associated with the feed system, hydraulic losses prior to injection varied from ring groove to ring groove. As a result, the mixture ratio in the outer periphery of the injection zone was below the rated value. To correct this problem, fuel flow to the outer ring was restricted. This modification resulted in an increased mixture ratio, and a reduction of the injection density along the outer periphery of the injector. Table 7 illustrates the effect of reduced flow to the outer fuel ring on stability and performance. Data presented in this table represent average values obtained during tests of modified 5U injectors operating at the conditions listed. Trends suggest that optimum performance was achieved when the flow was restricted to 70% of maximum; consequently, this modification was incorporated into the FRT configuration.

Figure 14 is a photograph of the FRT injector (type 5885F4), with relevant specifications given in Table 8. This is a modified 5U configuration, with the same basic injection element spacing and 13-compartment baffle design as the PFRT injector. Prominent features were improved dynamic stability and improved performance. In 38,798 s of accumulated test time, no incidents of self-triggered instabilities had occurred. The characteristic velocity had increased from 91.5 to 93.7%. Specific impulse had increased from 256.5 to 264.5 s. Major factors which contributed to the increase in performance were reductions in the fuel coolant to the thrust chamber wall from 10.9 to 4.6%, and in the oxidizer-injection velocity from 46.6 (153) to 40.5 m/s (133 ft/s). In comparison with the PFRT configuration, a marked improvement in damping characteristics was achieved. Figure 15 shows a typical pressure-time trace exhibited by this unit. Reduction of the fuel coolant to

Table 8 FRT Injector specifications

Injector pattern	
Fuel element type	Doublet
Impingement half-angle, deg	15
Orifice diameter, mm	7.14
Orifice spacing, mm	10.9
Oxidizer element type[a]	Doublet
Impingement half-angle, deg	20
Orifice diameter, mm	6.15
Orifice spacing, mm	10.6
Nominal injection conditions	
Fuel injection velocity, m/s	17.1
Fuel-side pressure drop, kPa	655
Oxidizer injection velocity, m/s	40.5
Oxidizer-side pressure drop, kPa	2151
Fraction of fuel used as film coolant, %	4.6
Fraction of total outer fuel ring flow, %	70
Stability rating	
Number of tests	7
Average damp time, ms	46
Performance	
Characteristic velocity efficiency, %	93.76
Specific impulse, s	264.5

[a]Impingement half-angle and diameter of orifices directly adjacent to radial baffles were 28.2 deg and 6.35 mm.

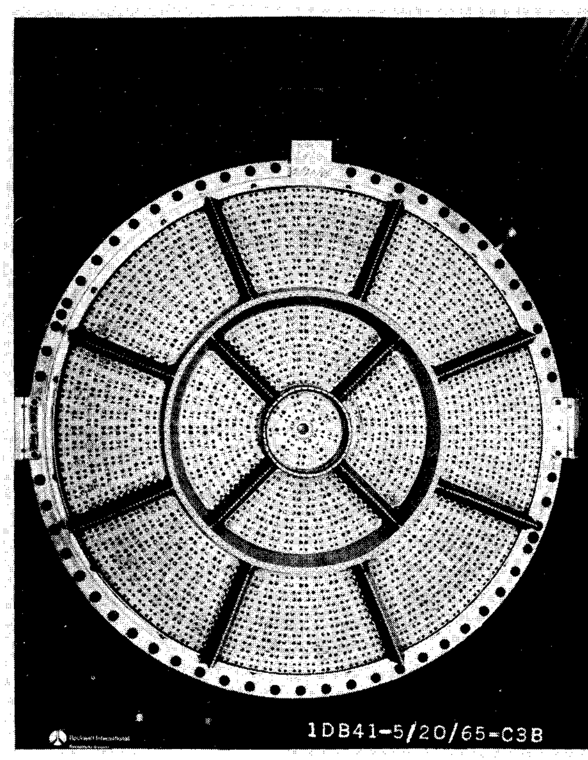


Fig. 14 FRT injector configuration.

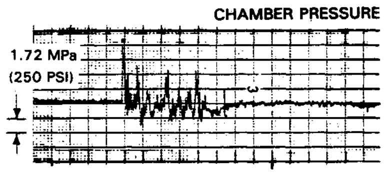


Fig. 15 Pressure trace exhibiting the damping characteristics of the FRT injector when perturbed with a 13.5-grain bomb.

the thrust chamber wall was considered a key factor in eliminating the resurging problem since this eliminated sizable quantities of unburned propellant. Although a significant reduction in the resurging phenomena was observed, a 500-Hz buzz mode became predominant.

Development of the Flight Qualification Injector

The flight qualification injector evolved from the results of component tests conducted within the period between January 1965 and September 1966. Investigation of near-wall effects continued during this period. The most significant analyses were those dealing with the effect of orifice element modifications near highly confined corner regions on the outer periphery of the injector (i.e., the radial-baffle, injector-face, chamber-wall interface). Analysis of the 500-Hz buzzing instability continued throughout this period. The success of the above studies resulted in completion of qualification stability demonstrations by November 1965. Upon achievement of a qualification injector design which performed consistently within stipulated damp time limits of 45 ms, investigation focused on performance enhancement. The goal was attainment of maximum characteristic velocity by way of improved propellant distribution. Major design concepts incorporated were enlarged oxidizer feed passages, tapered radial fuel feed ports, and "programmed" injection density. The latter entailed modification of element orifice diameters about the injector face to produce the desired mixture ratio distribution. A final effort was made to determine the effect of a variety of baffle patterns. Incorporation of regeneratively cooled baffle systems was also considered.

Physical Trends

There was considerable evidence from HP2D tests designed to simulate the FRT configuration that incomplete mixing between unlike gas streams in the downstream portion of the combustion chamber was limiting the performance potential. This was attributed to differences in the vaporization rates of RP-1 and LOX; a condition which promoted striation of the propellants. Calculations performed by Wieber[53] to determine the histories of RP-1 droplets injected into the flow field of the HP2D combustion chamber indicated that heat transfer to the droplets took place much more rapidly than heat loss due to evaporation. This suggested that the droplets were heated to a critical temperature when only a very small fraction of their mass had evaporated. Calculations performed by Combs,[54] Kesselring,[55] Ingebo,[56] and Campbell[57] suggested that LOX and RP-1 droplets were fully vaporized in less than 7.62 and 25.4 cm, respectively. Combs calculated propellant droplet heating under F-1 pressure and velocity conditions, using a mean initial drop size for the LOX spray as coarse as 300–350 μ. Calculations showed that all the LOX vaporized within 7.62–12.7 cm; conversely, calculations performed on RP-1 droplets with the same initial drop sizes indicated that only 80% of the fuel was vaporized after traveling 30.5 cm. These results were considered conservative since they did not include secondary atomization caused by the imposition of a high relative gas velocity on the atomizing spray. Kesselring based his calculations on data acquired during HP2D tests which indicated that up to 70-μ droplets could exist in an accelerating flow 7.62 cm from the injector without shattering, and that only 45–70-μ droplets could exist without shattering during the first 25.4 cm of travel from the injector. The above analyses suggest that from the baffles to the region where RP-1 was fully vaporized (~25.4 cm), wave interactions most likely induced rapid mixing, atomization, gasification, and consequently rapid burning. Downstream of the 25-cm region, combustion instability coupling was believed to occur due to wave velocity effects on mixing of the outer gaseous RP-1 pockets with the surrounding oxidizer gas stream layers.

Injector Modifications Near Highly Confined Regions

Exceptional improvements observed during development of the FRT configuration through near-wall canting of injection element orifices led to consideration of high confinement regions at the radial-baffle, injector-face, chamber-wall interface. Injection density and mixture ratio in regions adjacent to this locale were found to be critical in terms of wave amplification. As a consequence, attention focused on the fuel and LOX element orifices immediately adjacent to the radial baffles. A series of modifications were made to determine the effect on dynamic stability and performance. Results of pertinent tests are given in Ref. 1.

Initial tests were conducted on injector unit 054 which, with the exception of the modifications listed, was identical to the FRT injector (type 5885F4). Nineteen bomb tests with 13.5-grain bombs were conducted at rated operating conditions and with the oxidizer doublets eliminated. Results exhibited an average recovery time of 29 ms, and a characteristic velocity efficiency of 89.5% compared to 91.3% observed for FRT injectors tested on the same component stand. Three tests with both the fuel and LOX orifices eliminated resulted in a degradation of stability. After restoring this injector to its original configuration, fuel orifices 2.49 mm in diameter were installed to minimize high-density oxidizer flow near the baffle surfaces. Five tests exhibited an average recovery time of 36 ms and a characteristic velocity efficiency of 90.7%. The incidence of resurging was observed to increase with this modification.

Results of a similar series of tests conducted on units 051, 075, and 076, which were also identical to the FRT configuration, can be found in Ref. 1. In general, loss in performance was attributed to the maldistribution of propellant mixture ratio caused by radial flow of oxidizer-rich gases into regions void of propellant injection. Oxidizer-rich gases passing into the void regions were believed to react further downstream with the excess fuel injected from the corner regions. Increasing the diameters of the oxidizer orifices increased the injection density and mixture ratio, and resulted in an increased incidence of resurging. Combined results led to the conclusion that stability improved as the local mixture ratio in the outer corner regions was decreased. In addition to the favorable damping characteristic resulting from optimization of the above test series, injector X051 exhibited a specific impulse of 266.1 s; thus, this unit emerged as the most promising qualification candidate.

Buzzing Phenomenon

Analysis of the buzzing phenomenon continued with only moderate success. Tests conducted with lengthened baffles, at both full scale and using the HP2D motor, had little effect on the problem. These results implied that this phenomenon was not simply a low-level first tangential mode. In general, the tendency to buzz was observed to 1) increase with increasing LOX impingement angle; 2) appear more often on injectors which incorporated LOX doublets in comparison to those with LOX triplets; 3) decrease when LOX fans were canted away from radial baffles; and 4) decrease by the addition of ring groove dams and circumferential baffle dams. Injectors with high oxidizer impingement angles exhibited a strong tendency towards buzzing. One hypothesis suggested that this was caused by the inability of hot gases to recirculate in a steady manner between like impinging elements because of high oxidizer vaporization rates. Instead, recirculation became cyclic, giving rise to alternating periods of high combustion rates manifested as buzzing. In an attempt to isolate this problem, the need for recirculation was circumvented by drilling 146 unlike impinging doublets throughout the injector-face area of an FRT configuration (unit 021). Although buzz was not eliminated, some improvement was noted. Overall, it appeared that changes associated with LOX orifice element parameters, especially those near confining surfaces, had a primary effect on the buzzing phenomenon, while injector body modifications had a secondary effect.

Performance Considerations

With confidence in the stability characteristics of FRT configurations established, more attention was directed toward performance. The distribution of injected propellants was found to be a strong function of axial feed hole placement and kinetic head effects. In an effort to achieve maximum-delivered characteristic velocity, a variety of injector body alterations were investigated. Objectives were to produce uniform propellant distribution across the injector face. Reference 1 gives a detailed account of modifications and the effect of each on performance and stability. The most significant improvements in performance were noted through variations of the oxidizer distribution. Reduction of the oxidizer axial feed passage area from a total area of 537 (83.2) to 397 cm^2 (61.5 in.^{2}) on FRT injector 098, produced a characteristic velocity efficiency of 92.1 and specific impulse of 263.7, while maintaining single-cycle damping characteristics. It was also noted that changes to the radial fuel feed ports enhanced stability. A 40-deg included step-angle (in comparison to the existing 90-deg step), and a constant angle tapered port design were considered. Of these two configurations, the tapered port design provided optimum distribution.

Improvement of propellant distribution by varying both fuel and oxidizer orifice diameters in the outer six rings (designated "injection density programming") was also conducted. Determination of favorable orifice diameters was made through a series of water flow tests. Little data exists which allows isolated evaluation of this alteration. The most extensive efforts focused on unit X033, where orifice sizes were programmed tangentially as well as radially. Design features of unit X033 were similar to the FRT configuration; however, nominal fuel and LOX-injection velocities of 24.2 (79.5) and 41.8 m/s (137 ft/s) were used. Characteristic velocity efficiencies of 92.9% were achieved for this injector, compared to 91.2% for FRT injectors. A bomb-induced instability during the third test, which showed typical 500-Hz oscillations coupled with resurging, did not damp until chamber pressure decay. These results suggested an inverse relationship between stability and performance.

As a result of the test series discussed above, a modified 5U injector (unit 077) was completely rebuilt to incorporate enlarged oxidizer feed passages, tapered radial fuel feed ports, and programmed injection density. This unit exhibited a characteristic velocity efficiency of 93.1% and produced a specific impulse approximately 1-s higher than the FRT injector. In general, a radial distribution of the injection density from 36.8 (5.24) to 21.1 kg/s-m^2 (3.00 lbm/s-in.^{2}) uniformly distributed in the circumferential direction was found to produce the most favorable conditions in terms of both stability and performance. These modifications permitted the removal of the splitters used in the LOX-side axial feed passages on the FRT configuration.

Investigation of Baffle Configurations

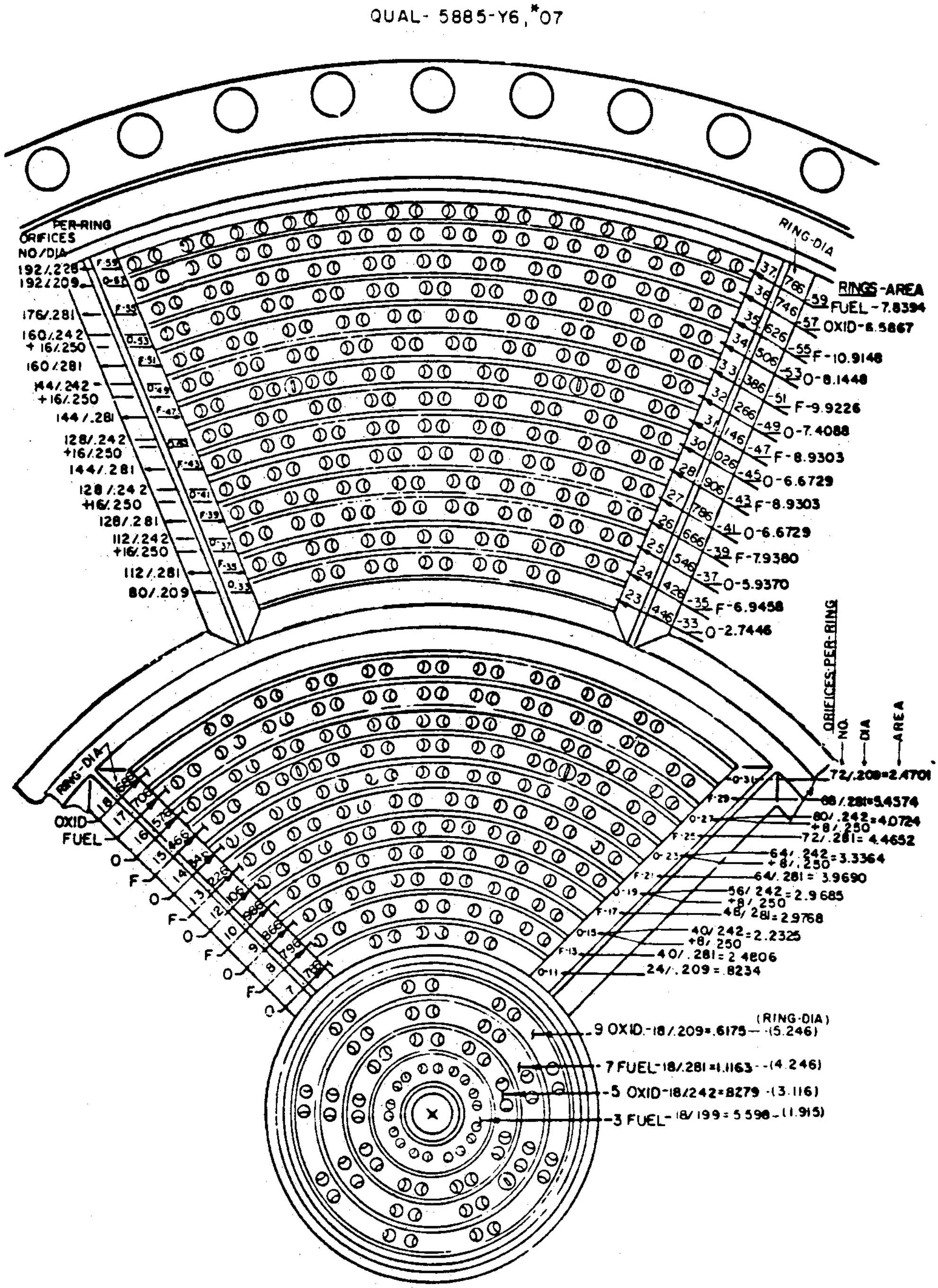
Throughout the development process, baffled injector configurations clearly demonstrated a distinct influence toward dynamic stability. Flatface injectors never exhibited stable combustion regardless of the injector pattern used. This raised questions concerning the exact influence of baffles on stability. Reference 1 summarizes the collective effects observed throughout the development process. Values of 1) frequency, 2) amplitude, 3) damp time, 4) characteristic velocity efficiency, and 5) specific impulse corresponding to each injector pattern, and for each baffle configuration, are given. While direct comparison is difficult due to local modifications required to fit the baffle, some general trends were noted.

Tests corresponding to the qualification development period were conducted using modified 5U configurations similar to the FRT design. In addition to the usual 13-compartment by 7.72-cm pattern, designs of the same length with 4, 9, 21, and 53 compartments were tested. A 13-compartment by 15.24-cm pattern was also investigated. There did not appear to be any consistent connection between damping characteristics and the number of baffle compartments. However, reduced frequency of oscillation and amplitude were consistently demonstrated with both increased baffle length and increased number of compartments. Similar results were observed during tests conducted using both LP2D and HP2D combustion chambers. The frequency reduction observed during these tests was comparable to that observed between the flatface and baffled injectors. Results such as these were also observed during the Gemini stability improvement program[58] and by Priem.[59] These trends suggest that the reduced frequency was caused by increased path length traversed by fluid particles driven by the first tangential mode in the vicinity of the baffle tips. Incorporation of regeneratively cooled 13 compartment by 7.62-cm baffle configurations (as opposed to the typical dump-cooled configurations) was also investigated. Two systems were considered: one with regeneratively cooled radial baffles, and another with a regeneratively cooled outer circumferential baffle. A complete evaluation of both systems is given by Stickling.[60] Substantial improvement in baffle durability was realized with the incorporation of these systems; however, a slight loss in specific impulse was incurred. The loss in performance was attributed to degradation of the combustion process in the vicinity of the cooler baffles. In general, combustion instability was not affected by either system. As a result, fuel dump cooling for both radial and circumferential baffles was selected for the qualification injector.

Stabilizing effects induced by baffles on transverse modes of instability had been observed to 1) modify the acoustic properties of the combustion chamber; 2) restrict oscillatory flow patterns; and 3) provide damping of oscillations through vortex generation, separation, or frictional effects.[61] Analysis of combustion characteristics produced by the FRT configuration clearly indicated that most of the combustion process occurred beyond the baffle region. In light of this, a hypothesis regarding the effect of the baffle on stability focused on downstream alterations to the flowfield. Research done by Rocketdyne[62] and at the NASA Lewis Research Center[63] with hydrocarbon fuel had shown the importance of recirculation zones within the combustion chamber. Qualitatively, it was observed that propellant flow rates were much faster than the flame propagation velocity of the mixture. Recirculation zones set up by the aspirating action of the mixture were necessary to provide low velocity regions capable of supporting "piloting flames." Any disturbance of these flames (i.e., velocity or mixture ratio fluctuations) could affect the combustion characteristics of a large amount of propellant. Studies indicated that the resultant increase or decrease in the flame front area induced by unsteady motions could account for the necessary coupling between the combustion process and acoustic oscillations. These observations led to conjecture that the baffle acted as a shield for piloting zones.

Selection and Analysis of the Flight Qualification Configuration

Figure 16 is a drawing of the qualification injector, with relevant specifications. Major design changes incorporated



PATTERN GENERAL	FUEL	OXIDIZER
Orifice Area, cm^2	548.4	396.8
Ring Groove Depth, cm	1.367	1.367
Wall Gap (Fuel Ring)	1.778	-
Injection Velocity, m/s	17.07	40.54
Wall Coolant, %	3.2	-
Flow to the -59 Ring, %	70	-
Baffle Coolant Area, cm^2	15.23	-

Notes:

- Oxidizer doublets next to radial baffles are canted 28.2°/20.0°, and overlapped 6.325/6.147 mm diameter, respectively.
- Axial feed holes to -9, -15, -19, -23, -27, -31 oxidizer rings are restricted.

Fig. 16 Flight qualification injector configuration.

into this unit in comparison to the FRT configuration were enlarged oxidizer feed passages, tapered radial fuel feed ports, and programmed injection density. Typical accelerometer- and pressure-time traces are given in Fig. 17. Improved performance and damping characteristics were attributed to an increase in the oxidizer flow in the outer baffle compartments by approximately 90.7 kg/s (200 lbm/s) and improved mixture ratio distribution. In 703 engine tests (61,564 s) at the 6770 kN (1,522,000 lbf) thrust level, an average engine specific impulse of 265.4 s, and a characteristic velocity efficiency of 94.32% were observed.

Figure 18 presents the results of a limits study conducted on the flight qualification configuration (type 5885). This figure includes the combined effect of mixture ratio and mean chamber pressure on combustor damping attributes and characteristic velocity efficiency. Variations in chamber pressure correspond to thrust variations of 5347 kN (1,202,000 lbf) to 8047 kN (1,809,000 lbf). The effect of fuel-injection temperature on characteristic velocity efficiency is available in Ref. 1. In general, an inverse relationship between stability and performance was observed. More rapid damping was obtained at rated chamber pressure and mixture ratio. Additionally, specific impulse was observed to increase with increasing thrust level. These improvements were very close to those predicted from theoretical performance data. One additional observation was a decreased incidence of low amplitude resurging at

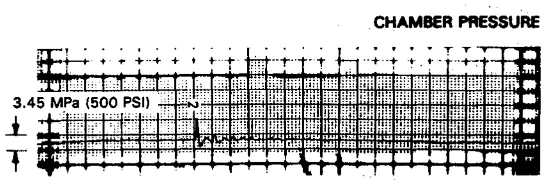


Fig. 17 Pressure-time trace exhibiting the damping characteristics of the flight qualification injector when perturbed with a 13.5-grain bomb.

elevated thrust levels. The opposite trend was observed at lower thrust levels.

Research and development programs which followed development of the flight qualification injector (Fig. 19) were the F-1 Engine Acoustic Absorber Task,[64] the F-1 Uprating Study,[65] and the Low Cost F-1A Evaluation. Achievement of a dynamically stable flight qualification configuration also fostered investigations into the upper limit of F-1 engine performance. Both theoretical calculations based on the Bray criterion,[66] and the use of oxygen fluorine (FLOX) were considered.

The Bray criterion uses both "frozen composition" and "shifting equilibrium" flow models. This technique proposes that the expansion process in the nozzle should be handled as shifting to a certain point and then considered as frozen composition for the remainder of the expansion. The crossover point, dictated by thermodynamic considerations, is defined as the point where the rate of change in concentration of various constituent species becomes equal to the rate at which those species are being carried away by the gas stream. Comparison of the performance levels of six qualification type injectors by means of 10 component tests were made with a theoretically determined maximum. Results indicated that the theoretical upper limit of the flight qualification configuration was approximately 287 s.

The possibility of using various mixtures of oxygen fluorine with RP-1 to enhance performance was considered by McCarty and Walker.[67] Data compiled provided rocket performance predictions for both equilibrium and frozen composition calculations over a wide range of combustion chamber pressures, expansion area ratios, and oxidant-fuel weight ratios. Application to the F-1 suggested a potential increase in specific impulse to 280 s at rated operating conditions. However, compatibility problems in the form of leaking at seals between moving parts was induced by the FLOX. Increases in fluorine content above 30% would require material changes in the engine system to maintain compatibility.

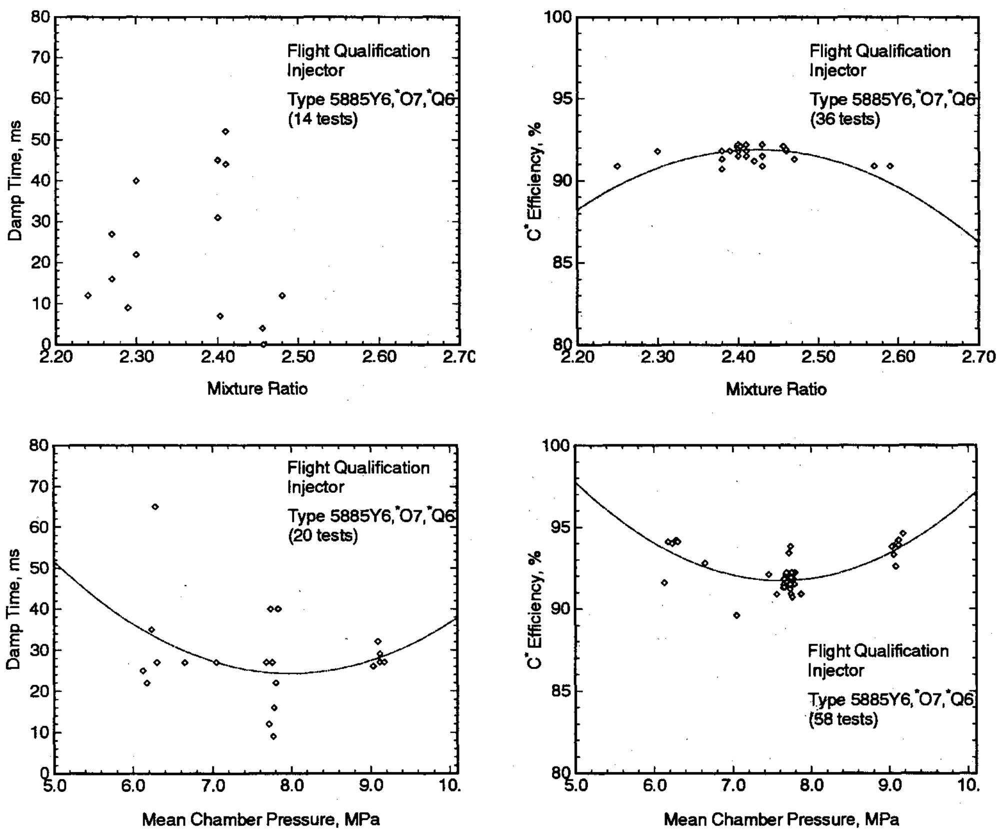


Fig. 18 Results of limits study conducted on the flight qualification injector (type 5885).

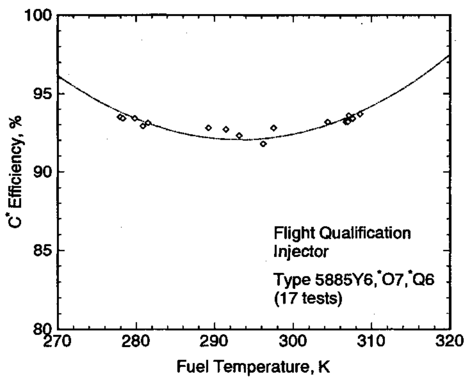


Fig. 19 Effect of fuel temperature on the flight qualification injector (type 5885).

Conclusions

Development of the F-1 engine system spanned the period from the mid-1950s to early 1970s. Fourteen basic injection patterns in combination with fifteen basic baffle patterns were tested under the auspices of the Project First program through an extensive array of basic and applied research coupled with over 2000 full-scale tests. Of the patterns investigated, the 5U and modified 5U injectors with the 13-compartment baffle exhibited the most promising stability and performance attributes; thus, most of the testing focused on these configurations. First tangential spinning modes, oscillating in the vicinity of 500 Hz, were the primary fluctuations encountered throughout development for both baffled and flatface injector configurations. Resurging and sinusoidal oscillations characteristic of buzzing were also observed.

Considerable evidence suggests that there are three distinct regions within the combustion chamber for which different mechanisms of combustion instability manifest themselves. These are 1) the spray fan region in the immediate proximity of the injector face; 2) the fuel vaporization region which extends approximately 25 cm away from the injector face; and 3) the gas-phase region which begins immediately downstream of region 2. In region 1, displacement of impinging jets provide proper conditions for maintenance of a spinning tangential mode, the sensitivity of which was shown to be dependent on the location and distribution of the combustion zone. High energy release near the injector face was directly linked with combustion instability. In region 2, RP-1 droplets undergo vaporization and breakup by shear forces. LOX, on the other hand, is essentially fully vaporized within 7.62 cm from the injector face. Biplanar impingement coupled with a high relative velocity between GOX and RP-1 provide the most suitable environment for fuel vaporization in this area. Finally, in region 3, axial striations of both RP-1 and LOX vapor exist, a condition which creates mixture ratio gradients. Transverse acoustic fields imposed under these conditions promote mixture ratio oscillations which elevate the possibility of burning rate fluctuations, a condition that is undesirable in terms of performance and one which produces a significant source of acoustic energy.

Sensitivity toward instability was always observed if the major combustion zone was relatively close to the injector face, where oxidizer vapor existed in a sufficient degree of angular nonuniformity. If the combustion zone was moved to a region downstream where the oxidizer vapor concentration was essentially uniform, displacement effects decayed to a level incapable of supporting instability. In light of these observations, orifice diameter variations have a marked effect on droplet sizes and spray fan characteristics, and as a consequence play an important role in the spray fan region. Large orifice diameters cause greater concentration of the propellant in the center of the spray, and therefore spread the propellant combustion longitudinally in the thrust chamber. Smaller orifices generate smaller droplets and provide a more concentrated area of energy release close to the injector face. Axial distribution of relatively large fuel droplet sizes (~400 μ initially), vaporizing in a uniform GOX environment, minimized acoustic coupling by moving the flame zone away from the injector face such that a fuel-lean condition in the gas-phase was achieved.

In general, fuel droplet size, relative velocity between fuel droplets and GOX, and the axial and circumferential velocity components of injected LOX (i.e., LOX orifice impingement angle and nominal velocity) had the most significant effect on the location, distribution, and combustion attributes of the flame zone. Axial LOX velocity components altered the combustion distribution, which affects performance. Circumferential LOX velocity components affected stability through interaction with adjacent elements. Fuel droplet sizes were predominantly controlled by the fuel orifice diameters and impingement angles. While the precise effect of secondary atomization caused by the imposition of high relative gas velocity on the atomized spray was unclear, it undoubtedly played a significant role in the overall combustion process.

Analysis of the combustion characteristics of the flight qualification injector clearly indicates that the bulk of combustion occurred downstream of the baffle tips. These observations suggest that baffles protect the spray fan region near the face from unsteady oscillations and/or exert an attenuating effect on amplitudes of transverse modes downstream of the baffle tips. Comparison of baffled vs flatface F-1 injectors indicated that baffles exert a marked influence on self-damping. Self-damping was never observed when testing with flatface injectors, regardless of the injection pattern used. On the other hand, introduction of the baffles produced regions of high acoustic intensity near the tips. Alterations of local injection density and mixture ratio in these regions demonstrated excessive sensitivity in terms of wave amplification. In general, a decrease in both the local mixture ratio and the LOX-injection density along radial baffles, and in the highly confined regions adjacent to injector face and wall interfaces, produced marked reductions in the average damp time from bomb-induced perturbations.

Incomplete mixing between unlike gas streams in the downstream portion of the combustion chamber was the single most limiting factor affecting of performance. This was attributed to differences in the vaporization rates of LOX and RP-1, a condition which promotes striation of the propellants. Maximization of performance, with no degradation of stability, was achieved by minimizing mixture ratio gradients downstream through a series of injector body modifications. Distribution of injected propellants was found to be a strong function of axial feed hole placement and kinetic head effects. Optimization of these parameters produced more uniform mass and mixture ratio distributions across the injector face.

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