c

933906

[redacted]

ROCKETDYNE TIC
CANOGA

A036

R-5615-1

5

(Unclassified Title)

HISTORY: PROJECT FIRST,
F-1 COMBUSTION STABILITY PROGRAM
VOLUME 1, BOOK 1

FILE COPY

[redacted]

ROCKETDYNE
A DIVISION OF NORTH AMERICAN AVIATION, INC.
6633 CANOGA AVENUE
CANOGA PARK, CALIFORNIA

Contract NASw-16
Mod 36 and Mod 44, Attachment B

Classification Changed
To: unclassified
By Authority of DD254
Date 4/18/69 By Stanley [illegible]
12/22/69
a.p.

PREPARED BY

Rocketdyne Engineering
Canoga Park, California

APPROVED BY

D. Klute
Assistant to the Chief Engineer,
Liquid Rocket Division

NO. OF PAGES 92 & v

DATE 16 April 1964

REVISIONS

DATE	REV. BY	PAGES AFFECTED	REMARKS

FOREWORD

This is Volume 1, Book 1 of the History: Project First, F-1 Combustion Stability Program Report, prepared in compliance with the provisions of Contract NASw-16, Mod 36 and Mod 44, Attachment B, the Rocketdyne F-1 Engine Development Program for the National Aeronautics and Space Administration.

ABSTRACT

A history of the F-1 Combustion Stability Program from October through December 1962 is presented. Results of studies, tests, and procedures are discussed and graphically presented, and problems encountered are described.

(Unclassified Abstract)

[redacted]

CONTENTS

[redacted]

ILLUSTRATIONS

TABLES

PURPOSE

This documentation delineates historically the processes that were involved in the development of a dynamically stable F-1 engine for the National Aeronautics and Space Administration. The objective is to provide a technical insight into the logic and action that resulted in demonstrable solutions to the combustion instability problem.

Influences contributing to the formation of engineering ideas and decisions are presented. These include applicable Rocketdyne experience in other programs as well as the F-1 program; the experience and conceptions of the individual Combustion Stability Committee members, of other Rocketdyne engineering and research personnel, of consultants to the program, and of NASA representatives; and the information provided by theoretical studies, analysis, model experimentation, and hot-firing tests.

To implement this purpose the history of Project First (as the program was titled at Rocketdyne) is presented in manner most consistent with clarity, rather than chronologically. The contents reflect the broad spectrum approach which encompassed the development of sophisticated instrumentation, data reduction and analysis methods, and parallel design and test projects conducted at facilities in Canoga Park, Santa Susana, and Rocket Site/Edwards Air Force Base.

For convenience of presentation, the history is divided into volumes, each encompassing a 12-month period, and each volume is composed of four books, each inclusive of a 3-month period. It is anticipated that in this way the completion of the history will coincide with the termination of the program. To provide clarity and continuity, subheadings denoting dates and ensuing subject matter are used. Pertinent illustrations and photographic material are included to ensure comprehensive documentation.

The material for the program history is derived from progress reports, internal Rocketdyne memoranda, and the daily record kept of Combustion Stability Committee meetings from the inception date of the program.

[redacted]

INTRODUCTION

In October of 1962 the Combustion Stability Committee was established within the Liquid Propulsion Division of Rocketdyne. Designated to preside over the Committee's activities were P. D. Castenholtz and Dr. D. O. Klute. The Committee was charged with the technical direction and management of the F-1 Combustion Stability Program. Its charter named two principle objectives: (1) the achievement of a dynamically stable F-1 engine design within the engine's development schedule and contractual specification, and (2) the determination of what design and operational parameters are fundamental to the development of dynamically stable liquid-propellant rocket engines.

F-1 STATUS

At the time the Combustion Stability Committee was formed, two basic injector configurations had been evolved in the F-1 program, one of which had performed stably but would not successfully damp a bomb-initiated disturbance. This injector was a 5U design, then being tested in flatface and baffled configurations. A double-row-cluster injector design was also considered a promising configuration. The 5U type had 34 copper rings, uniplanar 0.571-inch impingement, and a 13-compartment by 3-inch-long baffle system (when baffled). Injector face burning problems had been overcome, and work was being conducted on baffle cooling. Three self-triggered instabilities had occurred within the quarter in engine tests with flatface injectors, but the first full-duration engine test (150 seconds) had been accomplished at 1,500,000 pounds of thrust. Engine 003 had also experienced spontaneous instability with a 5U baffled injector. Testing on test stand 2A at RS/EAFB was under way with 50-grain bombs. It was evident from the test history that baffled injectors caused less hardware damage when instability was encountered, but both baffled and unbaffled injectors at this stage were subject to spontaneous instability.

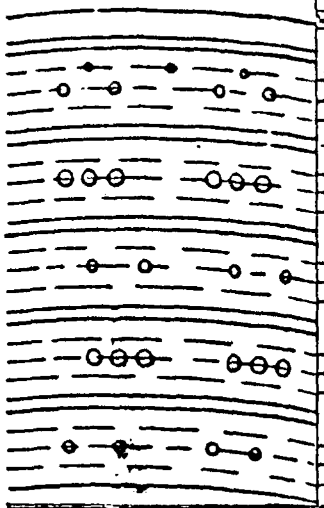
Injector U/N 076, a baffled 5U injector, was ready for firing at test stand 2A, RS/EAFB.

Typical 5U-pattern injectors are shown in Fig. 1 through 4. A typical double-row cluster configuration is shown in Fig. 5 and 6.

INJECTOR DESCRIPTION

UNIT B005, TYPE 485F, S/N 3504(5-U)

Orifice Pattern

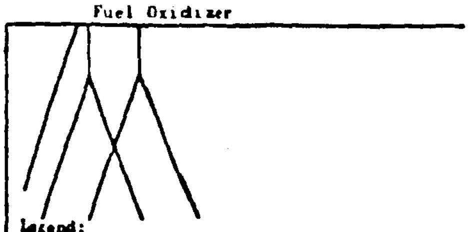


No.	D	d	Groups	x	θ	S_p	X_{jc}	X_{ji}
Wall	39 68							
-69	37913	089	200 R	R R	20	597	—	—
	37764	120	100	416	20	119	.571	4.07
---	37261							
-67								
	36 746	159	100	4.6	20	115	.571	352
-65								
	35 626	144	94	416	20	119	.571	373
-63								
	34 506	159	94	416	20	116	.571	352
-61								
	33 386	144	87	416	20	121	.571	373

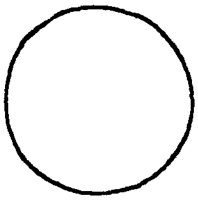
Pattern, General	Fuel	Oxid.
Orifice Area	28 46	52 0
Ring Groove Depth		
Ring Material	COP	COP
Wall Cool (Fuel Ring)	.711	
Wall Cool (Outer Zone)	966	
Inj. Velocity 1500	673	516

Baffle Design	None
Number of compartments	
Baffle construction	
Baffle coolant	
Baffle length	

Divergent Profile



Baffles



Legend:

D = Ring diameter, inches

d = Orifice diameter, inches

Groups = Number of orifice groups

x = Centerline distance between outer orifices of a group, inches

θ = Half-angle of impingement, degrees

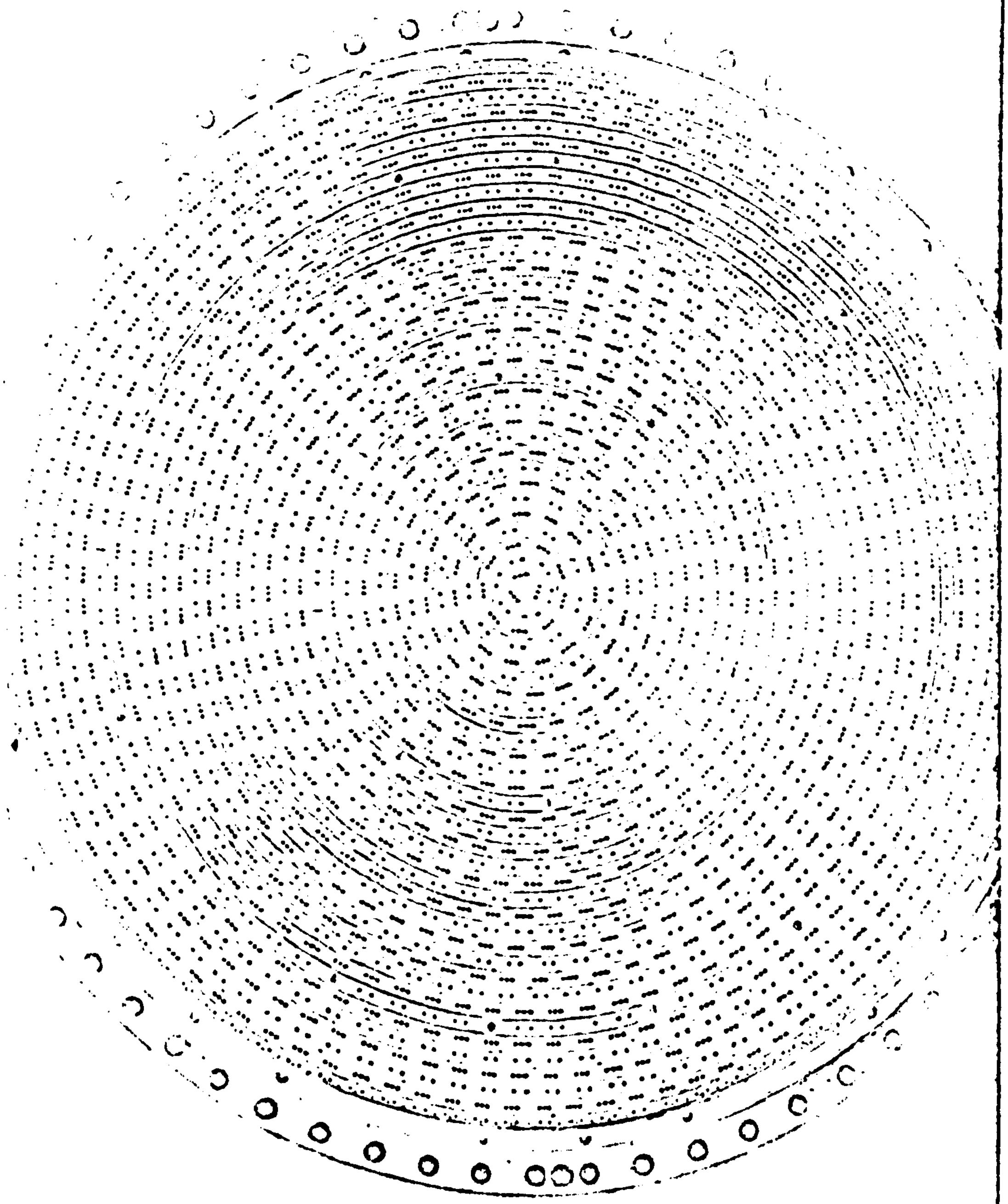
S_p = Centerline spacing between orifice groups, inches

X_{jc} = Centerline impingement distance, inches

X_{ji} = Initial impingement distance, inches

Remarks: Standard 5-U injector 1500K flat-face. There are 200 body coolant holes (.032 dia). The design is the same as for the type 5[illegible] [illegible] with the exception of [illegible]

Figure 1. Flatface, 5U Injector



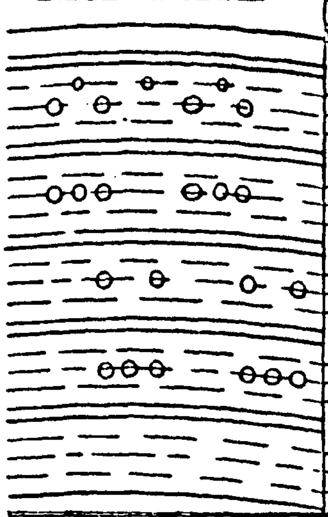
1DB45-1/11/63-C1B

Figure 2. Injector U/N 079, a Typical 5U Flatface Injector

INJECTOR DESCRIPTION

UNIT 076 , TYPE [illegible]S , S/N

Orifice Pattern



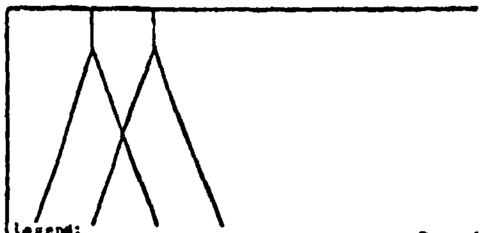
No.	D	d	Groups	Z	θ	Sp	Xjc	Xji
Wall	39 od							
	37961	089	184/208	—	20	.572	—	
	37766	159	36/24	4:6	20	114	.571	.353
	36746	1695	96/104	4:6	20	1.11	571	339
	35626	.159	89/36	416	20	117	.571	.353
	34506	.1695	88/96	.416	20	113	571	339

Pattern, General	Fuel	Oxid.
Orifice Area	34.81	47.45
Ring Groove Depth		
Ring Material	CU	CU
Wall Cor(Fuel Ring)	711	
Wall Cor(Outer Zone)	966	
Inj. Velocity (1500K)	49.6	172.5

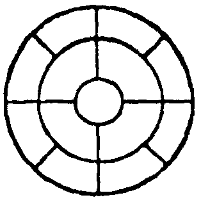
Baffle Design	
Number of compartments	13
Baffle construction	WIDE BASE
Baffle coolant	FUEL
Baffle length	3"
Length Center Can	3.6"

Divergent Profile

Fuel Oxidizer



Baffles

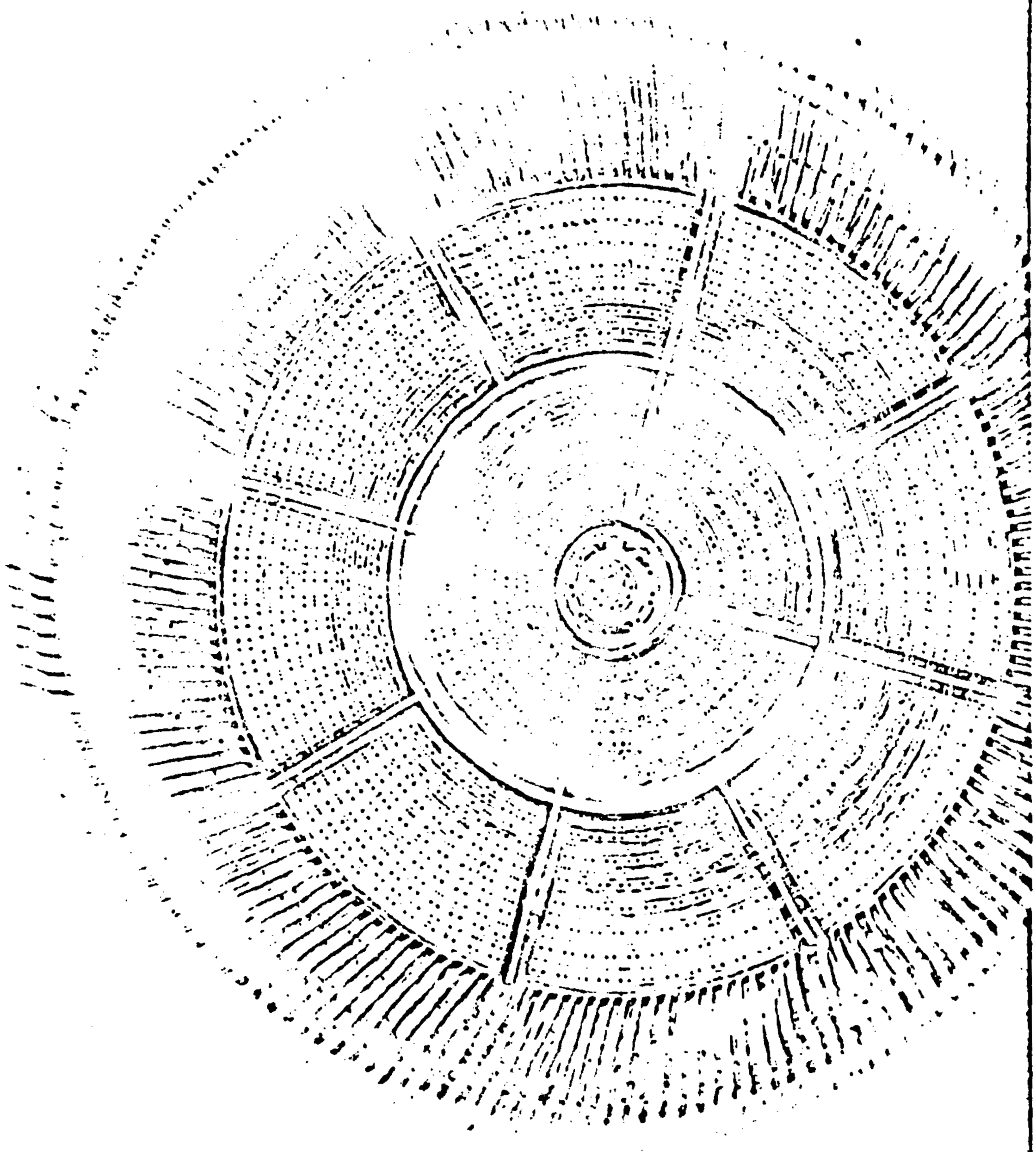


Legend:
D = Ring diameter, inches
d = Orifice diameter, inches
Groups = Number of orifice groups
Z = Centerline distance between outer orifices of a different group, inches
θ = Half-angle of impingement, degrees
S_p = Centerline spacing between orifice groups, inches
X_{jc} = Centerline impingement distance, inches
X_{ji} = Initial impingement distance, inches

Remarks: Same as basic 5-U pattern except added 24 shower heads of dia 0.159 and blocked out 144 ox holes of dia 0.1695.
104 body coolant holes .0635 dia. No fuel port inserts. Has [illegible] pulse deflectors at the entrance to two fuel ports.

% film coolant = 10.65%

Figure 3. Baffled, 5U Injector



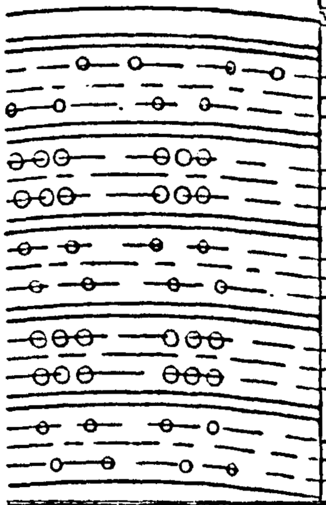
5732-10/24/62-E3

Figure 4. Injector U/N 076, a Typical 5U Baffled Injector

INJECTOR DESCRIPTION

UNIT 043, THE [illegible], S/N [illegible]

Orifice Pattern



No. Wall	D	d	Groups	Z	θ	Sp	Xjc	Xji
	37961	.104	96	.416	20	124	571	429
-69								
	37685	110	84/96	416	20	123	571	420
	36926	129	88/96	416	20	121	571	(217) .395
-67								
	36566	.129	88/96	.416	20	120	571	395
	35806	.110	88/96	.416	20	117	571	420
-65								
	35446	.110	88/96	.416	20	116	571	420
	34686	.129	88/96	.416	20	1135	571	395
-63								
	34326	.129	88/96	.416	20	1125	571	395
	33566	110	88/96	.416	20	1.095	.571	.420
-61	33206	110		.416	20	1.088	571	

Pattern, General

	Fuel	Oxid.
Orifice Area	29.1	51.2
Ring Groove Depth		
Ring Material		
Wall Gap (Fuel Ring)	692	
Wall Gap (Outer Zone)	941	
Inj. Velocity ([illegible])	63.6	154.5

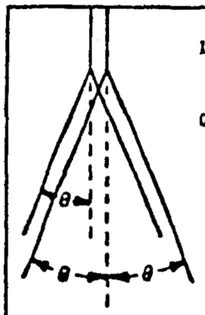
Baffle Design

Number of compartments	13
Baffle construction	SLM
Baffle coolant	BIPROPELLANT
Baffle length	3"

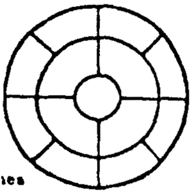
Divergent Profile

Fuel Oxidizer

$X_{ji}(t) = 0.217$



Baffles



Legend:

D = Ring diameter, inches
d = Orifice diameter, inches
Groups = Number of orifice groups
Z = Centerline distance between outer orifices of a group, inches
θ = Half-angle of impingement, degrees

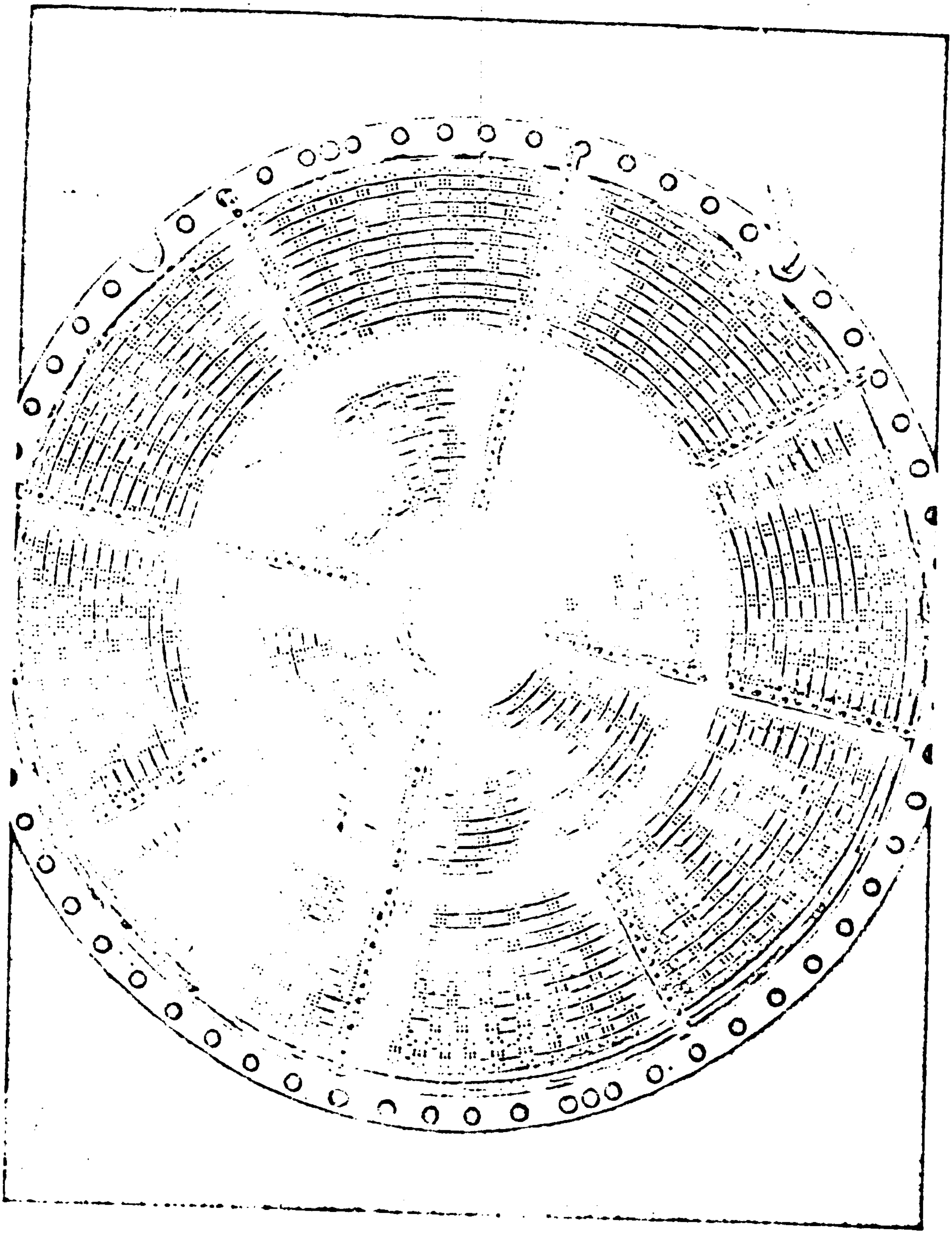
S_p = Centerline spacing between orifice groups, inches
X_{jc} = Centerline impingement distance, inches
X_{ji} = Initial impingement distance, inches

Remarks: Double row cluster pat'n.
Rings are .370" th'k.

Number Date: 12-1-61

% film coolant = 6.15%

Figure 5. Double-Row, Cluster, Baffled Injector



5732-12/26/61-1A

Figure 6. Typical Double-Row Cluster Baffled Injector

SUMMARY

In the quarter, October through December of 1962, the Combustion Stability Committee was formed and the F-1 Combustion Stability Program initiated. An historical survey of the F-1 program and other Rocketdyne engine programs in which instability had been encountered was completed. A deep study of theory related to the instability phenomenon was undertaken. By the end of the quarter, design criteria had been established, instrumentation, data reduction and analysis requirements had been developed, and a comprehensive program was under way. Experimental work was in progress with two-dimensional transparent thrust chambers, F-1 operation was being modeled and parameters examined with the H-1 engine, and designs were in review for modifications to the standard F-1 injection system and advanced concept injectors.

[redacted]

DISCUSSION

INITIAL EFFORT

The initial effort of the Committee was to undertake an intensive investigation of F-1 development history. In a series of meetings with the F-1 Program Team, which began on 5 October 1962, the F-1 program was reconstructed from the date of its inception. Because of the desire to approach the instability problem unhindered by preconceived notions or attitudes restrictive to open and accurate evaluation, every aspect of the development program was reviewed. The operative regime of the engine and its sequencing, start through cutoff, were carefully defined. A complete geneology of injectors developed in the course of the program was presented and studied. Development of the turbopump, lines and ducting, control systems, dome and manifolding, thrust chamber and exhausterator was also given detailed scrutiny. All documentation, films, photographs, and instrumentation records accumulated during the program were acquired and subjected to study by the Committee. As an adjunctive effort, similar information pertaining to earlier Rocketdyne experience with combustion instability in the conduct of the Redstone, Atlas, H-1, and E-1 programs was gathered and studied. A survey of the literature was initiated, and experts in the field working under NASA auspices were contacted for consultation (Table 1).

TABLE 1

CONSULTANTS
TO
COMBUSTION STABILITY COMMITTEE

11-9-62	Richard Priem	NASA-Lewis
11-12-62	David T. Harrje	Forrestal Research (Guggenheim) Princeton Univ., Princeton, N. J.
11-16-62	Donald Bartz, Jack Rupe	JPL, Pasadena
12-12-62	Prof. E. S. Starkman	University of California at Berkeley
12-14-62	Herbert B. Ellis	Aerojet, Azusa
12-17-62	Jack Rupe Max Clayton	JPL, Pasadena JPL, EAFB
12-20-62	Prof. Robert J. Osborn	Purdue University, Lafayette, Indiana

REVIEW OF THEORY

Early in October, 1962, the Committee began a compilation of theories bearing upon combustion stability. The component structure of the F-1 engine was examined, as well as its operation. A completely open-minded and candid approach was taken (within the prescribed limits of scientific method). The following list of potential sources of instability was compiled:

1. Structural integrity of thrust chamber mounts
2. Thrust chamber nozzle stiffness
3. Structural integrity of baffles in the combustion chamber
4. Characteristics of the material of the thrust chamber
5. Flow straightness in the propellant lines
6. Diameter of the propellant lines; length and stiffness
7. Pressure drop in the feed system
8. Velocity changes during operation; cross velocity changes
9. Cavitation in the injector orifices
10. Cavitation in the feed system
11. Gas pockets in the feed system
12. Diameter of the combustion chamber
13. Length of the combustion chamber
14. Splash plate and turbulence ring disturbances
15. Chamber shape (cone vs cylinder)

16. Spacing of injection orifices
17. Temperature of the combustion chamber wall
18. Mixture ratio uniformity

Individual members of the Committee then presented their own theoretical views of the instability phenomenon. These were as follows:

Droplet Breakup

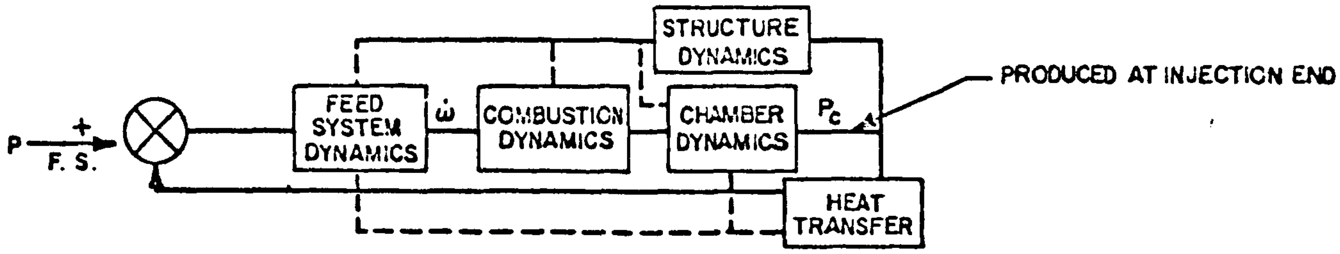
The prevailing theories developed to comprehend droplet burning were presented by a member of the Committee. In the final resolution it was noted that certain critical assumptions must be made in the development of theories explaining the formation and action of droplets in a combustion chamber; these being initial droplet velocities and sizes. Concommitant assumptions follow:

1. The velocity of the drop changes as it burns.
2. As droplets approach gas velocity, droplets get smaller.
3. The entire process is gradual.

The theoretical evaluation suggested that a transverse mode would have the following effect in the chamber: burning gas could be moved from one zone to another in the chamber where droplets exist, cause shattering and more rapid atomization, create mixtures of LOX-rich gas and fuel-rich gas, and "blow out the flame."

Practical application of this concept suggested the use of flame holders in the combustion chamber.

As the discussion proceeded it became apparent that definitions that all members of the committee agreed upon would be necessary before the application of theory to the F-1 problem could prove productive. The following definition was set forth and agreed upon:



Only "combustion dynamics" can be individually and actively unstable. The "pipes" are passive.

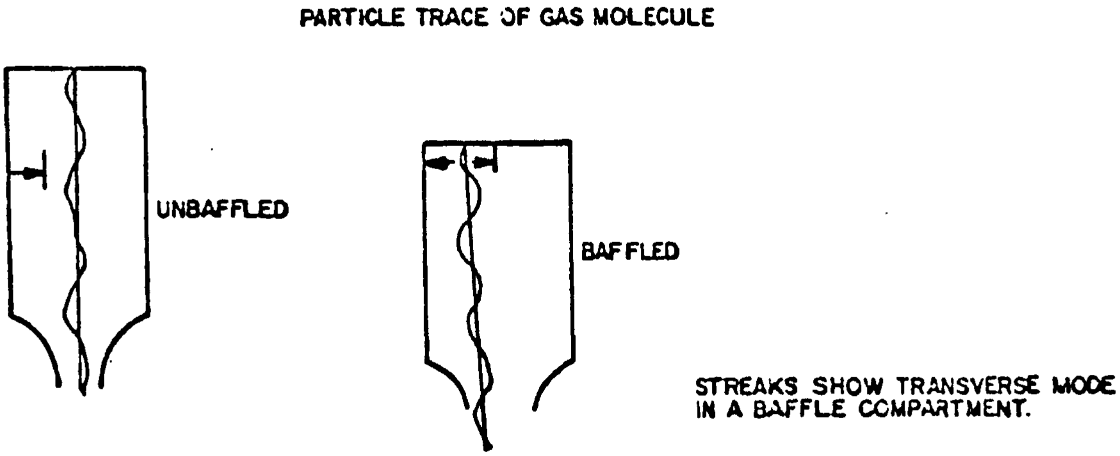
Definition:
Anything that happens to the flowrate is "combustion dynamics".
Feed system dynamics include anything that produces a flowrate at the orifice edge.

It was then postulated that if $\dot{\omega} = C$ (a constant), consideration of effects upstream of the orifices could be eliminated and only combustion dynamics would require consideration.

Baffle Theory

At this time in the F-1 program, the unbaffled 5U type injector appeared the most promising, but there was considerable controversy over the value of a baffle system. The oscillation data then available indicated variations in the operation of the engine and thrust chamber with and without baffles. A history of stable operation achieved with the Atlas and H-1 through the addition of baffles prompted a close examination of the effects of baffles on the combustion process.

A theoretical explanation of the effect of baffling systems on engine operation was put forth by one of the Committee members; this explanation was based on streak photograph data.



Baffles isolate transverse oscillation to one compartment.

[redacted]

Assume:

Q = energy absorbed/cycle ~ ratio of total energy stored in a cantilever beam divided by what is lost.

$Q = C \rightarrow 0$

$EA \sim S$ when $S < S_c$

$S \sim$ length of baffle

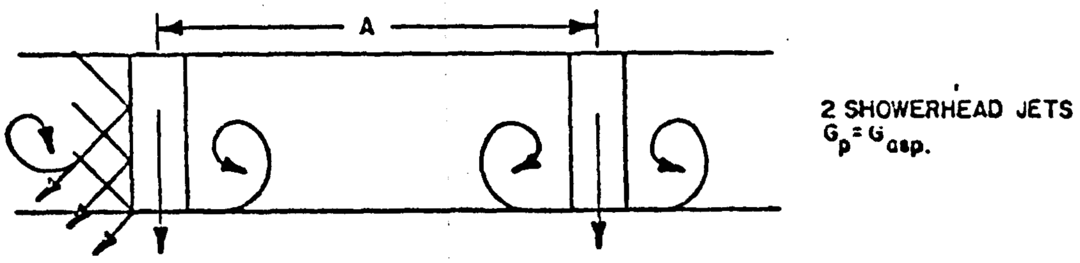
$\therefore$ Stable

$$E_A \frac{\geq}{<} E_Q$$

A conclusion drawn at this point was that, from pop to pop, the thrust chamber is ringing at the natural frequency of the baffled compartment. This concept led to the thought that the propellant might be used as a damping medium, this to be accomplished by designing the baffles as a secondary injection station, thus reducing the injection density at the face of the injector. (This concept led, eventually, to consideration of staged injection designs which spread the combustion process axially). An additional conclusion was drawn at this time to the effect that baffles serve to reduce the amplitude of gas motion in the chamber and increase the frequency.

[redacted]

An "ignition limited theory" was presented for the Committee's consideration:



Amount of gas heading toward face = gas pumped.

t = thickness of external gas caused by aspiration of jet at velocity V at point X

W_G = volume

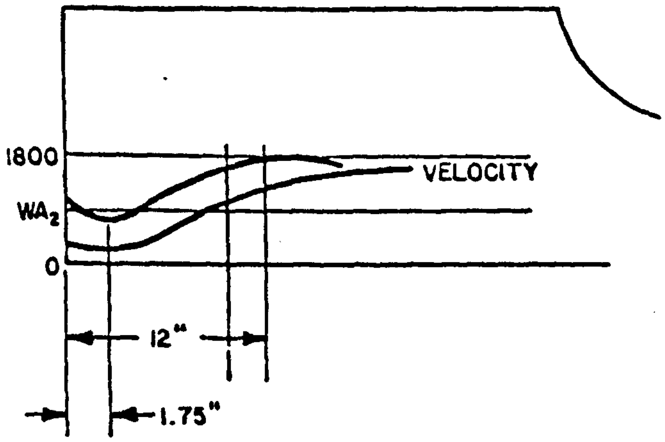
$\dot{E}_I = W_G \rho t\ DV = \rho AV$

The boundary layer grows faster if the jet is impinged, because of turbulence. By moving the impingement point up, the amount of turbulent gas is increased.

The more gas that is moved, the more energy there is available for ignition. The gas mass pumped gets larger with increased distance between jets. Recirculated hot gas acts as a pilot (gas flame) that ignites and maintains combustion. The conclusion, then, is that:

1. Random oriented holes are bad
2. The transverse mode is the result of drop shattering

The energy release rate was defined:



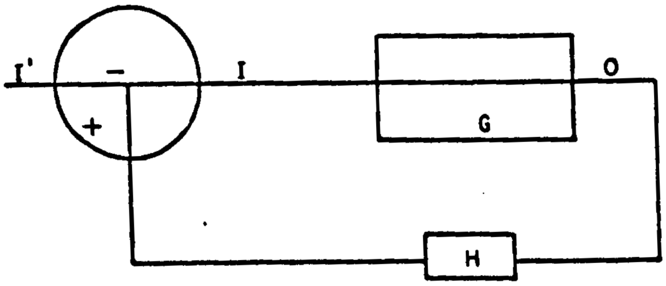
Acoustic Theory

The acoustic theory of instability was examined. When related to the instability phenomenon evident in the F-1, the theory failed to explain the evidence of the data.

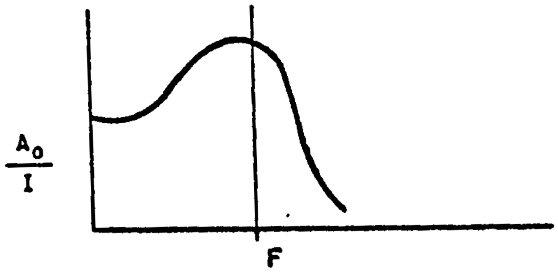
Two means of evaluating acoustic effects were proposed:

1. Use power spectral density analysis to read the results of F-1 bomb tests with baffled injectors and determine the influence of acoustics.

2. Build and test a model motor with a shroud to "collect" and damp tangential mode acoustics of the kind identified in the F-1. This would provide a means to isolate combustion stability from acoustic disturbance and either eliminate the stability problem or at least radically narrow the field of possible causes.



G = GEOMETRY OF CHAMBER (NATURAL FREQ.)



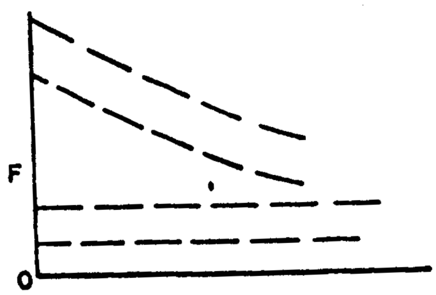
OPEN LOOP

O = GI OPEN

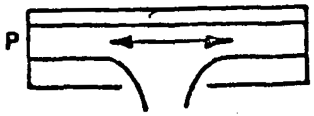
$O = \frac{G}{1+GH} I'$ CLOSED

Solid Acoustic Problem as Analogy to Liquid

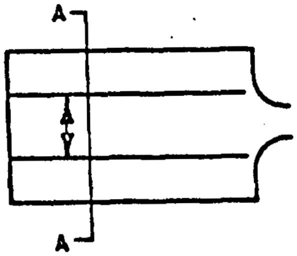
In solids, first and second harmonics of the tangential mode were detected existing independently. Frequency changes with increasing size of core in burning grain were noted.



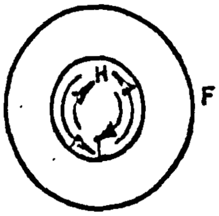
An experiment with a solid propellant motor was conducted.



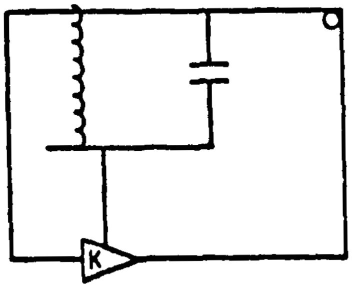
A longitudinal mode was recorded, sustained by the propellant at the ends of the motor, where there are pressure fluctuations.



"Plastic" has spring-mass system -
Solid drives at almost any frequency
it wants to.



The question was posed as to why the system oscillates at its open-loop frequency and not at its closed-loop frequency? The answer was as follows:



K = combustion = gain function
K a function of length
There is a pure K in the dynamics of
the feedback.

In baffled chamber, amplitude in baffle area smaller; getting larger down the chamber.

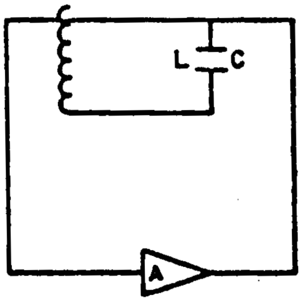
PROPOSED

Ring lower end of thrust chamber and correlate results with known effects in baffled section.

Downstream of the combustion process there may be critical damping because of liquid.

Proposed: Use power spectral density analysis to read results of F-1 bomb tests with baffled injectors and determine relative acoustic tangential frequencies at point on the chamber.

Question. (1) Does combustion process merely amplify acoustics of chamber? Natural frequency or compartment? (2) Is this system but LC as well as A vary with length and not necessarily simply amplitude + acoustics?



Answer. Get rid of A

Proposed: separate combustion phenomena.

Repeated Pressure Surging

In examining the oscillation traces of F-1 and H-1 tests, and instability characteristic was noted that appeared unique to these engines. In these the peaks are of approximately equal height and equidistant on the traces, and exhibit a sharply inclined pressure spike (brisant). The phenomenon was tentatively designated "repeated pressure surging."

A number of possible causes of repeated pressure surging were postulated:

1. Gel explosions on the wall
    a. Waves of liquid on the wall
    b. Carbon flaking from the wall
2. Gas products downstream of the baffles
3. Wave growth through droplet residue
    a. Near injector end
    b. Near nozzle
4. Contamination in LOX ring grooves

At this time other oscillatory modes were evident on the traces and certain possible causes for these were postulated:

1. Longitudinal mode driven by:
    a. Pressure-sensitive mechanism
    b. Flow-sensitive mechanism
    c. Displacement
2. Feed system resonance
3. Explosions in the exhaust jet

A summary conclusion regarding the origin and peculiarities of repeated pressure surging was subsequently expressed:

> "Repeated pressure surging is a function of random explosions resulting from 'globs' of unburned propellant going off in odd places downstream of the injector; this condition is related to individual injectors more or less prone to cause this phenomenon."

In examining the oscillation traces of F-1 and H-1 tests, repeated pressure surging was identified (tentatively at this time) as a phenomenon unique to these engines.

ROCKETDYNE CONSULTANTS

A review of studies conducted by the Combustion Devices Subdivision of Rocketdyne was presented, and the following theory was provided for the Committee's consideration:

These studies had been conducted on previous full-scale F-1 injector designs which included 5 dynamically stable injectors out of 12, based on 2-second tests at RS/EAFB.

The hypothesis was made that the closer propellants are burned to the injector face, the more stable the system.

An "old" theory, defined for flatface injectors, was presented. This theory held that higher oxidizer atomization and reduced fuel atomization with the fuel injected <u>into</u> the oxidizer would provide the desired stability. This theory, however, did not apply in studies of injectors with divergence. A "new" theory was defined, which stated that closer orifice spacing and uniplanar impingement at a relatively steep angle would provide stability. It was further stated that a higher mixture ratio caused by tangential wind has a bad effect; principally the result of misaligned holes.

An equation in support of the new theory was also presented:

<u>Stability Equation:</u>

$$F_s = \frac{F_p \cdot F_d}{C_f'}$$

$$= \frac{1}{(X_{co}+2)\,(X_a+.5)(|X_{co}-X_{cf}+23)} \cdot \frac{1}{C_f'} \cdot \frac{X_c - .5X_s}{\int_{5X_s}^{X_c} \cos^2 O_{dx}}$$

It was anticipated that injector U/N 046, then in build, would prove stable.

On 9 November 1962, a presentation was once more made by Rocketdyne's Combustion Dynamics Unit. A summary of design parameters was tendered the Committee:

1. Very small drop size (mean), corresponding to a resonant frequency >2000 cps

2. Possibly a very wide droplet size distribution such that few droplets can resonate with any one frequency

3. Build injector as acoustic reflector to eliminate feedback to feed system (umbrellas)

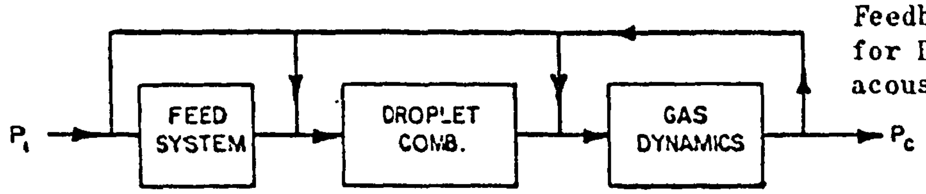
4. Build thrust chamber with all resonant frequencies as close together as possible; build injector to put all of these frequencies in stable region

5. Possibly a very large mean drop size, corresponding to resonant frequency <100 cps

6. Very high relative velocity (gas-droplets) during atomization and initial burning

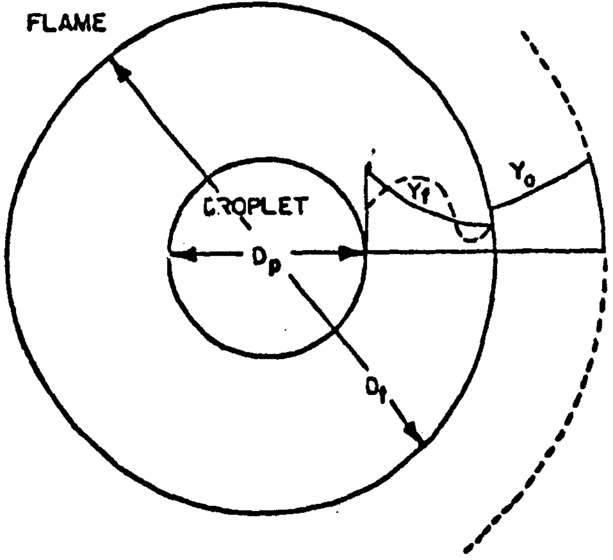
On 2 November 1962, a presentation was made to the Committee by a member of Rocketdyne's Dynamic Sciences Group on droplet combustion mechanisms. Droplet combustion was defined as "the delay between atomization and combustion." A schematic diagram was drawn to illustrate the droplet combustion mechanism.

Droplet Combustion Mechanism



Feedback schematic for Buzz and acoustic instability

It was stated that there are pressure and velocity gradients in a compressible medium, and several combinations of three mechanisms that could sustain instability. The feed system was then defined as "...motion of fluid through the injector up to the point of combustion." Injector passages were considered to be the blank factor in the knowledge of acoustics. Combustion time delay was termed "transport" and a diagram was drawn to illustrate the concept.



Model of Droplet Combustion

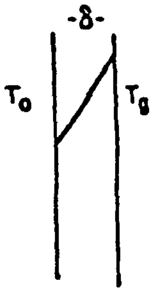
Limits of Laminar Boundary Layer

Assume longer transport time than burning time. Transport time is independent. Larger drop size = larger D_F.

[redacted]

In the discussion that ensued one of the Committee members provided the following explanation of D_F:

$$\frac{h D_d}{k} \qquad q = \frac{k_g(T_g - T_o)}{\delta} = h(T_g - T_o)$$



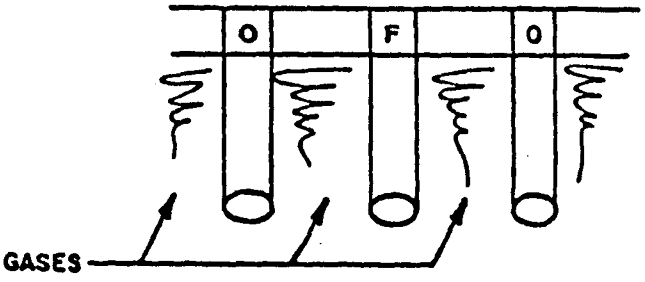
$$\frac{hD_p}{k} = \frac{10p}{\delta} = 10$$

Nusselt numbers vary from 3 to 15; average is 10.

Therefore: thickness of boundary layer is 1/10 thickness of the droplet.

Subsequent conclusions arrived at were: (1) relative velocity in the first 3 inches of the thrust chamber is an unknown, (2) recirculation is caused by a pressure differential (pumping action: the drag of moving fluid pumps gas away from the injector face), (3) the total drag of droplets is far greater than that of jets.

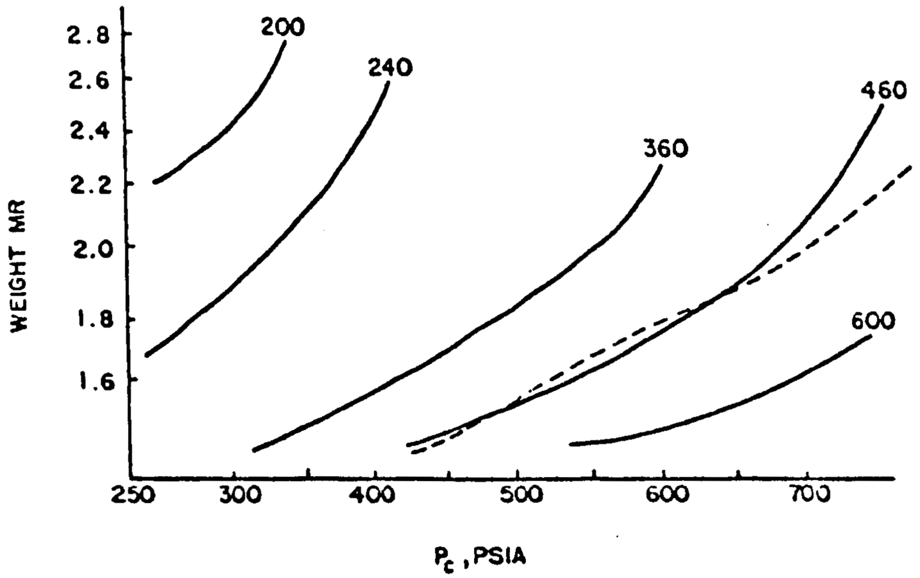
A preliminary design concept resulted from this discussion intended to decouple the feed system from combustion.



Stream-baffled injector

Jupiter engine instability data were then presented in support of the droplet combustion theory, and was equated to F-1 conditions.

Correlation of Jupiter Engine Instability Data



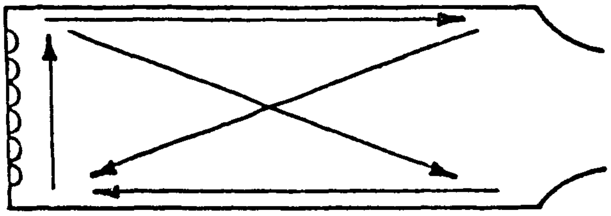
To determine empirical constant

It was stated that the limiting parameter of combustion, as illustrated by the Jupiter engine instability graph, is the vaporization rate of the fuel. In a summary of the droplet combustion mechanism concept, the following was stated: (1) there is a drop size that is bad for a particular mode in any given thrust chamber, (2) on a frequency change basis, changing the drop size to change the frequency should do away with instability, and (3) the oscillations generated in the feed system exist in the chamber. Application of the concept could be achieved by coupling with the feed system and changing fuel hole velocity and/or fuel hole size. The major parameter change suggested was to reduce orifice diameters to 0.15 to 0.17 inch, thus detuning the forcing function. An implicit aspect of the theory suggested that every hole should be of a different size to provide droplets of different sizes, droplet energy, and therefore, being "held to each droplet" (sic).

[redacted]

In summarizing its thinking at this time, the committee concluded that the stability problem results from multiple processes that are out of phase. "It is not a simple process confined only to droplet formation or shattering, or acoustic frequencies, or others:

1. The wave effect concept considers combustion at the injector face pressure-sensitive and frequency-insensitive.
2. The concept which postulates that the combustion process is always essentially unstable considers drop size and chamber length critical parameters."



A wave starting longitudinally will return to injector face, become a low-amplitude transverse wave, and trigger and retrigger instability.

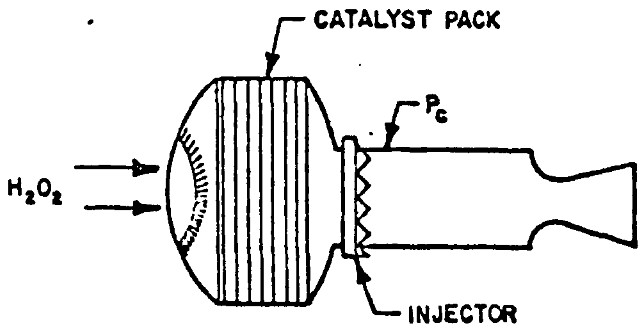
A conception reached at this time held that the combustion process competes with droplet formation.

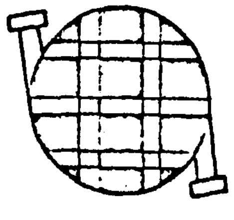
The discussion turned to staged combustion; this based on the contention that the potential energy in the chamber should, ideally, be spread axially and radially.

An aircraft rocket engine, designed and built at Rocketdyne, was recalled as a smooth-running, stable system. The design parameters of this unit were considered by the Committee:

[redacted]

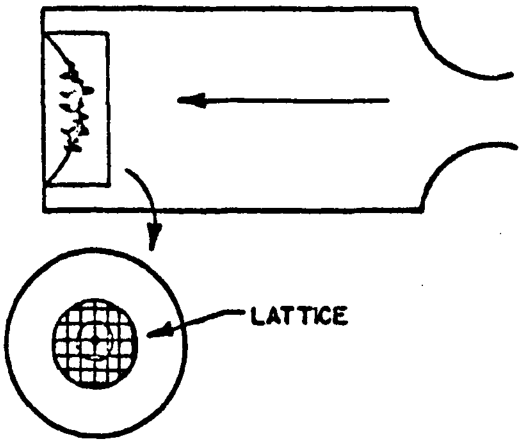
The aircraft rocket engine was the smoothest running engine ever built at Rocketdyne.





A 20,000-pound-thrust engine, made at Jet Propulsion Laboratory, was also recalled in reference to the staging concept. This unit was, reportedly, a "backward" (sic) injection scheme, and ran stably with the most critical propellant combinations. The system was described as "essentially a two-stage" which maintains strong ignition energy and reduces injection-loading density in the first stage--in the "combustion sensitive" region.

An engine design proposed for the Vanguard was also recalled:



[redacted]

The research chemists were called in for consultation. They represented the following conclusions:

1. The time involved in the chemical kinetics is too short to be a dominating factor at frequencies in the neighborhood of 1000 cps.
2. Chemical reaction may be a factor in combustion instability at frequencies of 500 cps and temperatures of 1500 F.
3. A sustained chemical reaction at 5000 F is impossible.
4. Popping might be initiated by a chemical process (may be periodic restarting).
5. The "knocking" phenomenon in automotive engines may correspond to rocket engine "popping." It may be possible to synthesize "knock" conditions in a rocket through the use of additives; analines may prove to be good additives; neat fuels worth some investigation; try iso octane and normal heptane.

There does not appear to be an experimental method of investigating triggers. It was postulated that if the sustaining mechanism could be isolated and understood, an hypothesis could be developed to understand triggers.

The chemist suggested that carbonaceous products could cause wild ignition, and aromatic fuels are notorious for carbon deposition. Additives might prove useful in eliminating carbon deposits.

A member of the Committee noted that the best wall coating to reduce heat flux in a LOX/RP engine is carbon.

A probing technique was recommended:

1. Optical spectrosity
2. Mass spectometry
3. Mass spectography

An instrument costing $100,000 would be required and would take 6 to 7 months to set up.

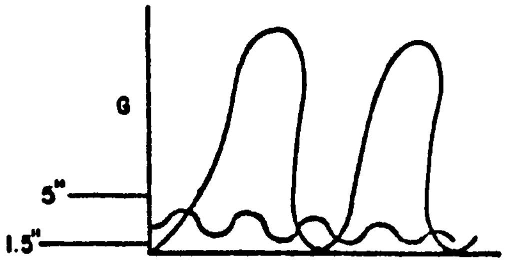
It was decided to hold the idea in abeyance.

ROCKETDYNE RESEARCH

The latest thinking of the research scientists was presented to the Committee for consideration in the development of the two-dimensional program:

The contention presented was that in the F-1 the surface temperature of each droplet does not get to the saturation point; this is because surface tension is reduced at higher pressures, and because high velocity tends to shear droplets.

This conclusion was based on 1000-psi shock tube experiments. The conclusion drawn from this concept was that burning rate/area is the critical factor in F-1 instability. It was stated that in the F-1 the mass burning rate goes up, but the surface burning rate remains constant.



On the basis of an independent parameter: that droplets shatter when heated, and shattering occurs at differing distances from the injector face, it was then theorized that a disturbance near the throat of the thrust chamber will propagate upstream; it is damped, but occurs again.

A solution was offered which recommended that very fine droplets should be shattered near the injector face so that no fine droplets will manage to get downstream; this to be accomplished through the use of many very small injection orifices and many baffles.

The concept was held in abeyance by the Committee, and a program plan for the two-dimensional program was formulated.

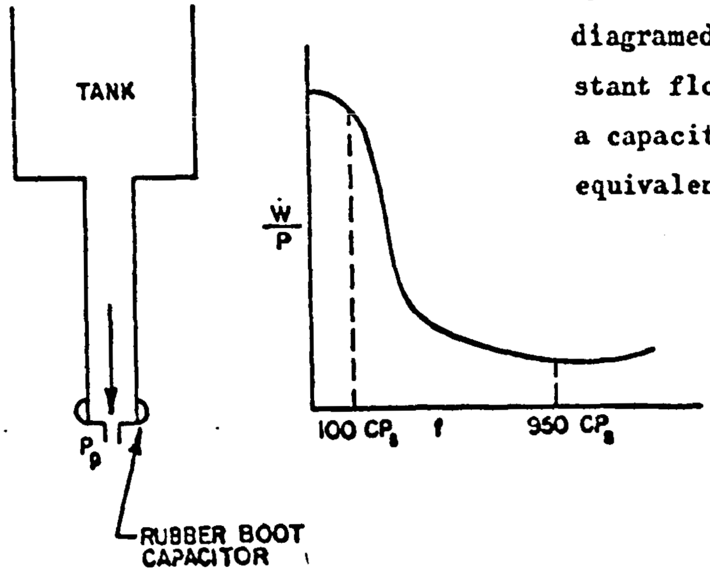
[redacted]

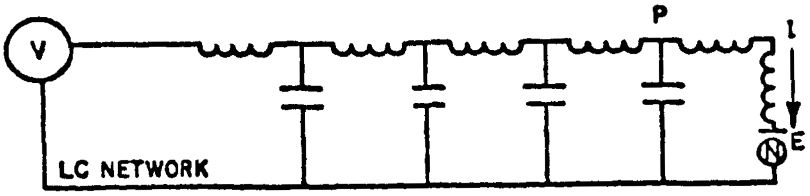
INDUSTRIAL AND ACADEMIC CONSULTANTS

Richard Priem, Ph.D., of NASA Lewis Research, visited Rocketdyne for consultation with the committee on 9 November 1962. In a discussion of feed system coupling effects on the combustion process, Dr. Priem expressed the following conclusions based on his observations.

1. There is an inherent sponginess (capacitance) in propellants which makes a "perfect" feed system impossible.
2. The best means of decoupling the feed system is the cavitating venturi, but it will not function with LOX.
3. All rocket engines are essentially unstable, and decoupling the feed system will solve nothing.

A concept for a mechanical capacitor that would ensure constant feed system flow was described and diagramed for Dr. Priem. Constant flow can be achieved with a capacitor. The capacitor is equivalent to an enormous tank.





[redacted]

There is a 600-to-1 relative capacitance at the 1-inch rubber boot. The unit depends on the inertia of fluid at the exit to keep flow constant. It was planned to line the back side of the ring with laminated Mylar.

It was generally agreed that such a device would require a drastic hardware change because of resistance in the current system design.

The staged injection concept was presented for Dr. Priem's consideration. His judgment was: "Fine, but impossible to do without losing efficiency and performance. Two-stage injection will result in too much burning by classical theory. Stability and performance are incompatible. Acoustic waves arise with rising performance."

The Committee at this time was tone-deaf to acoustic theory as the sole explanation of the phenomena of instability. A short debate ensued, but the question of the applicability of acoustics to the F-1 problem remained unresolved.

Dr. Priem subsequently offered the following observations:

> The Q (amplification factor) of a 100-percent efficient engine is so high that it will drive the system unstable. If the system "drives" in phase (at the nodal points) it will be stable, but it cannot possibly damp out between two points. By knowing the dimensions of the chamber, it can be determined whether a longitudinal or radial wave will result. Waves will go to certain types of frequency according to the shape the chamber favors. Amplitude is something else. The chamber will go unstable in whatever mode has the highest Q. In a 1.25:1 chamber, "combination waves" are possible. The velocity gradient at the throat will have no effect. The pattern of the injector controls whether instability will occur; the chamber geometry controls the mode.

Injector divergence was mentioned, and Dr. Priem's opinion requested. He was of the opinion that divergence will not affect the "waves" but will affect combustion. He suggested that cold flow tests be used to determine reflectance.

As the discussion continued, Dr. Priem stated that there are two damping factors:

1. Velocity gradients of gases
2. Viscous drag

He recommended that the Committee look into out-of-phase injection. He also said that local velocity gradients will disperse but will not get rid of energy; that a disturbance that will grow has to be near the injector; that waves can be nullified by angles (divergence), but this will only provide a small percentage of the required damping; that a high-burning-rate, low-velocity gradient will give good damping; that transverse waves can be eliminated with longer baffles.

David T. Harrje, of Princeton University, visted Rocketdyne for consultation with the Committee on 12 November 1962. Mr. Harrje stated that work then in progress at Princeton with an IBM 7090, in applying acoustic theory to combustion instability, would include F-1 combustion parameters. It was his opinion that baffles would definitely eliminate the tangential mode, but not the longitudinal mode. If the longitudinal mode is encountered, the length of the thrust chamber should be altered. He stated further that Princeton could predict mode problems for a given engine at various pressure loads and for a given geometry, and that curves (pressure level/geometry) could be made up for the F-1 when the predominant frequencies are known.

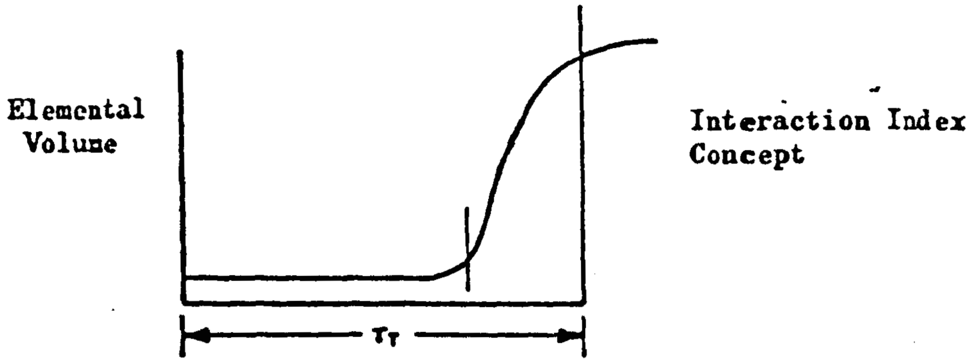
[redacted]

At the Committee's request, Mr. Harrje summarized his then current evaluation of the F-1:

> "On the F-1, the bulk of the combustion occurs at the outer walls of the chamber. From the displacement effect, you're in a favorable situation. If you could take the 5U and turn it 90 degrees, you'd have an advantage in the tangential mode, but I don't think the tangential is the F-1 problem. A major test on the F-1 would have the main bulk of the injection coming in very close to uniform denisity from the sides. The 5U is not doing that for you. I distrust showerhead schemes because of the large droplets, where droplets depend on turbulence mixing in the chamber."

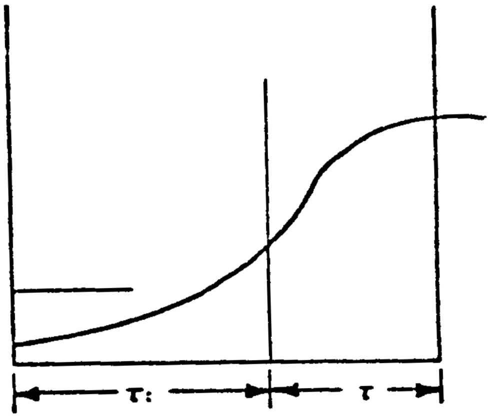
Asked to elaborate on the work being done at Princeton, Mr. Harrje presented the following:

> The initial approach took after Crocco's simplified approach: time lag.



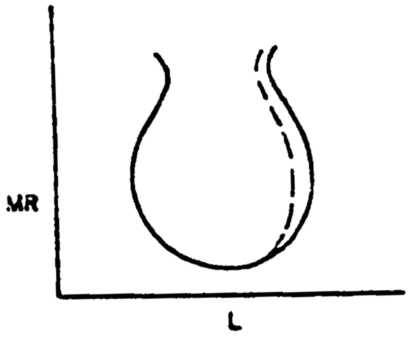
(Total time for combustion)

Little coupling between combustion processes and pressure processes. In vaporized state interaction develops.



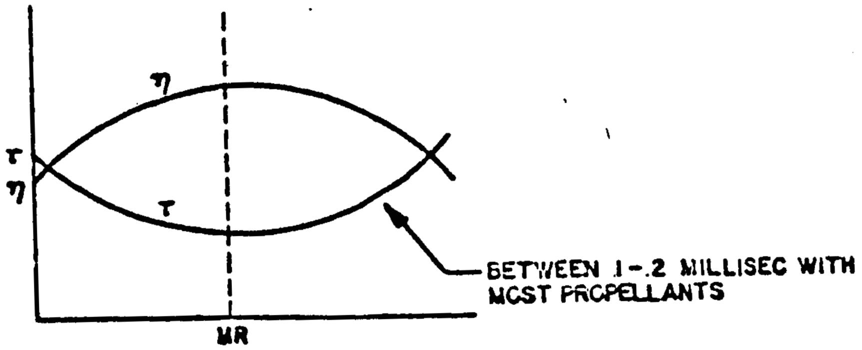
(Insensitive area)(Sensitive time lag)

All processes were lumped under one broad general concept. Rough tests were surveyed for length vs mixture ratio, and good agreement for the concept was found.

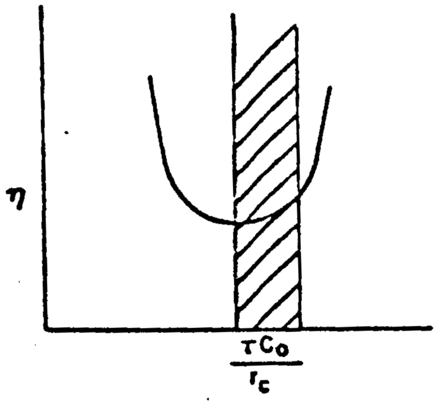


Length really a frequency factor

Concept in the ARS Journal:



The time scale is changed by the varying geometry of the chamber. Once you know the range of time lag values, you can determine critical regime.

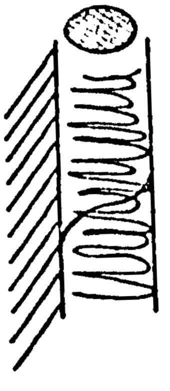


It can be calculated where combustion instability is going to occur.

Because τ and η vary with mixture ratio, one can get stability limits by varying mixture ratio.

Most promising condition:

....time required for final droplet heated to vaporization point to vaporize. If you characterize droplet as shown, the gradient of "slab" looks most like a theoretical picture. Final droplet is extremely fine up to temperature burning rate, and P_c fluctuations are interrelated.



Mr. Harrje's concluding statement was that the rate of vaporization is the most important factor. He defined η as a "sensitivity" at different stages of the process, and τ as a rate of vaporization factor.

As the discussion progressed, Mr. Harrje stated that all like-on-like injector patterns are stable in the longitudinal mode.

For the η τ concept, it is assumed that the entire chamber is filled with gas. τ does not include feed system coupling.

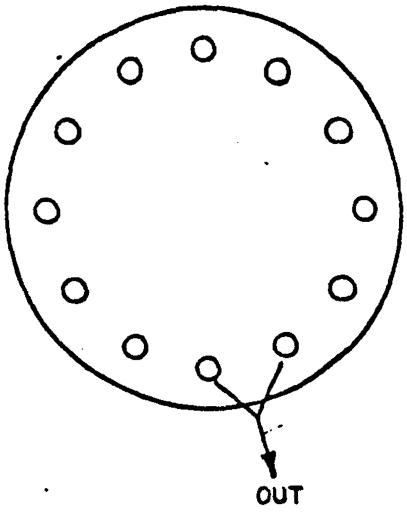
He said that cavitating venturis had been used at Princeton to isolate the feed system, and no mass flow fluctuations had passed into the chamber through the cavitating venturi.

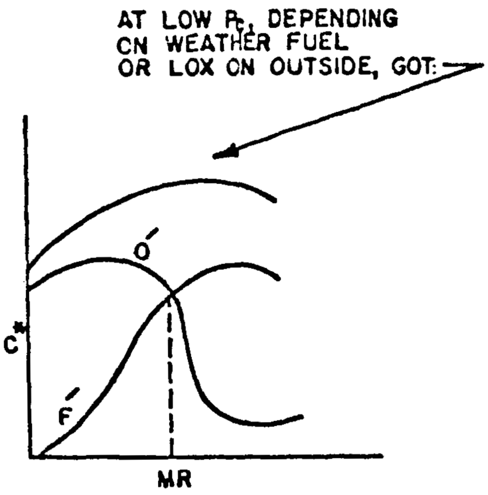
He related that an engine had been built and tested at Purdue with injection at the nodal point, and that Princeton had predicted the engine's acoustic operation.

The highest amplitudes were found at 90 percent (in the outer 10 percent of the injector diameter) of the chamber (outer 1-inch) periphery in the Princeton engine. Once this engine goes into its mode, it stays there; when baffled, it was stable.

Mr. Harrje expressed the belief that an engine will choose the lowest mode available to it; further, that the spinning mode is affected by gas flow velocity. He then diagrammed the Princeton spud engine and agreed to remove one of the spuds, thus creating a time delay as a test for the acoustic theory which he had presented.

Each of 12 spuds has a fuel fan
and a LOX fan--these interchangeable





There is always a small radial
velocity with LOX outboard of
fuel, and little or no mixing.

When asked his opinion of the value of additives, Mr. Harrje said he thought that chemists lack the stable operation characteristic parameters to judge additive effects by. He suggested, then, that the Committee think "in terms of having something going on between a chemical and acoustic process--a forcing process--an amplification function," when trying to understand the instability phenomenon.

It was generally agreed, by the end of the meeting, that radial winds are a major factor affecting F-1 instability.

Don Bartz and Jack Rupe of Jet Propulsion Laboratory consulted with the Committee on 16 November 1962. F-1 history, data, and the Committee's thinking were outlined for the vistors. In the ensuing discussion, they postulated that the F-1 instability problem appeared to result from a

[redacted]

"detonation front," and that acoustic theory would be excluded by the fact that the F-1 is a "high-energy" system. They imagined the instability phenomenon as a complex wave front driven by energy release--a helix with two motions involved--and with an axial orientation. They also suggested that a detonation front is a steady phenomenon which does not require coupling with the feed system to be sustained. Mr. Rupe stated that there is always coupling with the feed system and this cannot be avoided; the injection scheme of the system prohibits the control necessary to achieve repeatable injection densities.

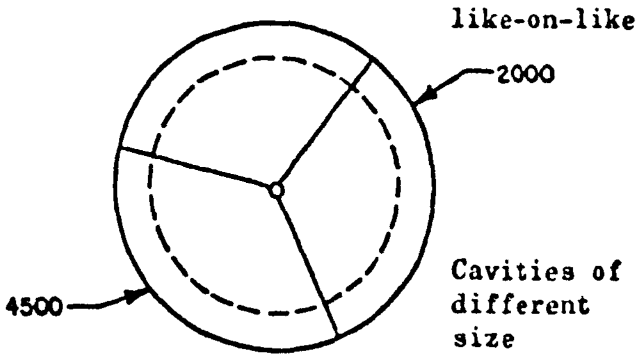
Baffles

In discussing the effects of baffles, observations based on experience at JPL were offered to the effect that the spray pattern will influence baffle placement and length requirements. Mr. Rupe illustrated this observation with the following:

With 2-inch baffle magnitude of P_k disturbance dropped by order of magnitude.

Added an inch; could detect no characteristic frequency; peak-to-peak amplitude was about 3 psi.

High-intensity combustion zone moved down to end of baffle when baffle lengthened to 3 inches.



Unstable with any one of the baffles removed.

Further observations on baffles were that a wave below the baffle has little or no effect on the mix-reaction area near the injector face; that baffles act much like a screen and prevent the wave from getting a long "running start."

Spray Fans

In the discussion on spray fan parameters, JPL conclusions were elucidated as:

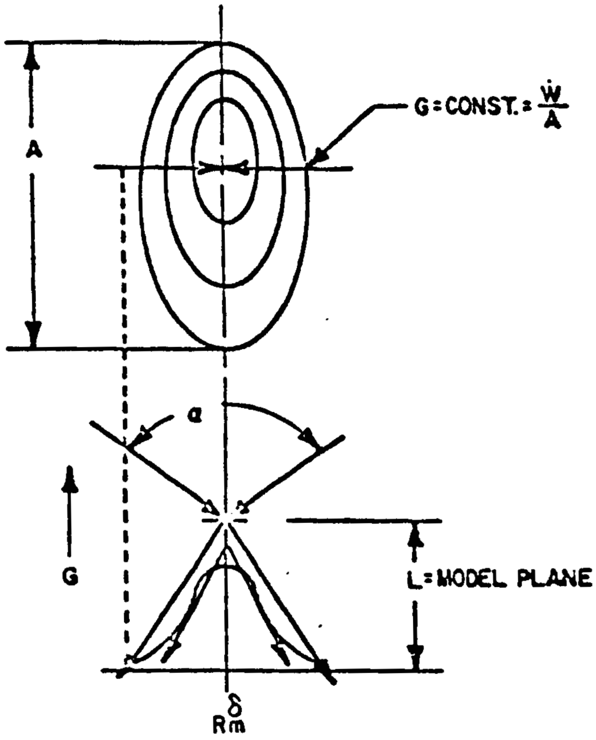
1. How the particular mass and mixture ratio is achieved makes no difference to the distribution; but radically modify the mass distribution and the type of disturbance resulting is radically changed.
2. Droplet size is a secondary parameter.
3. The most sensitive zone is where the propellants are most completely mixed.
4. Fans do not really impinge; they disperse.
5. Liquid phase mixing is just one way to get macroscopic combination of the two fluids in the chamber at a proper mixture ratio.
6. A uniform mixture ratio distribution establishes the exothermic point at which combustion occurs.
7. The model plane (best mass distribution plane) would be effective in the gas phase area of the chamber, where combustion effects take over.
8. Mass distribution does not alter axially, but goes right on out the nozzle.
9. At the present state of the art, we are not taxing the ultimate combustion rates.

[redacted]

Mr. Rupe illustrated the results of his work in spray fan formation and evaluation with the following:

Near Uniformity:

1-on-1 pair of impinging streams - unlike

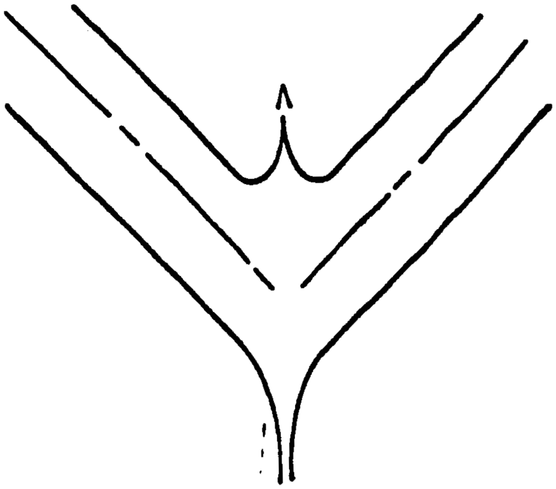


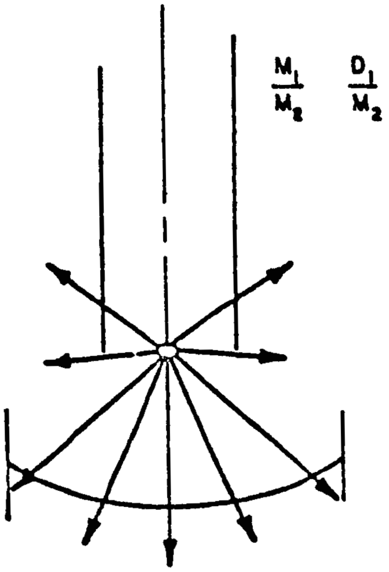
Will form a spray with identical features.

Plane of symmetry bisecting centerline and bounded by mass flux lines.

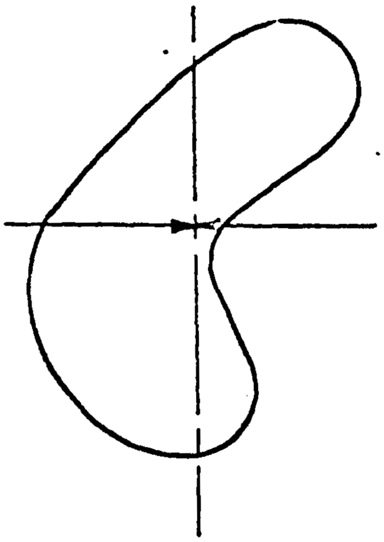
Particularly valid for small impingement angles.

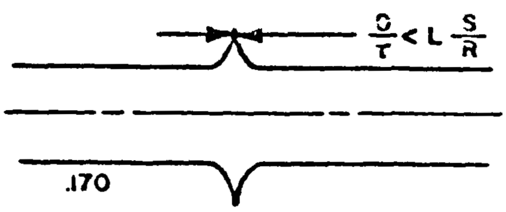
180° impingement angle is limit.





With non-identical streams:





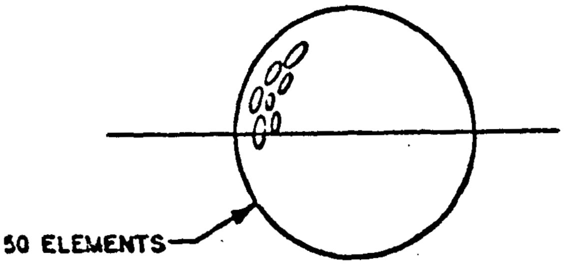
With width stream goes feet before breakup.

Disturbance here will propagate into the sheet.

For all practical purposes, you can ignore all aerodynamic processes.

Extraneous forces (gas fields, recirculation) can affect how spray is formed at or near injector face. But because of high kinetic energy of spray, these effects must be small.

Spray is formed as though it is not in a combustion field.

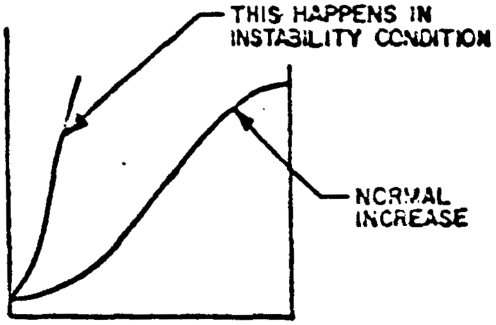


If geometry could be fully known, chamber space could be completely filled.

Injector should be designed for optimum mass distribution

We have mixture ratio problem; not necessarily a mass distribution problem.

Plot at model plane (distance to get 1/n of chamber area).



A summary of thinking on stability at JPL included the following assertions:

1. Instability is not necessarily acoustic, although a discernible mode may be present during instability. The acoustic condition is one in which no energy is being fed to the disturbance after its initiation.
2. Mass and mixture ratio distribution determine the combustion parameters of a system.
3. Chemical kinetics are dependent upon temperature. All propellant combinations are hypergolic at given temperatures.
4. Injector leaks are dangerous: leaks will not permit controlled reproducible and uniform stream characteristics or uniform mixture ratio, and are liable to produce instability-triggering conditions.
5. Hot walls and injection surfaces are favorable, and the recirculation of hot gases at the injector face is to be desired; hot-gas recirculation suppresses cold propellant from being suddenly triggered into violence.

[redacted]

6. Low-density mixing appears beneficial. High-injection density may provide superior starting and inhibit the triggering of instability, but when an instability does occur, it is of the most damaging variety.
7. Combustion is best staged, or "spread out" axially in the chamber.
8. In discussing chamber shapes: (a) a square chamber would prohibit tangential waves, (b) chamber length should be optimized; energy release vs length is completely dependent upon combustion time, and (c) extremely short mixing length and combustion extremely close to the face should provide stability.

Professor E. S. Starkman of the University of California consulted with the Committee on 12 December 1962. Professor Starkman's field of interest and background were directed to the combustion process in reciprocating engines.

In a comparison drawn between the characteristics of combustion instability experienced with the F-1 and "knock" or "ping" in reciprocating engines, Professor Starkman suggested that RP-1 fuel, as used in the F-1, is a "cut" which is highly paraffinic in composition and prone to knock. It was also established that the energy densities of internal combustion engines are of the same order of magnitude as rocket engines. Further discussion of the comparison led to the conclusion that the F-1 is most analogous to diesel engines.

It was suggested by Professor Starkman that if the F-1 problem is fuel-related, the frequency encountered might be the result of chamber stress (rates of pressure rise exceeding what the chamber can sustain). He also stated that a slight difference in the composition of the fuel would make a noticeable difference in engine operation.

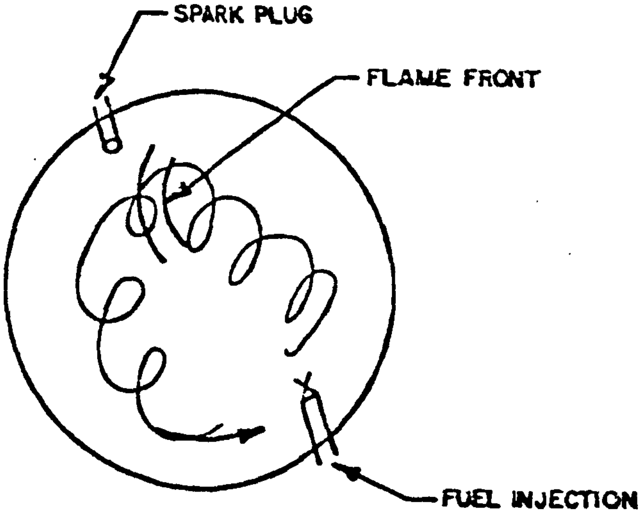
[redacted]

When questioned about the possiblility of using beneficial additives, he recommended trying ethyl nitrate and dinitropropane.

He also related that when "instability" characteristics were encountered in General Motors' diesels, changes that induced greater turbulence and finer spray overcame the problem.

In relating the latest design thinking in combustion chambers, Professor Starkman described the "stratified charge" system, which completely eliminates "knock" and is capable of operation on any fuel.

Stratified Charge Combustion Chamber



There is no sensitive region in this type of combustion chamber. "Radial wind" brings the ignition source past the sensitive zone.

Having noted that vibration traces taken to evaluate "rumble" in diesel engines were identical to F-1 sonic photos, a discussion of the "rumble" phenomenon began.

[redacted]

Professor Starkman stated that rumble arrived with the development of high-compression ratios, occurring naturally only when the engine was "dirty," and showed the characteristics of "fireflies" in the combustion chamber. The firefly effect is created by carbon flaking off the chamber wall and being recirculated into the hot zone by radial winds. He suggested that this mechanism might well account for instability triggering in the F-1. The Committee then considered the F-1 injector configuration in light of this concept, and concluded that wide-base baffles, because of cooling characteristics, may help such a phenomenon to occur.

Professor Starkman went on to state that if the mixture ratio gets rich, the RP-1 will be cracked (as in diesel exhaust smoke); a fuel-rich mixture, instead of oxidizing, will crack, and it appears feasible that a dumping of "fireflies" into the chamber will cause a fuel-rich condition and sudden cracking of the fuel.

This explanation, it was then thought, might well suffice to answer the riddle of the "black frame." (In studying high-speed films of an instability on test stand 1A at RS/EAFB, it was noted that the engine expelled a dense black soot, completely obscuring the normal exhaust jet flame, immediately before the first evidence of instability. There was speculation as to the cause of the black frame.)

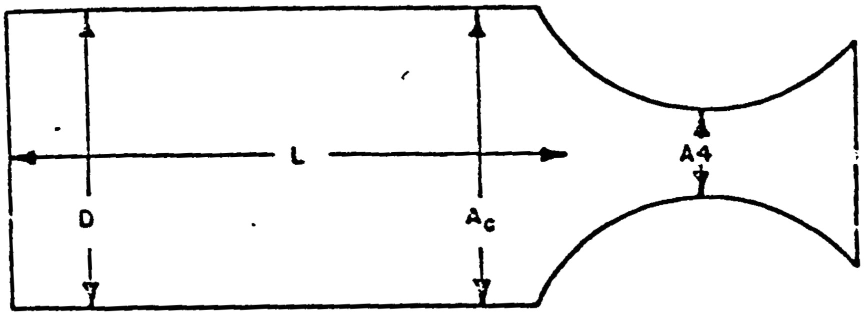
The discussion then centered upon dynamic system feedback during rough operation. Professor Starkman stated that during rumble there is no feedback (coupling with the feed system). He said that a diesel engine running at low loads will have cylinders starving because of waves in the system; that if the system is tuned to it, a disturbance in the chamber will carry back through the feed system. On this basis of comparison, it then appeared that an instability could be reinforced by a pressure wave traveling in the feed system. He added that "ignition accelerators" are used in diesels to eliminate knock. When asked his opinion of the potential efficacy of a control-phased anti-pulse, he said it looked fine in theory but would be difficult to the point of impossibility to incorporate.

The Committee reflected upon the use of antechambers in diesels wherein a precombustion chamber is used to forestall unstable combustion. It was considered that this conceptual approach could be analogously applied to the design of a rocket engine--had been, in fact, in a two-dimensional Research thrust chamber that had not yet been fired.

At the conclusion of the meeting, Professor Starkman suggested that reaction rate theory indicates an increasing reaction rate with increasing chamber pressure, and that mass transfer is not the only controlling factor in the F-1--rather, the question to be answered is whether LOX and RP-1 can mix in the liquid phase.

Herbert Ellis of Aerojet, Azusa, consulted with the Committee on 14 December 1962. After a short briefing about the F-1 problem, he presented his approach to the rocket engine combustion process.

It was his belief that in the liquid-propellant rocket engine, we are actually dealing with a chemical process that functions in a repetitive cyclic manner: new charge--combustion--scavenging--new charge--ad infinitum. He diagrammed the basic factors involved in combustion instability in general:



In presenting his observations on the combustion process and the instability phenomena, Mr. Ellis said the following:

1. The resonance of the entire feed system enters into the injection characteristics of a system.
2. A change of mixture ratio at the injector face will cause a change of temperature and pressure at the throat, and the smaller the area ratio, the greater the magnitude of fluctuations (this is a longitudinal effect).
3. The pattern of an injector should be predicated on the desired mixture ratio of the propellants.
4. When burning is localized in a chamber, the chances of cyclic instability are increased.
5. Given a mixture and ignition source, the mixture will burn; with no ignition source, the mixture simply gets hotter and hotter until auto-ignition occurs, and this can happen anywhere downstream in the chamber.
6. A longitudinal pressure wave will cause a detonation front which will trigger a mixture. The wave will build up if the mixture is below stoichiometric temperature.

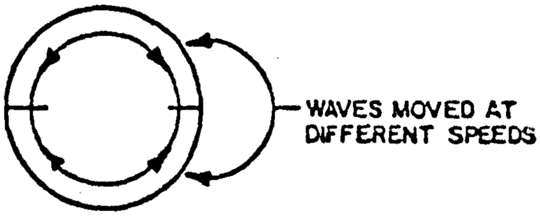
7. A flame front will move around the chamber to wherever there is something to burn; auto-ignition may occur in advance of the flame front depending on the chamber's time constants.

When questioned by members of the Committee as to his experience with injection systems, Mr. Ellis stated:

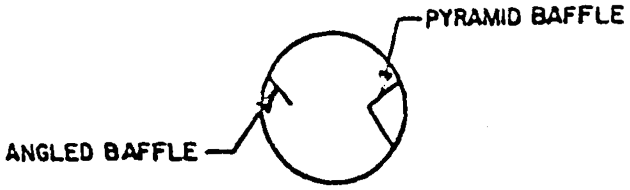
1. Like-on-like injection patterns are extremely susceptible to disturbance by bubbles in the propellants.
2. The longitudinal mode is the most difficult to cope with in combustion instability; axially distributed injection schemes should prove least susceptible to the longitudinal mode.
3. In operating a bluff body injector design to obtain staged combustion, Mr. Ellis obtained good results, but injector fragility proved too great a problem.
4. It is advisable to design the injection system so that reactions occur in the straight section of the chamber, because heat release in the converging section will cost performance.
5. Keep the combustion chamber and injector face as hot as possible to prevent heat being removed from the hypergolic reaction by cold surfaces.

Baffles

When asked about his experience with baffles, Mr. Ellis replied that in initial baffle investigations, two baffles were tried; the waves they got in the chamber then moved at different speeds.



They then tried four baffles and angled baffles, the latter requiring a greater pulse to create a wave front. A pyramid baffle was tested and found to be very effective.



Triggering Sources

Mr. Ellis submitted his conceptualization of possible triggering sources:

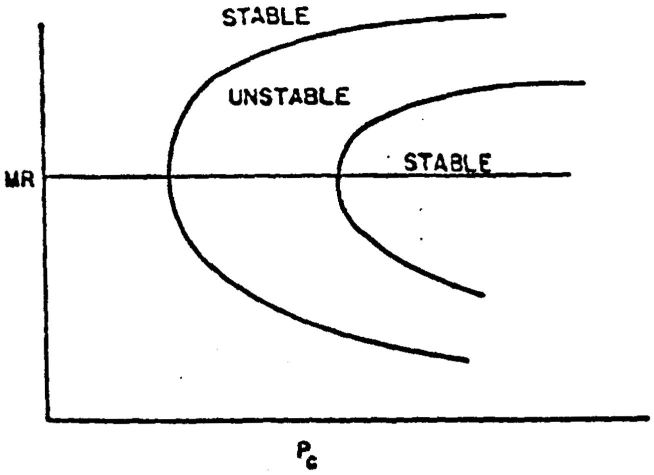
1. Random noise in the thrust chamber
2. Buildup of unburned mixture (cold chamber wall a cause)
3. Bubbles in propellants
4. Fluctuations in the feed system

He related that his experience included the use of a flexible rubber hose upstream of an injector, which provided very stable operation.

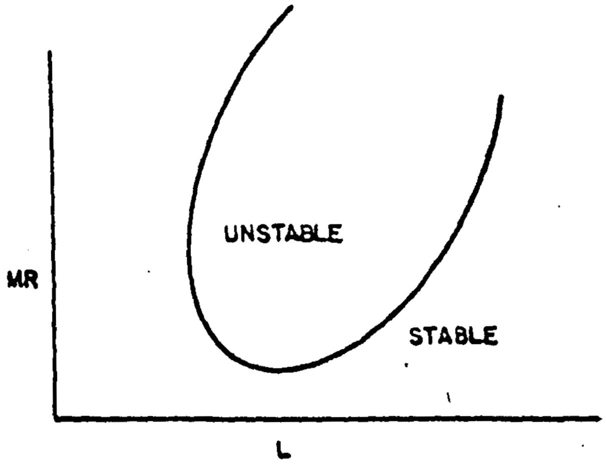
His summary recommendations were that fuel and oxidizer should be injected at different velocities and through different hole sizes to prevent the establishment in the chamber of a single critical plane. He also suggested that injection streams should be made larger with higher chamber pressures. He elaborated further with the suggestion that because of the high vaporization of LOX at high chamber pressures, angles of impingement lose their importance; that a showerhead orifice would prove best for LOX, and high velocities and varied half angles would help on the fuel side.

Mr. Ellis' final statement was to the effect that when the combustion time delay is tuned to the inherent frequency of a system, instability results. Instability can be prevented by proper "detuning."

On 20 December 1962, Professor Robert J. Osborn of Purdue University consulted with the Committee. His work had been focused upon combustion with unmixed and premixed gaseous propellants. He had found that by plotting combustion pressure as a function of mixture ratio, he could map regions of stability.



Air as oxidizer with H_2, CH_4, C_2H_4



His experimental work indicated a chemistry effect in the combustion process. To determine the chemistry effect, he had operated his engine with:

1. Mixed gases
2. Unmixed gases (showerhead injector and two-on-one impinging injector)
3. Liquid and gas
4. Gas and liquid
5. Liquid and liquid

1. Mixed Gases

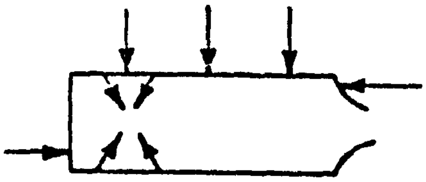
Studied effects of geometry - tried chamber lengths from 2 inches to 60 inches.

- tried chamber diameters from 3 inches to 28 inches.

Maintained throat diameter from 1/2 inch to [illegible] inch because of air limitation. Determined nozzle effect to be important for longitudinal mode - nozzle impedance velocity was design factor.

Studied injection system - used all uncooled systems.

a. Baffles
b. Uniform
c. Discrete - different locations along chamber axis

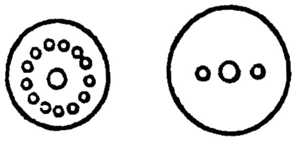


d. Different propellants - C_2H_2, H_2, C_3H_8, CH_4, C_2H_4 all with air as oxidizer.

2. Unmixed Gases

Studied:

a. Injection systems - showerhead impinging triplets.

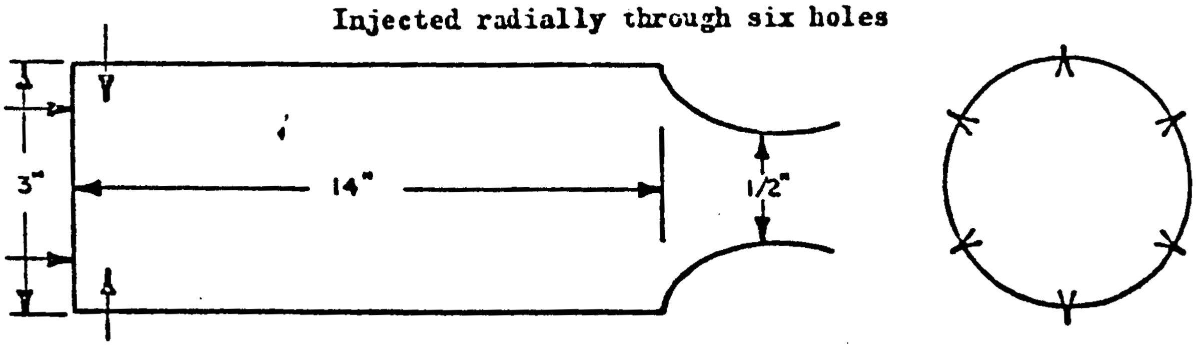


b. Propellants

c. Geometry - 7-inch and 14-inch chambers.

Professor Osborn had also concluded that, for the longitudinal mode, combustion instability is an acoustic phenomenon. He considered the thrust chamber a closed system. He described an experiment which he had conducted to define the effect on the longitudinal mode of injection along the chamber axis:

Injected radially through six holes



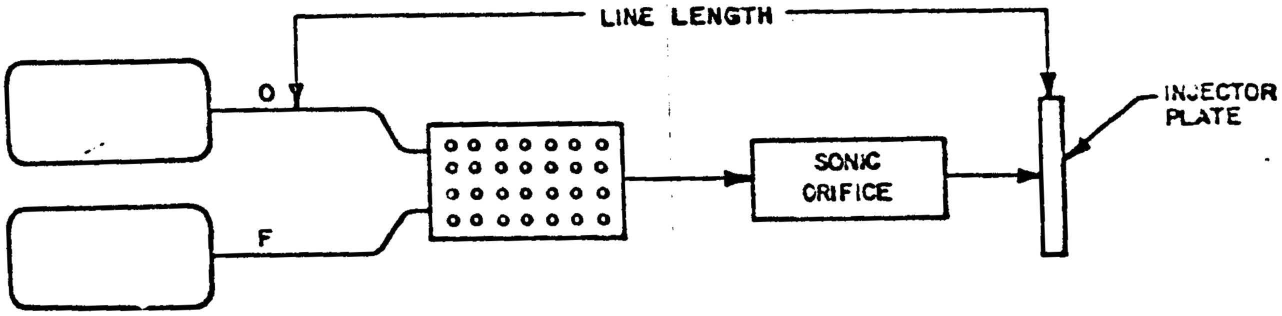
Professor Osborne described the gaseous propellant system he had been working with and stated that:

1. The system frequency was from 3 cycles to 40.
2. Combustion chamber acoustics are not involved in this system.

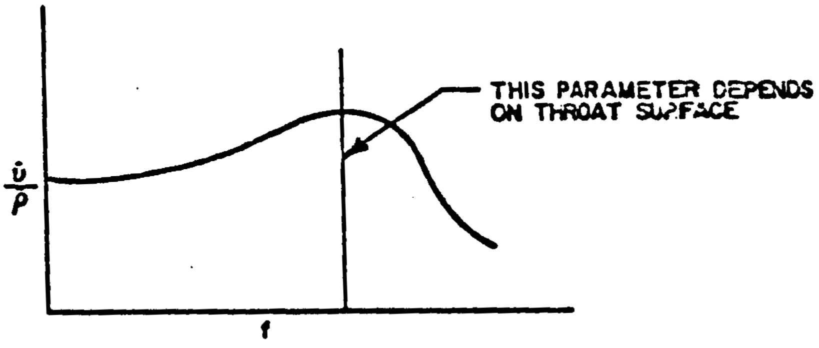
3. The system will flame with a smooth start and the flame will hold downstream of the injector; a rough start will cause burning back to the mixing tank.

4. A longitudinal whistle results from running with air.

Gaseous Propellant System



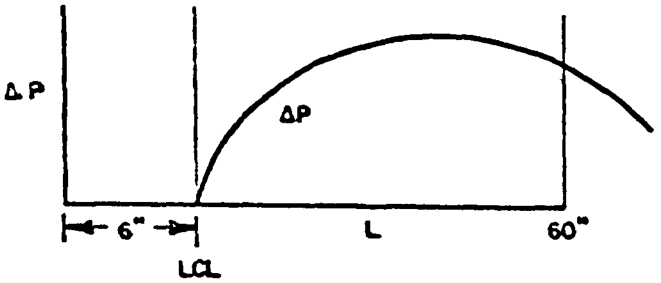
In a discussion of acoustic effects, Professor Osborne said that, "the definition of acoustic speed holds in the relatively unsensitive organ pipe region of a chamber, but at a point or points close to the flame front, acoustic phenomena cease to function." He went on to define acoustic impedance:



Acoustic Impedance: $\dfrac{\text{Velocity Perturbation}}{\text{Pressure Perturbation}}$

He described the effect of a longitudinal wave as: "A sonic longitudinal wave entering the combustion zone compresses the gases there, increases pressure, and increases the burning rate. The wave going through the combustion zone picks up driving force."

He stated that with no changes in the combustion zone of a system, if the chamber length is increased there will be a change in frequency and amplitude of the waves.



Using flame temperature of propellants, one could compute this effect.

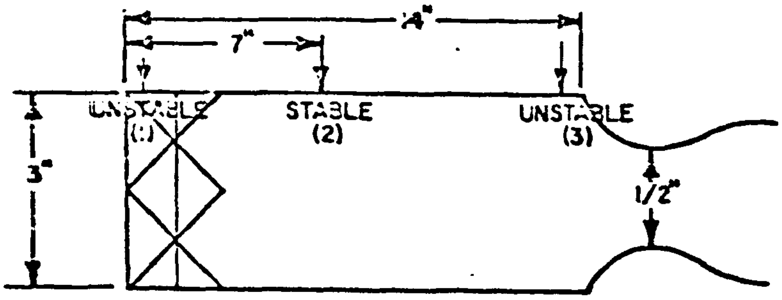
In confronting the F-1 combustion problem, Professor Osborne stated that "In a large system there is the possibility of all sorts of phenomena." This conclusion was conditional in view of his observations that "the combustion zone is frequency-sensitive," and "....if the 'reactor' is small enough, a stable system will be attained."

Another concept he presented was that with a nonplanar injection scheme, the laminar flame-front/pressure-front will cause flame wrinkling; and a wrinkled flame-front will burn faster.

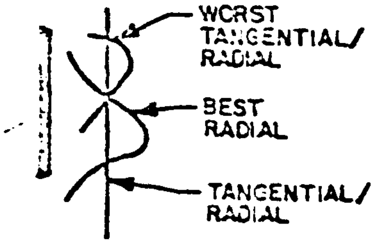
He stated that in his gaseous propellant system, changing the nozzle shape changed the wave shapes and amplitude, and by this change alone, stability could be controlled.

He also described the effect of injection halfway down the length of the chamber as an acoustic damper. The system, in this case, was stable--

the chamber pressure trace almost a straight line. Injection then at the nozzle end of the chamber caused the system to go unstable.

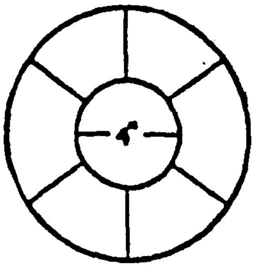


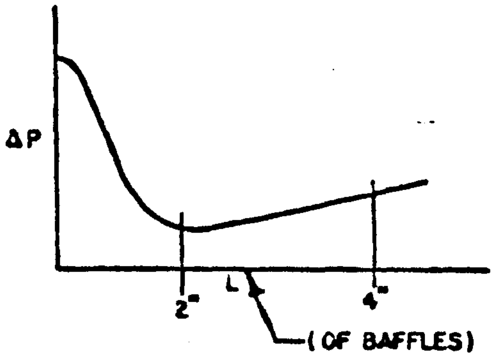
Density Profiles
All flatface
injectors



The frequency of (1) and (3) was the same; the amplitude varied.

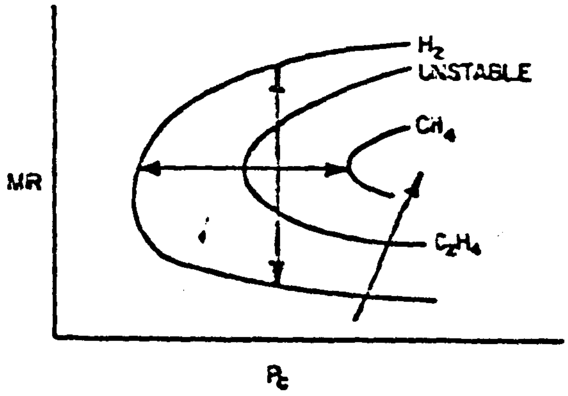
In further elaboration of his work, Professor Osborne stated that he had tried injection through a 2-inch-diameter ring in a 3-inch-diameter chamber, through a 6-inch-diameter ring in a 7-inch-diameter chamber (6 inches in length), and through an injector that provided uniform injection, and through variations of this one. All of these injection schemes drove the longitudinal mode. When he tried side injection, he observed first radial and first tangential modes. The transverse modes, he noted, had the same periodicity as the longitudinal, but the wave shape was different.





Professor Osborne presented the instability plot he had developed with his gas/gas system (with the reservation that the heat release rate controlling processes of a gas/gas system are different from those of a liquid/liquid system). He contended that the comparative stability of methane/air and hydrogen/air was dependent upon the rate of burning of each propellant combination; the latter (hydrogen/air), with a higher heat release rate, is more sensitive and therefore less stable, and will also "drive" a greater variety of modes. Hydrogen sensitivity could be reduced by adding iodine or helium--these additives lowering the flame speed and spreading out the flame front--with a resultant reduction in the ability of hydrogen to sustain wave propagation.

Purdue Instability Plot:



Based on a comparison of results he had obtained with premixed and unmixed gas injection, Professor Osborne concluded that the mixing process does not effect the phenomenon of instability.

A member of the Committee postulated that in a liquid/liquid system the frequency recorded is independent of injection density; that there is a given velocity of propagation independent of injector geometry; that this propagation wave travels at acoustic speed.

It was also postulated that "....once a wave gets started, its amplification depends upon damping and driving forces, and there is a threshold where viscous damping forces are greater than driving forces." In considering this idea, it was agreed that this effect may well be exaggerated in a gas/gas system and would not necessarily apply to a liquid/liquid system.

Some thought was then given to the idea of spreading propellants in the chamber by injecting at the longitudinal modal point. The design of a French rocket engine, the Veronique, was considered, as was the idea of baffling the entire thrust chamber, or at only an "antimode" point in the chamber.

ROCKETDYNE PROGRAM EXPERIENCE

E-1 Program Stability Experience

The E-1 Program, in which considerable work in high chamber pressures and high-thrust engines provided preliminary effort for the development of the F-1, was reviewed. Combustion instability in the E-1 was overcome through the use of wall gap with divergence, and close attention to pattern design that would provide "adequate" recirculation at the face. A 50-percent divergence was recommended as a good starting point for adaptation of the concept to the F-1. E-1 experience further indicated that the design parameters affecting performance are chamber length, injector diameter, and pattern.

Much of the E-1 Program work had been conducted with 22- and 25-inch hardware. It was agreed within the Committee that, although the instability phenomena apparent in the F-1 were unique, it would be beneficial (based on E-1 experience) to conduct tests of critical parameters with 150,000-pound-thrust engines and attempt to relate the results to the F-1.

Atlas MA-2

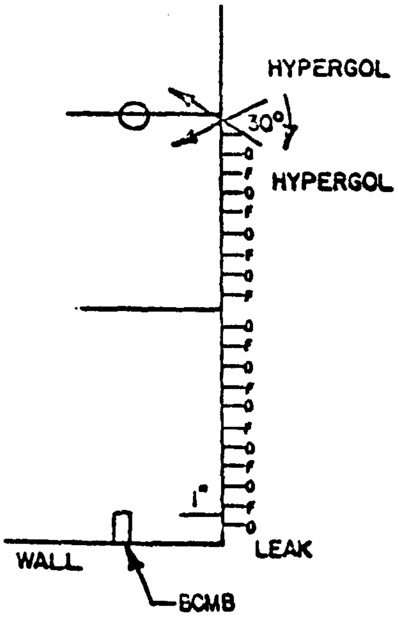
A program conducted on the Atlas MA-2 booster engine, to examine the effects of bubbles in the feed system, was reviewed by the Committee. Five cameras were mounted near windows installed in the ducting of the engine feed system. A normal engine static firing was conducted during which helium, gaseous nitrogen, and gaseous oxygen were separately introduced into the ducting. Bubbles visible at the inlet duct were not discernable at the high-pressure duct. No change was evident in the exhaust flame at any time. Carbon-dioxide and trichloroethelene were also introduced into the system with similar results. It was concluded that the pump eliminated bubbles from the system.

The Committee was satisfied with the evidence produced by this program, but felt that the possibility of a buble, or bubbles, produced in the injection stream downstream of the pump remained, and might still be a source of trouble.

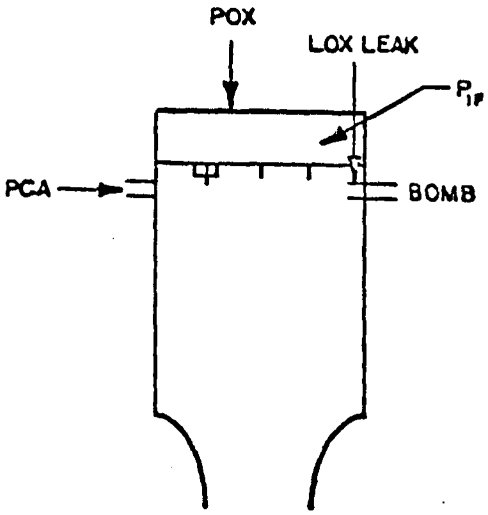
Two-Dimensional Research Program

In a review of studies conducted by Rocketdyne with two-dimensional transparent thrust chambers, the following conclusions regarding combustion stability were cited: (1) To describe combustion stability, it is necessary to know what stable combustion looks like (droplet size, breakup, etc.), (2) premixed injection holds great promise, (3) if propellants are mixed very rapidly, how they burn is relatively unimportant, (4) combustion gases directed toward the chamber walls speeds mixing and, thus, ignition (considered an important factor in maintaining stability). Wall gap and curved divergence were considered desirable elements of stable injector design.

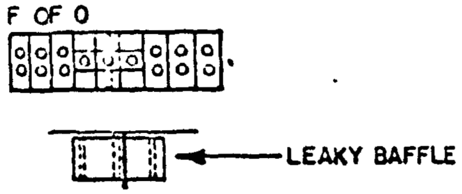
The effect of leaks from the injector face came under consideration once more with the presentation of results (films and pressure traces) from a test with the two-dimensional transparent thrust chamber in which a baffle had been purposely tack-welded into place, permitting a leak along the baffle. The injector used simulated a slice of the 5U injector used in the F-1. The leaky baffle simulated a radial 5U baffle. The system was bombed unstable in mainstage and did not damp. Examination of the leak problem in light of the available data from F-1 and firings led to the conclusion at this meeting that cannular baffle leaks surrounded by LOX can cause a gross disturbance; that the amount and distribution of LOX and fuel leaking are important stability factors.



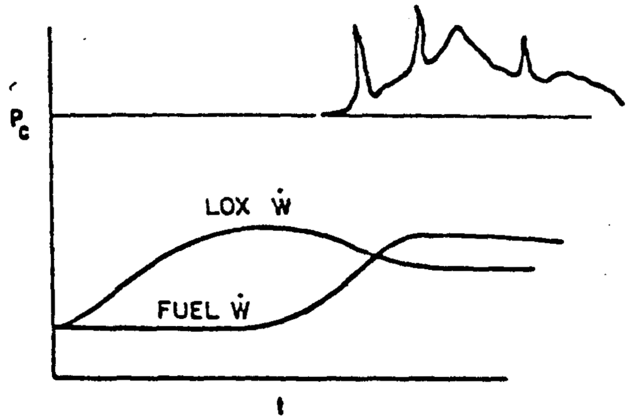
2D Injector



2D Injector With Like-on-Like Impingement



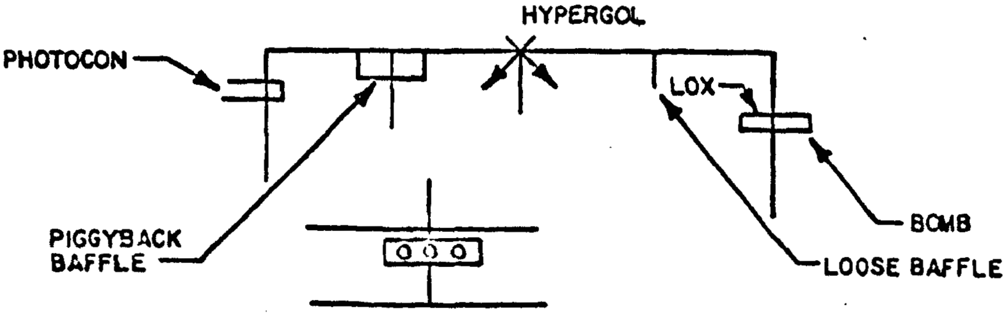
Pressure Trace



In tests to determine the effect on stability of leaky baffles with the two dimensional thrust chamber, one "pop" was recorded that appeared attributable to a baffle leak. The sequence of events was:

1. The "piggyback" baffle lighted with a bang and was knocked loose.
2. Six milliseconds after the bang, a bright zone appeared on the wall containing the bomb.
3. The returning wave bent the loose baffle.
4. The system then appeared stable.
5. The bomb detonated.
6. The pop was recorded.
7. The system stabilized.

This test was conducted at 100 psi.



[redacted]

CONCLUSIONS

DATA ACQUISITION AND REVIEW

Test procedures, instrumentation and data reduction were closely scrutinized by the Committee, and recommendations were made which resulted in the development of a highly sophisticated data gathering system.

Test Procedures

Study of the history of testing in the F-1 program disclosed that flowrates, mixture ratios, and resulting thrust values varied too widely from test to test to permit the establishment of a firm data base. A calibration prior to bomb tests was required. Testing requirements were stipulated by the Committee on a "run, no-run" basis:

Chamber Pressure, psi	1107
Mixture Ratio	2.35 to 2.5 (2.40 nominal)
LOX Flowrate, gpm	4005
Fuel Flowrate, gpm	1657
Thrust, pounds	1,500,000 (±3 percent)

Review Procedures

In reviewing significant tests, a data sheet was devised and used by the Committee which, when filled out, provided the information necessary to properly evaluate test results (Fig. 7).

[redacted]

F-1 THRUST CHAMBER ROUGH TEST DATA

ENGINE NO.____________________
INJECTOR NO.__________________
TEST NO.______________________
TEST DURATION:________________

TEST:____________________
STAND:___________________
DATE:____________________

I. Were there any disturbances prior to roughness? Yes_____No_____

1. Was there any drift toward roughness condition? Describe:

2. Is there any intermediate characteristic? Describe:

3. What parameter changed first?

a. Is the change significant? Yes_____No_____Why?

II. What triggers might have caused the roughness:

1.
2.
3.
4.
5.
6.

III. What sustaining mechanisms are evident?

1.
2.
3.
4.
5.
6.

a. Is there a significant mode:

(1) at what cycle?
(2) how long sustained?
(3) does it stop?
(4) is there a relationship between mode-defining parameters?

IV. Significant correlations?

1. Mixture ratio__________
2. P_c __________
3. f __________
4. $\Delta P_c/P_f$__________
5. $\Delta P_f/P_c$__________

V. Calculated flow data:

LOX flow, lb/sec______
Fuel flow, lb/sec________

VI. Accelerometer data:

1. f________
2. A________

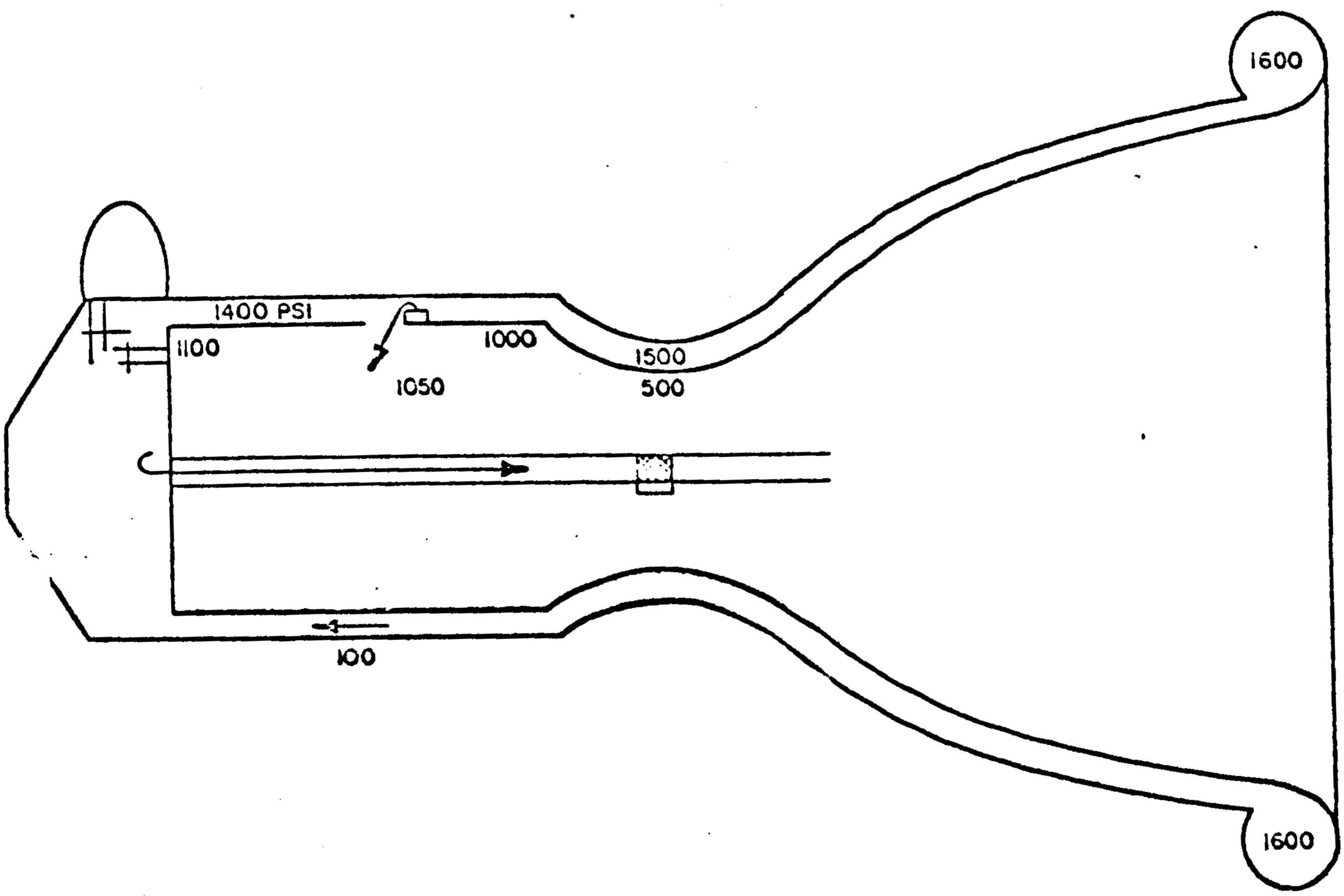
Figure 7. Data Sheet

[redacted]

Corresponding procedures were also devised for trace analyses and visual evaluations of tests. In all cases of instability a careful examination of the hardware was conducted by one or more members of the Committee.

[redacted]

Rough Test No. 053. An explosion had occurred in a test at RS/EAFB on 17 December 1962 with engine No. 006. Combustion instability was suspected as the cause of the explosion, but data were not yet available to properly evaluate the incident.



The possible causes were as follows:

1. Injector burnout
2. Hot spot in the manifold
3. Tube burnout

Evidence to support tube burnout as a cause of eventual combustion instability was as follows:

1. Streaks in jet
2. CF1A pressure drop
3. Excessive injector damage
4. Hot spot in the fuel manifold prior to instability
5. Injector burned prior to instability
6. Burn through manifold extremely fast

Further investigation with the aid of high-speed films and pressure records resulted in the conclusion that combustion flame had propagated upstream and behind the injector face before the explosion. This became one of the principal reasons for the subsequent development of the so-called "Kitchen Sink" devices--flow diverters designed to arrest reverse flow.

<u>High-Speed Instrumentation and Data Reduction</u>. Twenty-one pressure measurements (including ducting) were established as standard; these to be made with Photocon transducers providing a frequency response of 0 to 10 kilocycles. Transducers are flush-mounted in the combustion zone, 90 and 180 degrees apart axially, to obtain phase relationships and axial gas propagation velocities.

Data are recorded on magnetic tape, then time-base expanded at a ratio of 200-to-1 while being transcribed onto an eight-channel Brush recorder at a paper speed of 200 millimeters per second. This gives an equivalent of 200 millimeters of paper per one millisecond of real time, providing analysts with adequate spacing to determine phase relationships between parameters. Filtering of data is also relied upon to establish phase relationships at predominant frequencies; and power spectral density (PSD) graphs are obtained digitally on an IBM 7090 and on analog computers to determine the power of the frequency spectrum.

Piezo-Resistive Transducers. A piezo-resistive transducer, designed at Rocketdyne, was introduced to the Committee which ordered it into low-rate production for adaptation to the F-1. These units are small enough to place inside the thrust chamber tubes and on the face of the injector, are capable of sustained operation in a LOX environment, and provide excellent response rates.

High-Speed Photography. The Committee studied high-speed films of significant thrust chamber and engine tests, correlating visual evidence of instability with oscillation traces through the use of the binary timing code signal applied at RS/EAFB. Studies of these films were augmented by study of films taken of the operation of the two-dimensional transparent thrust chamber in a concerted effort to interpret visually the causative factors and signature of combustion instability.

A single special effect was detected which gave rise to considerable theoretical speculation: the expellation of an excess of black exhaust, completely obscuring the flame, just prior to the onset of instability. This "black shroud" was regarded as the result of three possible conditions:

1. The accumulation and sudden expellation of carbon on the chamber wall

[redacted]

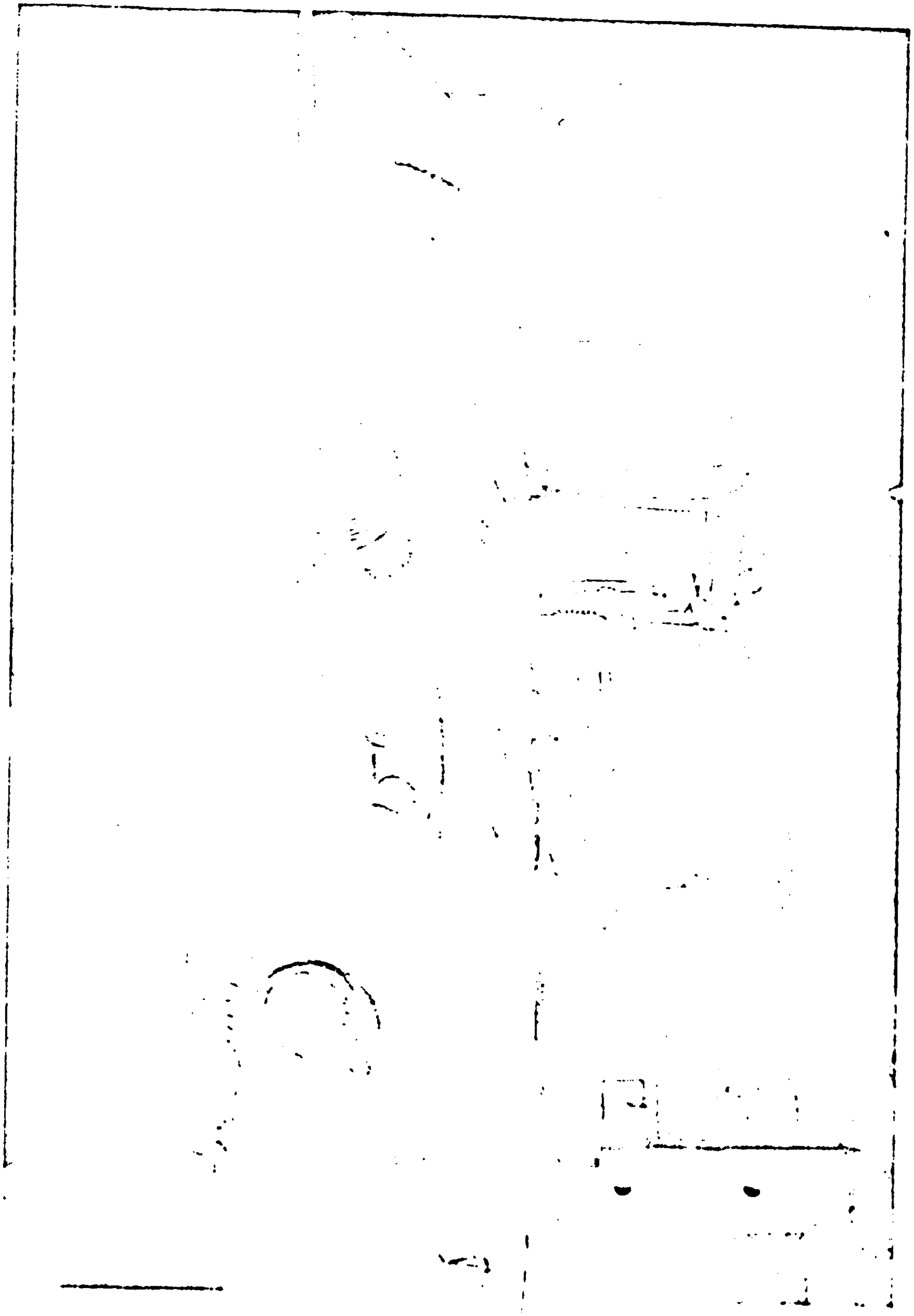
2. A change in the mixture ratio to an extremely fuel-rich state
3. The accumulation and explosion of fuel gel

Visualization through high-speed photography appeared to offer an excellent avenue of approach to the instability problem and the Committee ordered improved film coverage. More Fastair and Fastax cameras were installed on the test stands. Windows were devised for installation into solid-wall and tube-wall combustion chambers, fuel and LOX manifolds, and ducting to provide a view into the combustion process and feed system for framing cameras (Fig. 8 through 10).

Radiographic instruments were also installed on the test stand site, and streak photography windows located axially in the chamber walls for the calculation of longitudinal and transverse gas velocities.

Hardware Inspection. The Committee initiated hardware inspection procedures for post-instability situations which included the use of fibre-optic instruments permitting visual examination of ring grooves and injector body areas, sectioning of injectors in extreme cases of injector damage, and improved cleaning and dye check methods.

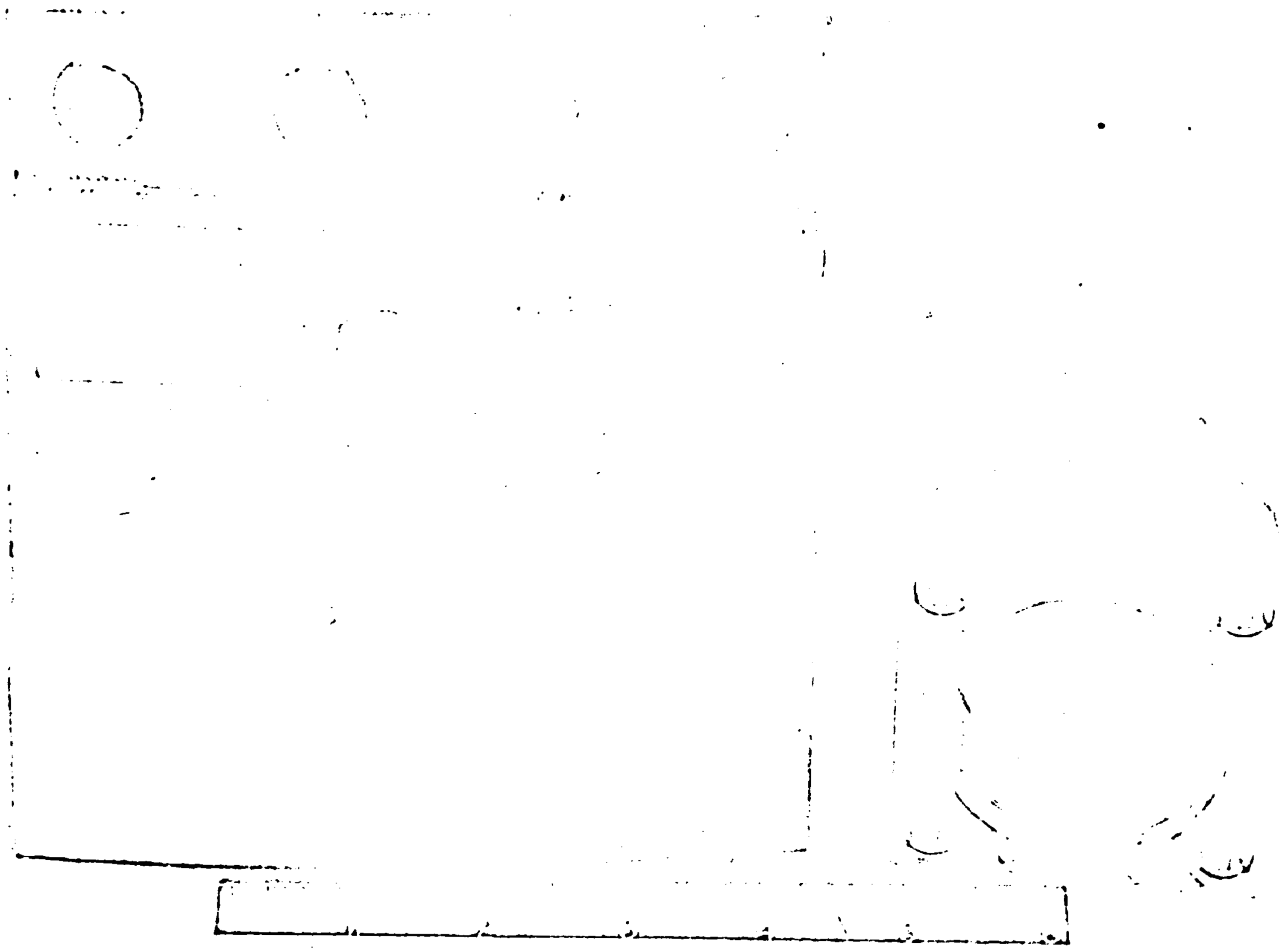
A Research project was undertaken to find an injector cleaning agent safer then the trichlorethylene then in use. The new procedure required that every injector be pulled, inspected and leak-checked after 300 seconds of operation plus one test. Improved cleaning and leak check methods, such as ultrasonic cleaning, were investigated.



1DB35-1/15/63-C1G

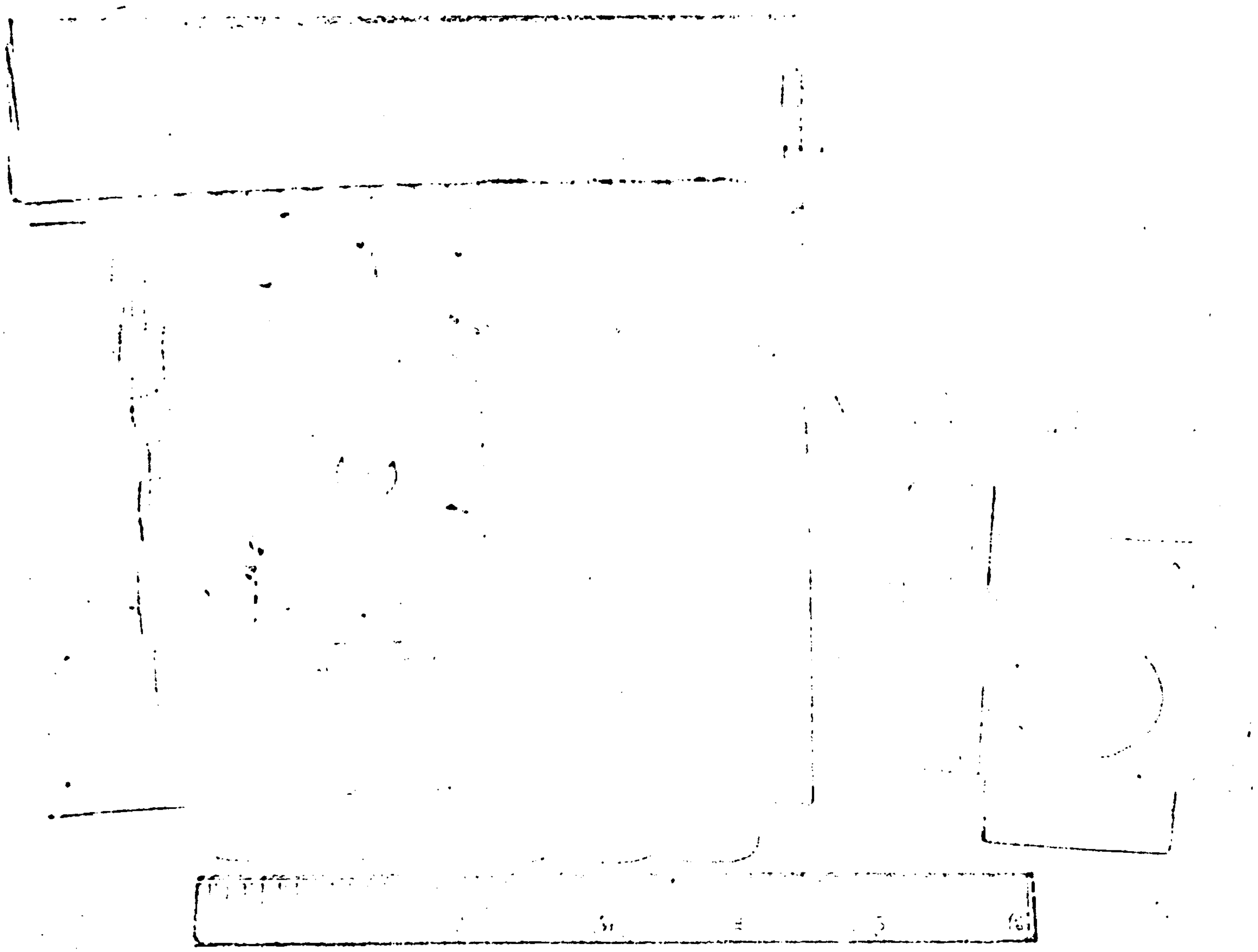
Figure 8. Thrust Chamber Window Installation

[redacted]



5731-12/28/62-1B

Figure 9. Thrust Chamber Window Installation (External View)



5731-12/28/62-1A

Figure 10. Thrust Chamber Window Installation (Internal View)

[redacted]

PROJECT FIRST PROGRAM

F-1 Combustion Stability Group

The F-1 Combustion Stability Group was formed in mid-December as a functional organization under the technical guidance of the Combustion Stability Committee. The Group is composed of an Analysis Unit and a Design Unit, and includes staff personnel reporting to the Senior Principal Engineer, whose functions are trouble shooting, liaison, investigation, and engineering advisement.

The Analysis Unit was charged with four broad areas of effort:

1. Identification of the mode or modes of instability encountered in testing
2. Parametric correlation of test data to define stable and unstable operating characteristics
3. Analysis of test data on the basis of correlation with theories of instability
4. Examination and evaluation of experiments conducted to illuminate aspects of the stability problem

This unit is also required to maintain a file of all data pertinent to the F-1 Combustion Stability Program, devise and employ more effective measurement techniques, data transmission and reduction, and make recommendations for hardware design.

The function of the Design Unit is to receive design objectives and concepts from the Combustion Stability Committee, and translate them into hardware. This unit is responsible for and coordinates with the Research Group for two-dimensional motor hardware, model element, and engine design. All of its efforts are coordinated with and reviewed by the Committee. The Design Unit takes ideas from conception through preplanning, analysis, layout drawings, design analysis, review, manufacturing and quality control problems, fabrication and installation, to final test results. This effort requires constant job follow-up and reporting at all stages.

Two-Dimensional Transparent Thrust Chamber Program

The initial test program for the two dimensional transparent thrust chamber was formulated at this time; the effort to be based on the precept that this unit would be best suited to determining principles, and would not be considered a model of the F-1.

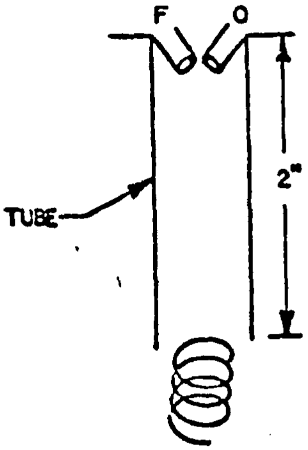
The two-dimensional thrust chamber effort was directed toward:

1. Locate perturbation axially to explore P_c and drop-shattering theories.
2. Baffle length and placement should be determined. Timing should be correlated with pressures for movie study of baffle effects.
3. Try angled baffles: baffles at different locations, of different lengths, etc.

[redacted]

To accomplish this effort, the following was planned:

1. Run divergence injector
    a. See recirculation
    b. Bomb
    c. Get streaks
2. Run divergence
    a. Check injection pattern
3. Water-slug run: water uniformly across injector
    a. Water after bomb as a tripropellant
4. Bomb at downstream locations
5. Hot-gas injection to simulate recirculation: use gas generator and augmented spark igniter
6. Try hot and cold baffles: fuel on them, LOX on them, LOX/fuel on them
    a Try also: fine injection: instant and complete burning
7. Premix injector



H-1 PROGRAM

Late in November, a program of H-1 testing was established with the objective of modeling certain F-1 operational conditions. The reasons for using the H-1 were: (1) stable operation parameters had been established at 165,000 pounds of thrust with the H-1, which would provide a point of departure for evaluating the effect of design modifications at 165,000 pounds of thrust and above, (2) the H-1 had an excellent history of test data for reference, (3) the H-1 could be driven unstable by a pulse gun, permitting the acquisition of test hardware quickly and cheaply. Also of importance was the fact that the H-1, in many parameters, closely approximated the F-1, and would thus serve as an excellent model.

The first test series with the H-1 included 13 tests, to be conducted at 188,000 pounds of thrust with the standard engine. The objectives were to acquire data on six modified injector configurations and one standard injector configuration, and to establish a rating technique for the pulser (then being adapted to the F-1). Special instrumentation was requested for these tests.

FUEL PULSER TESTS

A method of inducing instability that had worked well with the H-1 engine was adapted to the F-1. This method relied upon a fuel-side pulsing device. The technique was first used during this quarter. Five tests were attempted using a modified solid-wall thrust chamber (U/N 008) and U/N 067 baffled injector. A test stand malfunction terminated one of the tests without achieving mainstage. The test objectives were met on the remaining four tests, but instability was not achieved. Instrumentation records indicated that the pulser assembly was functioning properly on each of the tests, producing a pulse of approximately 12,000 psi in the fuel injection pressure. Only a small fraction of this disturbance, approximately 50 psi, was observed on any of the chamber pressure traces. The Committee at this time was considering the adaptation of a hydraulic pulser capable of generating more power to make the technique applicable to the F-1.

BOMB RATING

At this time there was little clear-cut evidence indicating the superiority of a 5U baffled injector over a 5U flat-face injector. Bomb tests were all being conducted with 50-grain bombs. A graduated bomb-effectiveness evaluation was recommended to the Committee with the objective of establishing a rating system. The Committee felt that damping times were as yet too long to justify the development of a rating system.

DOMES

The appearance of a 300-cps oscillation in steady state, when testing on test stand 2A at RS/EAFB, came under close scrutiny by the Committee. The design of the LOX dome was examined. Considerable flow-bench work had been done at this time with the following:

1. Flow dividers in the dome cavity
2. Scoops
3. Enlarged dome cavity

4. Sleeved axial feed holes
5. Baffles in the dome cavity
6. Shallow-body injectors
7. Deep LOX grooves
8. Single-inlet dome
9. Torus dams (two and four dams)
10. Dams on the upstream side of the injector
11. Lowered dome cavity
12. Dome cavity radially divided into 12 compartments
13. Dished upstream side of injector

It was observed in flow-bench checks that the frequency recorded always changed as a function of flowrate. Three-hundred cycles was in all cases encountered.

A recessed transducer mounting was suspected as the origin of the 300-cps oscillation. It was decided to approach the 300-cps problem with a new and more intensive program.

INJECTOR DESIGN

On 21 December 1962, decisions were made by the Committee which reflected the conclusions arrived at as to the cause of the burnout of engine 006. The Committee was of the opinion that evidence of back-flash into the fuel side of the injector and burning behind the injector face as the trouble source warranted the installation of flame-arresting and flow-control devices to obviate a similar occurrence in future testing.

[redacted]

A literature search of flame-arresting techniques was ordered, and the Project First design team initiated a design program to develop effective flow-control devices for installation in the 5U injectors (Fig. 11 and 12).

A meeting was held on 18 December 1962, to evaluate the first concentric tube injector design. It was decided to build model elements and waterflow them to determine the degree of mixing they would provide with various vortical-flow devices installed. It was also decided to design and test a concentric-tube injector in the two-dimensional transparent thrust chamber for initial evaluation (Fig. 13).

DESIGN PARAMETERS

On 20 November 1962, a summation meeting was convened. Evaluation of instability data, damaged hardware, test records, theories had, at this time, evolved into six fundamental requirements for the design and fabrication of a stable F-1 injector. Because these requirements had not been test-proved, and were yet to be adequately supported by theory, they were termed "platitudes" by the Committee.

Stable Combustion Platitudes

1. No leaks
2. Isolate the feed system from the combustion process
3. Isolate combustion radially
4. Control axial distribution
5. Eliminate random ignition locations
6. Control chemistry

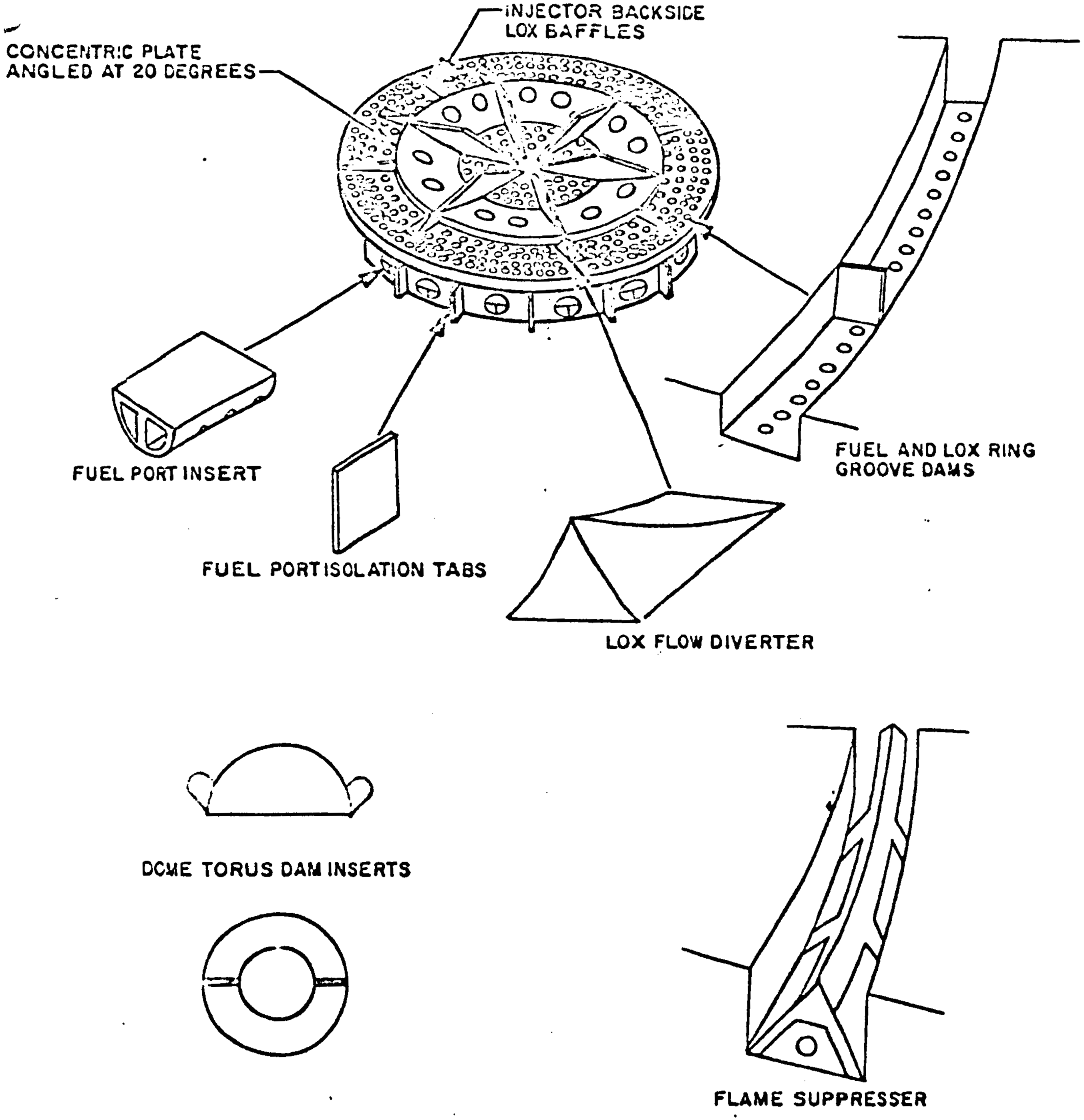
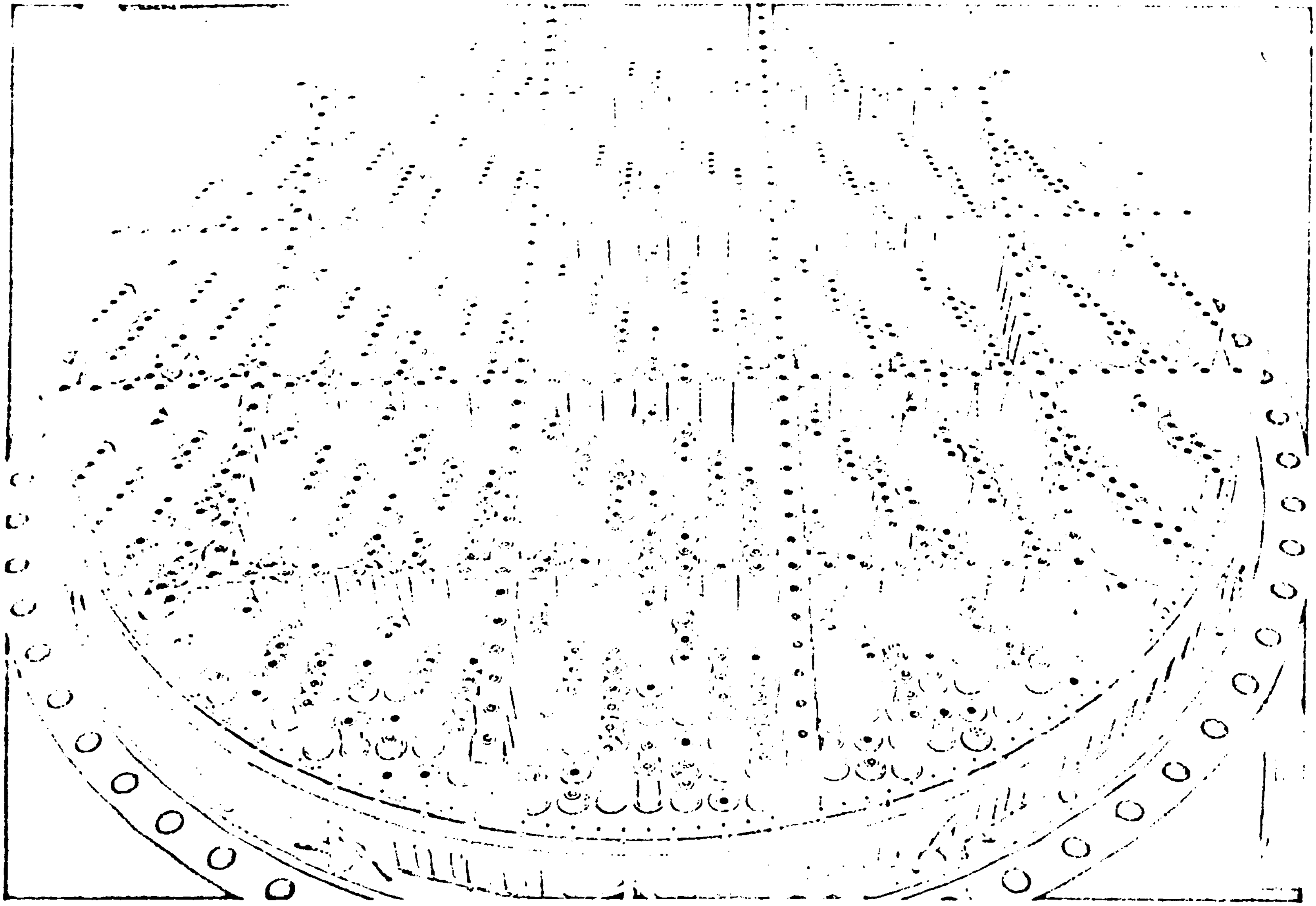


Figure 11. Injector Body Hydraulic Modifications

1DB45-1/25/63-E2C

Figure 12. Flow Control Devices on Injector U/N 079



1DB42-4/2/63-C1A*

Figure 13. First Concentric-Tube Injector

A design program was initiated, which was based on the accommodation of the platitudes; these, translated into an approach to hardware, resulted in the following design approach:

Design Approach

Platitudes	Design	Action
A. OXIDIZER PUMP INLET		
1. No uncontrolled bubbles 2. No collapse or geysering 3. No pulsations 4. No fuel, water	1. Tank filling 2. No vortex 3. No wall vibration in (tank or duct) 4. Proper sequence for start 5. No traps 6. No condensation and breathing	1. Photos in pump inlet 2. Review structure and procedures, MSFC 3. Review engine start 4. Pure LOX 5. Sample propellants
B. FUEL PUMP INLET		
1. No bubbles (no ingestion) 2. No pulsations	1. Proper tank exit and line design 2. Proper pressure gas diffusion	1. Fuel pump inlet photos
Propellant Condition		
1. Pure LOX 2. Pure fuel 3. No fuel in LOX 4. No water in LOX	1. Good fill filters 2. Good propellants	1. Analyze propellant sample 2. Analyze propellant sample 3. Analyze propellant sample 4. Analyze propellant sample 5. Analyze fuel and LOX specifications

C. PUMPS, LOX AND FUEL

1. Minimum pressure oscillations	1. Capacitors to filter	1. Design LOX and fuel capacitors
2. No induced bubbles	2. Start sequence	2. Evaluate causes of oscillations
3. Avoid blade wake frequency of system	3. Alternate number of blades	3. Discharge duct photos and review start sequence
		4. Evaluate new frequency

D. LINES DOWNSTREAM, INCLUDING VALVES

1. No valve traps		1. Review possibilities of traps
2. No valve flutter		2. Review valve flutter
3. Smooth flow		3. Look at duct with cameras

E. MANIFOLDS, LOX (DOME)

1. Control flow distribution	1. Avoid large cavities	1. Design concepts
	2. Avoid self-induced oscillations	2. Design concepts
	3. Eliminate uncontrolled cross-flow	3. Design concepts
	4. Compartment flow	4. Design concepts
	5. Isolate sectors	5. Design concepts
	6. Avoid cavities in series	6. Design concepts

F. FUEL INLET MANIFOLD: use tubes for direct injection

1. Minimize hydraulic surging and feedback	1. Eliminate series manifolds
2. Individual (non-cross flow) flow paths; fuel inlet to injector	2. Uniform tube flow distribution

[redacted]

The following were suggested as design objectives to minimize detonation supporting properties:

1. No premixed drops or globules
2. Thoroughly premixed droplets (fine and hot droplets)
3. Uniform injection at the proper mixture ratio
4. Burn fast
5. Build detonation dams
6. Use "chemical" baffles

To meet these objectives a series of injector designs were initiated. These included (1) the wagon wheel pattern, a 24-compartment baffled injector, with full radial pattern arrangement and full flow isolation (Fig. 14), (2) a deep-body injector, with baffles and long axial feed passages to provide high flow impedance, and (3) a flow isolated baffled injector with a standard pattern and hydraulic isolation.

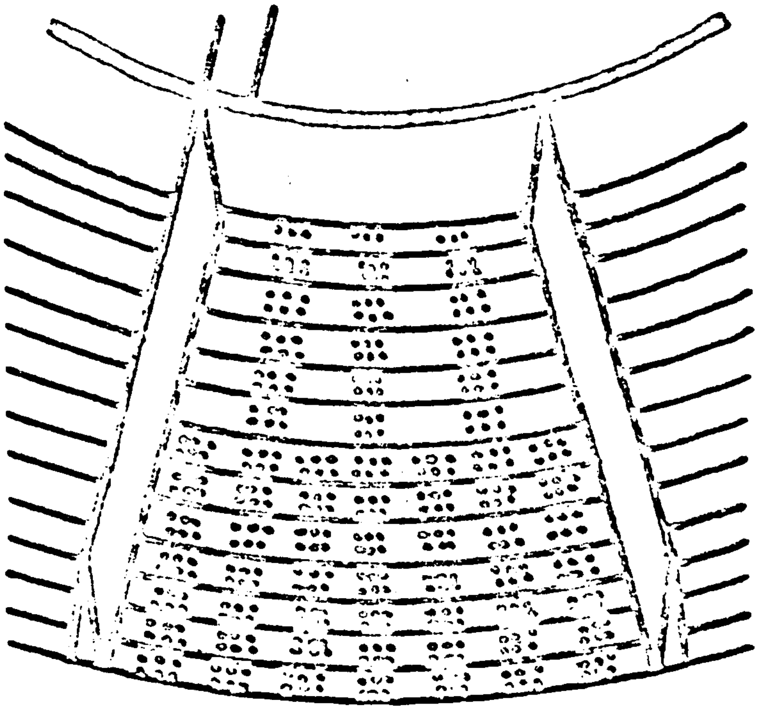


Figure 14. Wagon Wheel Pattern