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SPACE SHUTTLE MANEUVERING ENGINE REUSABLE THRUST CHAMBER PROGRAM

NAS9-12802

TASK XI

LOW ϵ STABILITY TEST REPORT

DATA DUMP

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INTRODUCTION

The like-doublet element type injector is one of the two main candidates for the Space Shuttle Orbit Maneuvering Engine Thrust Chamber. Rocketdyne's L/D #1 injector has been extensively tested at Rocketdyne and NASA/White Sands test facilities in solid wall and regeneratively cooled chambers to determine its performance and heat transfer characteristics. However, the only bomb tests conducted to determine its stability characteristics were performed without film coolant being injected across the cavities which were tuned to the first tangential mode. The L/D #2 injector which has undergone extensive stability tests under NASA/JSC contract NAS 9-12524, did not have boundary layer film coolant injected across the cavity entrance as does L/D #1 at present.

The L/D #1 injector is nominally stabilized by acoustic cavities which have gradual sloping entrances to facilitate regenerative cooling in this area with minimum pressure drop and low fabrication cost. Tests on other NASA sponsored programs have indicated this inlet configuration to be unstable with certain injectors while a sharper-edge entrance was stable.

The purpose of the present program is to define the stability characteristics of the L/D #1 injector over the range of OME chamber pressures and mixture ratios. The specific objectives are as follows:

1. If the injector is stable to determine the minimum cavity area required to maintain stability.

2. If the injector is unstable to determine the effects of entrance geometry and increase area on stability.

3. To determine whether stability has been influenced by injection of BLC across the cavity entrance.

To accomplish these objectives, the injector and cavity configurations were bomb tested in solid wall thrust chamber hardware typical of a flight contour with fuel heated to simulate regenerative chamber outlet temperatures.

TEST HARDWARE

The test hardware consists of the L/D #1 injector, solid-wall thrust chamber and cylindrical extension, the fuel manifold, and replaceable acoustic cavity rings.

The L/D #1 injector, shown in Fig. 1, has 186 elements arranged in 9 rows. Oxidizer orifice diameters range from 0.032 to 0.038 inches while fuel orifice diameters range from 0.028 to 0.033 inches. There are also 68 fuel orifices (0.020-inch diameter) to supply boundary layer coolant amounting to 2.7 percent of the total propellant flow. Under nominal conditions, the injector pressure drops are 56 psi on the oxidizer side and 62 psi on the fuel side. The diameter of the injector face is 8.2 inches. The injector has been fired 284 times for a total duration of 1695 seconds. It has been dye-penetrant inspected to verify that all welds are sound. Figure 2 is a drawing of the injector including the dams which were added to the fuel manifold after the first test series.

The solid wall chamber and combustor extension are shown in Fig. 3. The distance from the injector face to the throat is 16 inches. The heat sink capability of the chamber allows firing durations of up to approximately 5 seconds. The chamber and extension are instrumented for high response chamber pressure measurements. Steady-state chamber pressure measurements are made in the acoustic cavities. Two ports for bombs are located in the center of the eight-inch long extension.

The fuel manifold (Fig. 4) distributes fuel to the injector and retains the acoustic cavity inserts. The acoustic cavities are formed by the injector and the replaceable two-piece cavity rings shown in Fig. 5. The aft ring defines the inlet geometry of the cavity and can be replaced with a new ring to provide a different inlet geometry without machining

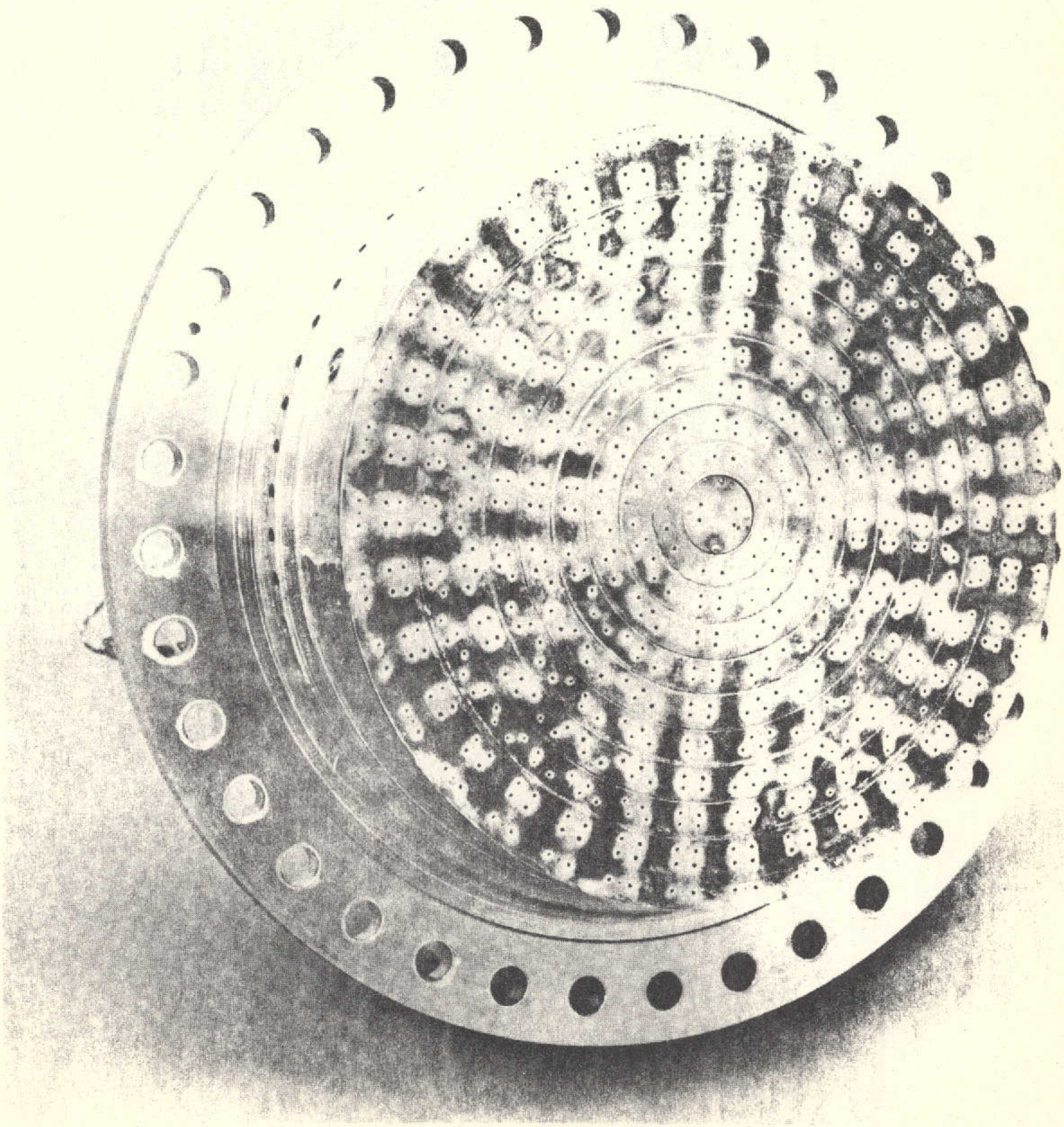

Figure 1. OME Like-Doublet No. 1

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the forward ring. The forward ring defines the cavity width and depth. Only the forward ring need be modified to change the cavity depth. The rings are pinned together and to the fuel manifold to assure consistent orientation.

The initial configuration of the rings provided the same configuration as that of the regeneratively cooled integrated thrust chamber. This provides a gradual entrance to the cavity which results in a gradual turn of the regenerative coolant passage in this area which maintains a low pressure drop. The same milling cutter is used in this area as for the throat and forward end of the chamber thereby eliminating additional set up costs during manufacturing. Eight of the cavities, the primary cavities, were tuned (1.75-inch depth*) to stabilize the first tangential mode; the remaining four cavities, the secondary cavities, were 0.92 inches deep* to stabilize the first radial and third tangential modes. All cavities were of the same width. The initial width (0.5 inches) resulted in the primary cavities having an effective open area of 14.8 percent of the chamber cross sectional area and the secondary cavities having an effective open area of 7.4 percent. For Tests 11-18, the cavities were modified to provide 12 and 6 percent areas for the primary and secondary cavities respectively.

TEST FACILITY

The tests were conducted at the Victor Test Stand of the Rocketdyne Research Test Facility at Santa Susana. A schematic of the feed system is shown in Fig. 6. NTO and MMH were supplied from pressurized tanks having maximum pressure capabilities of 2500 and 1500 psia respectively. The NTO and MMH pass through 40μ filters before entering the engine valves. GN_2 purges were supplied downstream of the engine valves.

The oxidizer flowed to the engine at ambient temperature while the MMH was batch heated in the quantities required for a single firing through the use of a 4.5 gallon heat exchanger (limited to 430 psia) located immediately

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*Effective acoustic depth

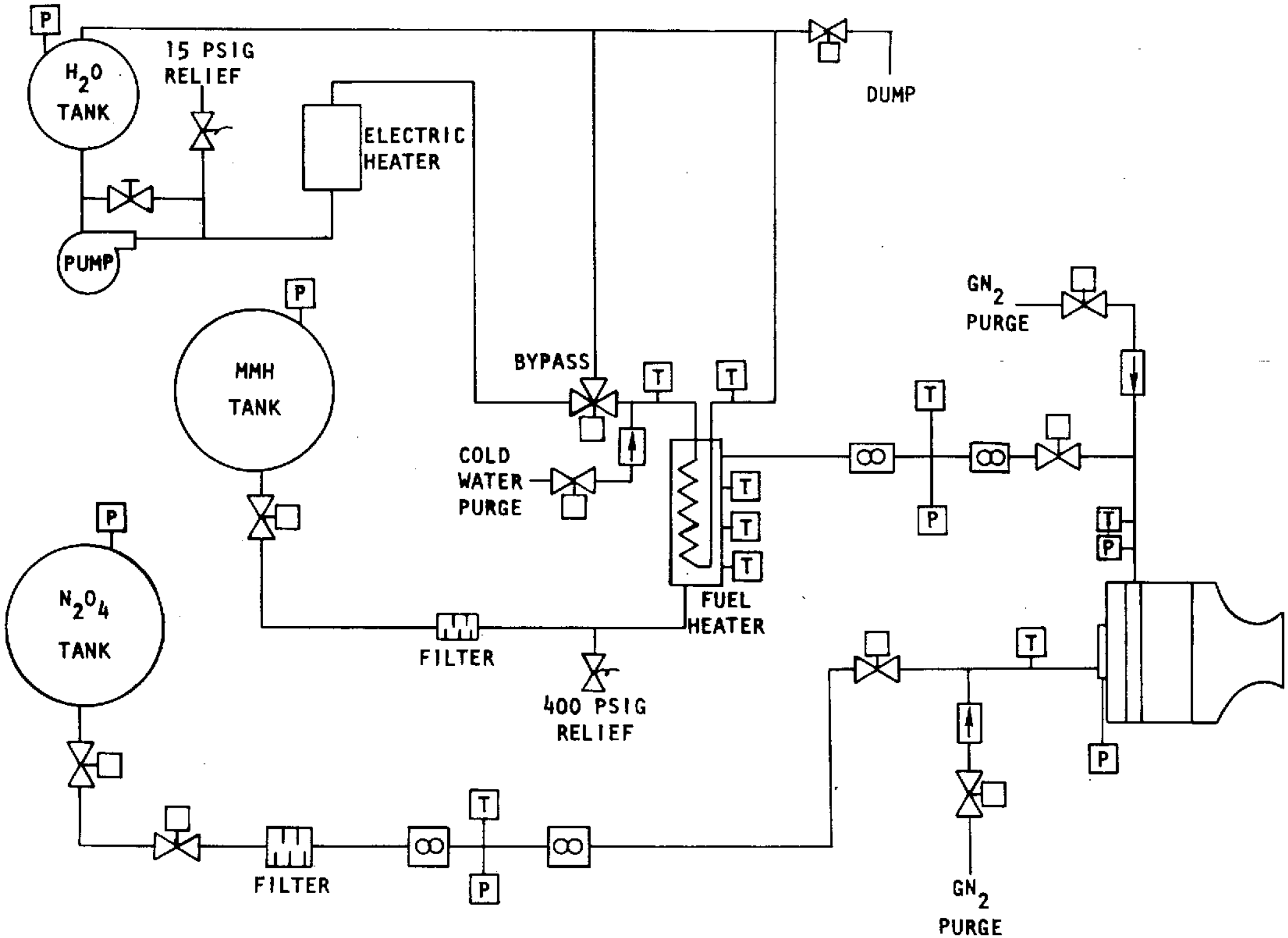

Figure 6. Propellant Feed Systems and Instrumentation Schematic

upstream of the main fuel valve. In this heat exchanger, hot water flowed inside four concentric coils of one-quarter-inch OD stainless tubing and provided a temperature-limited heat source for the fuel. The heating water was circulated in a closed system from a steel reservoir tank through a 2.5 gpm Burke pump, past an 18 kilowatt Chromalox electrical heater, and then through either the heat exchanger or a bypass loop back to the reservoir. An alternate supply of cold water was introduced into the system to quickly cool the heat exchanger between tests and thus permit test personnel to work in the immediate vicinity of the heater test stand. Heat up and cool down time for the system required approximately 30 minutes.

INSTRUMENTATION

High response pressure pickups were used to monitor chamber pressure. Three type 614A Kistler transducers were mounted in the cylindrical spool approximately 2 inches from the injector face at 12, 108, and 228 degrees location. The steady-state value of chamber pressure was measured using two Taber type transducers with sensing ports located in the acoustic cavities. These same type transducers were used to measure the fuel and oxidizer injection pressures and the feed system pressures. The temperature of the gas in the acoustic cavities was measured using tungsten/rhenium thermocouples. Propellant feed system temperatures were measured with iron/constantan thermocouples. Two turbine flow meters were used to measure each propellant flow rate. Thrust was also measured for computation of c*. The instrumentation is listed in Table 1. The estimated precision of each of the critical measurements (thrust, chamber pressure, and flow rate) is 0.25 percent.

High response data were recorded on tape and oscillograph. The oscillograph was also used to record the slower responding chamber pressure measurements, the flow rates, and the injection pressures. Most data except the high speed data were also recorded on a digital tape. Direct inking charts were used to provide quick-look data.

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*Effective acoustic depth

TABLE 1

INSTRUMENTATION LIST FOR L/D #1 STABILITY PROGRAM

Parameter/Measurement	Symbol	Transducer Employed	Recording System: Beckman Digital Data System	Recording System: Direct Reading Recorder	Recording System: Oscillograph	Recording System: Tape
MMH (Fuel) System						
MMH Tank Pressure	PFT	Taber*		X		
Fuel Flowrate #1	WF-1	Turbine Flowmeter	X	X	X	
Fuel Flowrate #2	WF-2	Turbine Flowmeter	X	X	X	
Fuel Line Pressure	PFL	Taber	X	X		
Fuel Line Temperature	TFL	I/C TC**	X	X		
Fuel Heater Temperature #1	TFH-1	I/C TC		X		
Fuel Heater Temperature #2	TFH-2	I/C TC		X		
Fuel Heater Temperature #3	TFH-3	I/C TC		X		
Fuel Injection Temperature	TFI	I/C TC	X	X		
Fuel Injection Pressure	PFI	Taber	X	X	X	
" " "	PFIK	Kistler			X	X
N_2O_4 (Oxidizer) System						
N_2O_4 Tank Pressure	POT	Taber		X		
Oxidizer Flowrate #1	WOX-1	Turbine Flowmeter	X	X	X	
Oxidizer Flowrate #2	WOX-2	Turbine Flowmeter	X	X	X	
Oxidizer Line Pressure	POL	Taber	X	X		
Oxidizer Line Temperature	TOL	I/C TC	X	X		
Oxidizer Injection Temperature	TOI	I/C TC	X	X		
Oxidizer Injection Pressure	POI	Taber	X	X	X	
Oxidizer Injection Pressure	POIPH	Photocon			X	X

TABLE I (Cont'd)

INSTRUMENTATION LIST FOR L/D #1 STABILITY PROGRAM

Parameter/Measurement	Symbol	Transducer Employed	Recording System: Beckman Digital Data System	Recording System: Direct Reading Recorder	Recording System: Oscillograph	Recording System: Tape
<u>Thrust Chamber</u>						
Cavity Temperature #1	TC-1	W/R TC***	X	X		
Cavity Temperature #2	TC-2	W/T TC	X	X		
Cavity Temperature #3	TC-3	W/R TC	X	X		
Cavity Temperature #4	TC-4	W/R TC	X			
Cavity Temperature #5	TC-5	W/R TC	X			
Cavity Temperature #6	TC-6	W/R TC	X			
Chamber Pressure #1	PC-1	Taber	X	X		
Chamber Pressure #2	PC-2	Taber	X	X	X	X
Thrust	F	Load Cell	X	X		
Chamber Kistler #1	PCPK-1	Kistler			X	X
Chamber Kistler #2	PCPK-2	Kistler			X	X
Chamber Kistler #3	PCP -3	Kistler			X	X
<u>Miscellaneous</u>						
Water Temperature @ Water Tank	TW-WT	I/C TC		X		
Water Temp @ Water Heater Outlet	TW-WHO	I/C TC		X		
Water Temp @ Fuel Heater Inlet	TW-FHI	I/C TC		X		
Water Temp @ Fuel Heater Outlet	TW-FHO	I/C TC		X		
Reference Junction Temperature	RJT	I/C TC	X			
Fuel Main Valves Power & Travel	---	------	X		X	
Oxid. Main Valve Power & Travel	---	------	X		X	X

*Taber Strain Gage Pickup
**Iron/Constantan Thermocouple
***Tungsten/Rhenium Thermocouple

TEST PROGRAM AND RESULTS

Three series of tests were conducted. Chamber pressure and mixture ratio were changed from test-to-test in each series. Test durations were approximately 5 seconds unless terminated by the combustion stability monitor. The first series consisted of six tests (1-6) with the nominal hardware condition previously described. Two bombs were detonated on each of the first four tests and one on each of the last two tests.

Three radial dams were placed in the internal fuel manifold of the injector and four tests (7-10) conducted. Two bombs were detonated during each test. The final test series consisted of eight tests (11-18) with two bombs detonated during each test. The open areas of the primary and secondary cavities were reduced for this test series as previously described in the hardware discussion.

Typical trace of thrust, chamber pressure, and propellant flowrates are shown in Figs. 7 through 10. The bomb detonations are clearly visible in the thrust and chamber pressure traces.

Stability

The test conditions at the time the bombs were detonated and the results are summarized in Table 2. The bombs were electrically detonated at 1.0 and 1.5 seconds but frequently detonated thermally before the electrical signal. During the first test series, two cases of instability occurred. The first bombs on Tests 2 and 3 triggered ~2600 hz oscillations which persisted until the second bombs detonated. A chamber pressure record from Test 3 illustrating this is shown in Fig. 11.

The results of stability tests on similar chambers are shown in Fig. 12 which is taken from Reference (a). The region of marginal stability for the

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Reference (a): Oberg, C.L., W.S. Hines, and A.Y. Falk, "Final Report: High-Temperature Earth-Storable Propellant Acoustic Cavity Technology, "R-9401, Rocketdyne Division, Rockwell International, Canoga Park, CA., May 1974

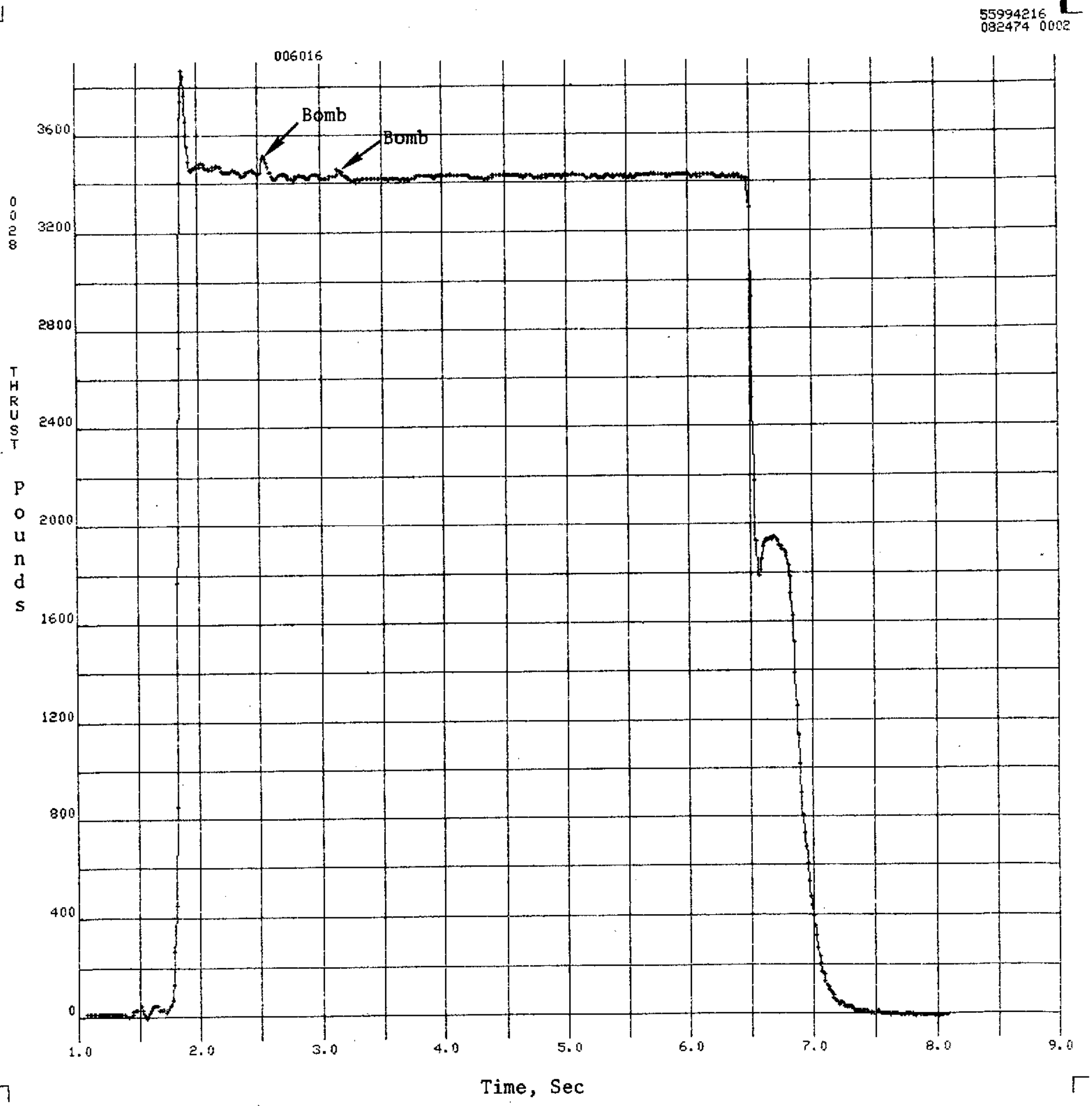


Figure 7. Thrust Record - Test 16

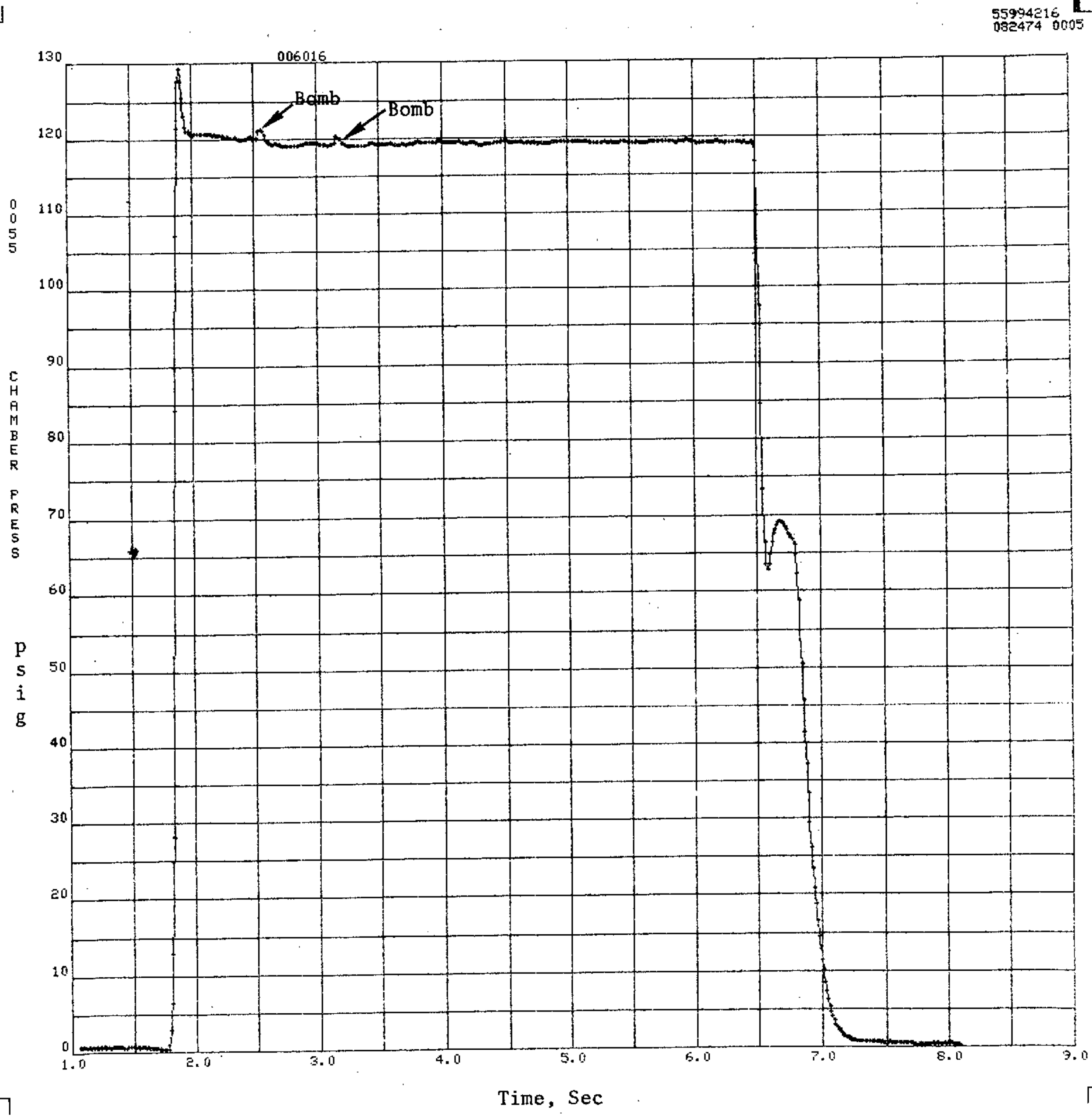


Figure 8. Chamber Pressure Record - Test 16

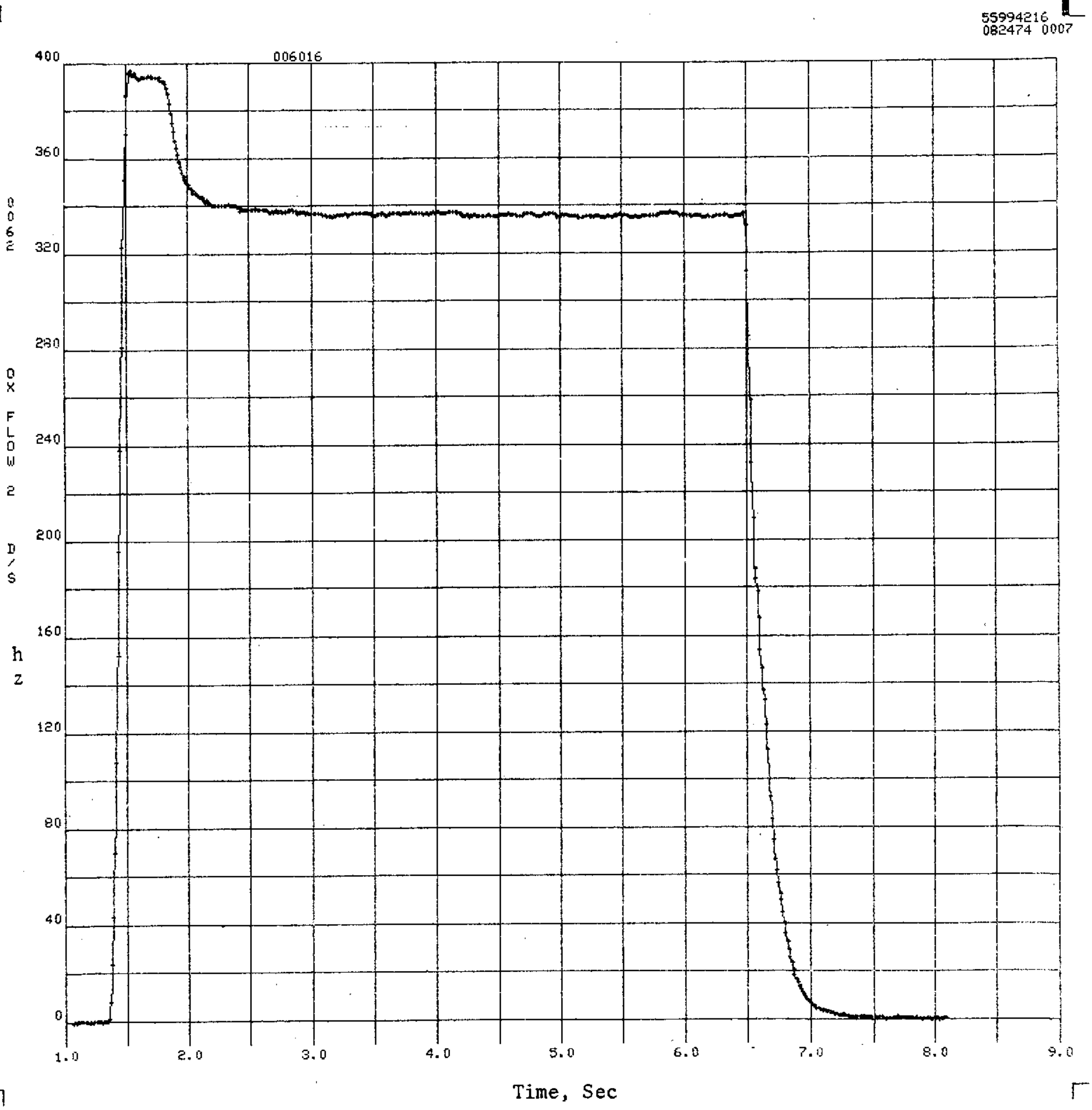
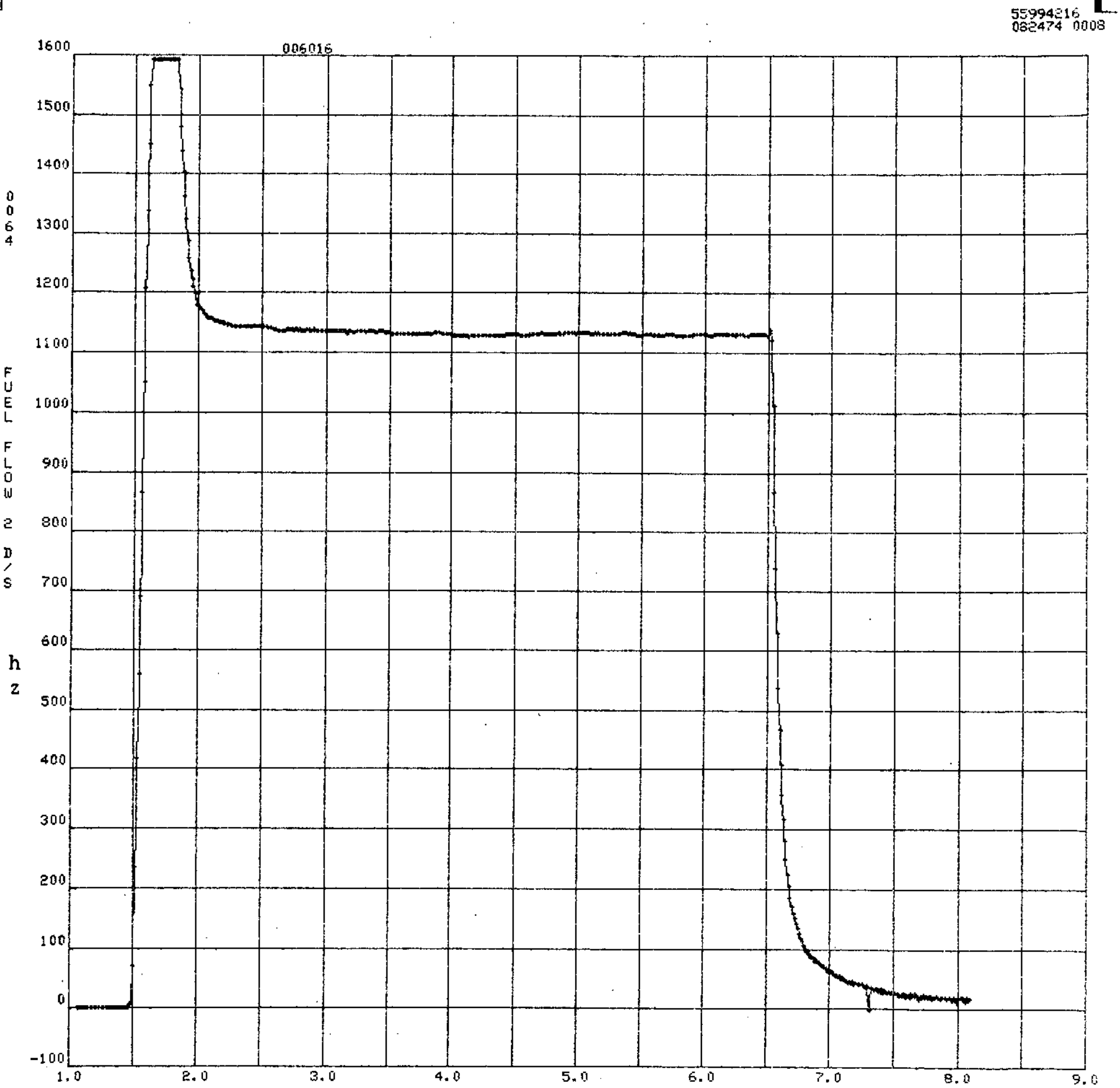


Figure 9. Oxidizer Flowmeter Output - Test 16



Time, Sec

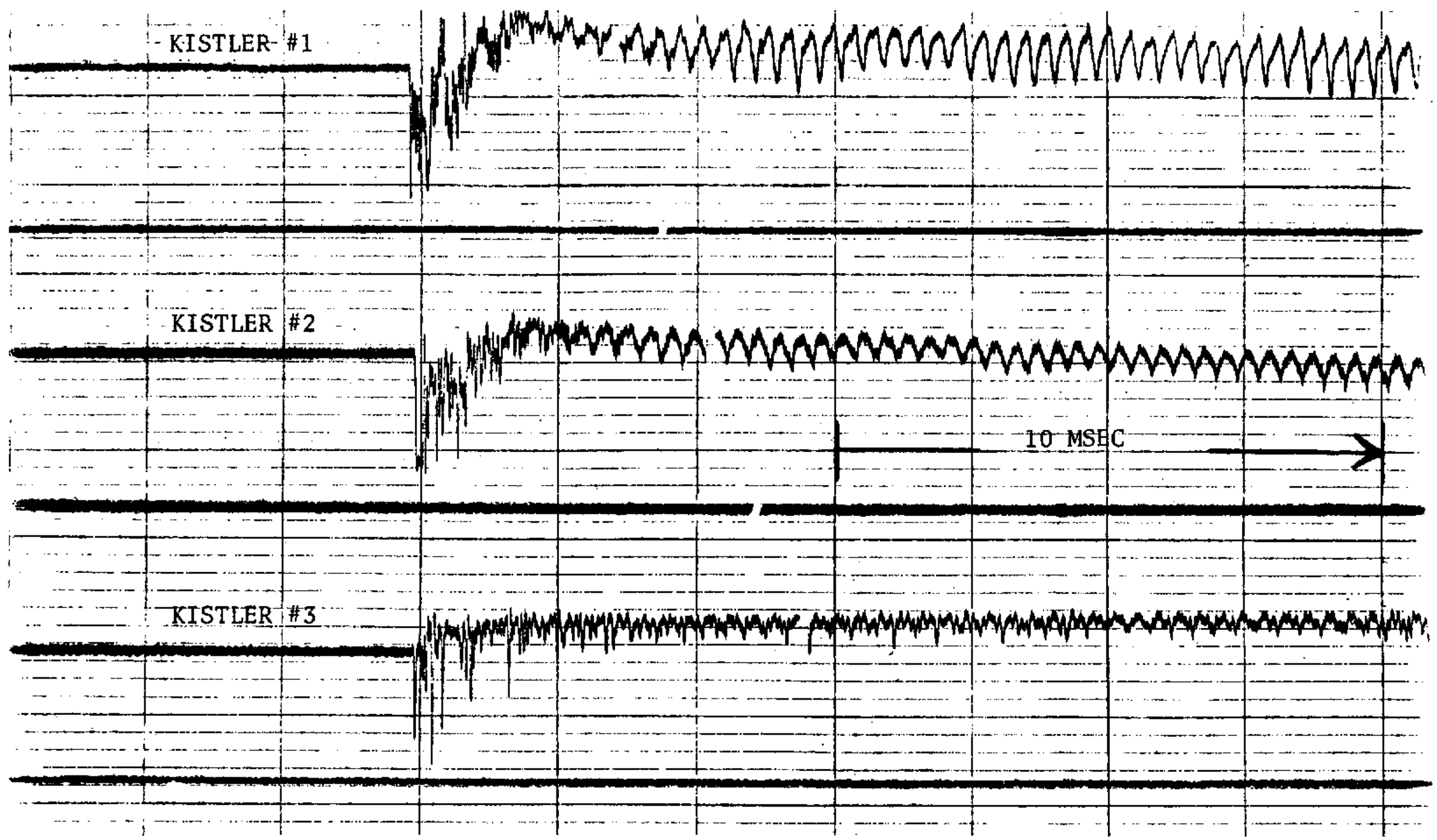
Figure 10. Fuel Flowmeter Record - Test 16

TABLE 2
STABILITY TEST CONDITIONS

TEST	DUR SEC	TIME OF FIRST BOMB, SEC	TIME BETWEEN BOMBS SEC	TEST CONDITIONS AT TIME OF BOMBS			BOMB	MAXIMUM Pc DUE TO BOMB, psia			DAMP TIME msec	FREQUENCY, Hz
				Pc, psia	O/F	FuelInj.Temp, F		Kistler #1	Kistler #2	Kistler #3		
1	3.7	0.6	0.5	130	1.80	180	1	200	310	530	12	2330
							2	304	270	220	14	
2	1.1	0.8	0.2	126	1.71	190	1	200	290	410	220 *	2550
							2	120	210	240	6	
3	0.9	0.6	0.07	125	1.69	160	1	220	>310	340	70 *	2570
							2	110	140	110	6	
4	5.1	0.65	0.03	140	1.55	165	1	240	240	410	11	
							2	260	250	110	11	2300
5	4.7	0.7	--	113	1.52	165	1	200	>310	160	11	
6	4.7	0.95	--	111	1.79	175	1	200	>310	170		
Added Radial Dams to Injector Fuel Manifold												
7	4.7	1.0	0.08	137	1.52	175	1	240	530	210	--	
							2	240	460	210	12	
8	4.6	0.8	0.6	123	1.66	160	1	270	530	200	11	
							2	230	460	230	13	
9	5.0	1.1	0.08	141	1.86	165	1	290	500	180	14	
							2	300	430	240	15	
10	4.7	1.1	0.06	111	1.42	150	1	220	480	190	14	
							2	290	390	200	14	
Reduced Acoustic Cavity Open Area From 14.8% to 12%												
11	4.7	1.5	0.5	136	1.44	220	1	320	260	430	11	
							2	320	260	430	10	
12	4.6	1.5	0.5	127	1.68	205	1	330	260	250	12	
							2	300	280	170	10	2770
13	4.6	1.5	0.5	140	1.80	195	1	320	280	230	70	2790
							2	300	280	190	12	2800
14	4.7	1.5	0.5	111	1.45	190	1	300	260	190	10	
							2	180	270	170	7	
15	4.6	0.9	0.1	111	1.84	175	1	290	280	170	21	2790
							2	260	260	170	12	2760
16	4.7	0.7	0.6	127	1.61	175	1	220	290	180	7	
							2	260	220	230	10	2770
17	4.7	0.6	0.3	143	1.65	170	1	280	220	180	7	
							2	260	340	190	18	2750
18	4.7	0.8	0.05	128	1.69	160	1	240	290	170	8	
							2	280	200	230	11	2800

*Continued until Second Bomb Detonated

Figure 11. High Frequency Pc Traces at Detonation of First Bomb On Test 3



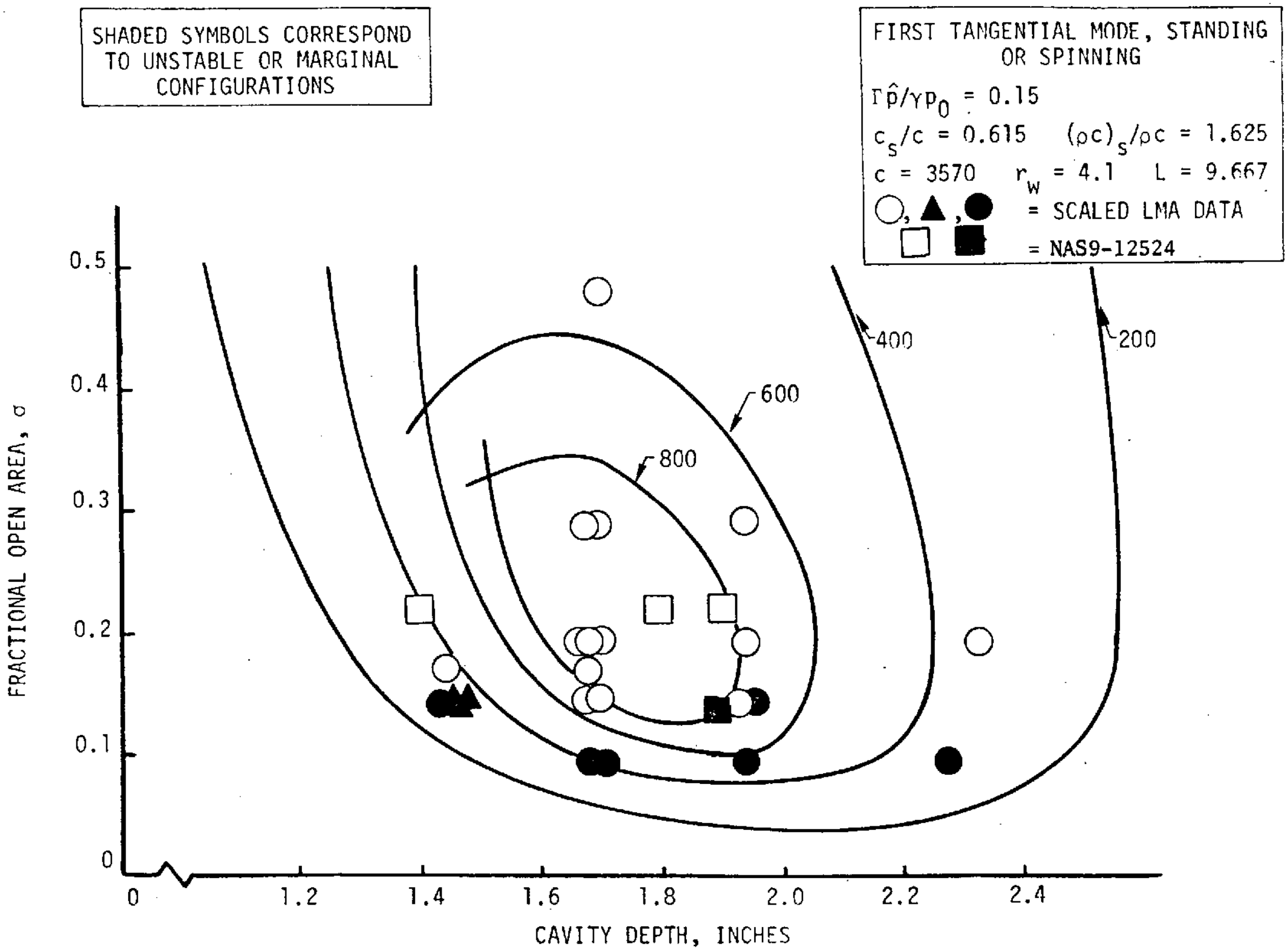


Figure 12. Comparison Of Stability Results With Predicted Trends For Primary Cavity

chamber tested under Contract NAS 9-12524 (which was 4 inches shorter than the present chamber) corresponded to an open area of about 15%. The frequencies of the instabilities on that program were 3000 and 2600 hz. The 3000 hz frequency corresponds to the first tangential mode for both the present and the NAS 9-12524 chambers. The results of an approximate acoustic analysis of the Rocketdyne injection and manifold system indicated the likelihood of a 2600 to 2800 hz oscillation as a result of transverse oscillation in the integral annular fuel manifold and ring grooves of the injector. Based on this analysis and the test results, the L/D #1 injector was modified after the first test series. Partitions were installed in the manifold, at three nearly-equally spaced positions, to suppress this mode.

Data from Tests 7-10, conducted with this configuration (8 bombs at 4 operating points) indicate that the dams and the cavity configuration together effectively suppress this mode. Figure 13 is a typical high-speed chamber pressure record showing the rapid damping of a bomb disturbance by this configuration.

When the acoustic cavity areas were reduced, the bomb disturbances generally damped rapidly as shown in Fig. 14. However, two of the 16 disturbances, introduced by the bombs used on Tests 11-18, required more than 20 msec to damp (21 and 70 msec). The disturbance which required 70 msec to damp (Test 13) is shown in Fig. 15. These results suggest that the reduced cavity areas resulted in a marginally stable configuration. Oscillations recorded with this configuration had a frequency of about 2800 hz. The slightly higher frequency (compared to the frequency with the undammed injector) suggests that the chamber may be coupling with the ring grooves of the injector which were not partitioned.

Cavity Temperatures

Seven gas temperature measurements were provided for in the acoustic cavities. The attrition rate of these thermocouples was quite high so that limited data was obtained. This data are presented in Table 3.

Figure 13. High Frequency Pc Traces At Detonation Of First Bomb On Test 8

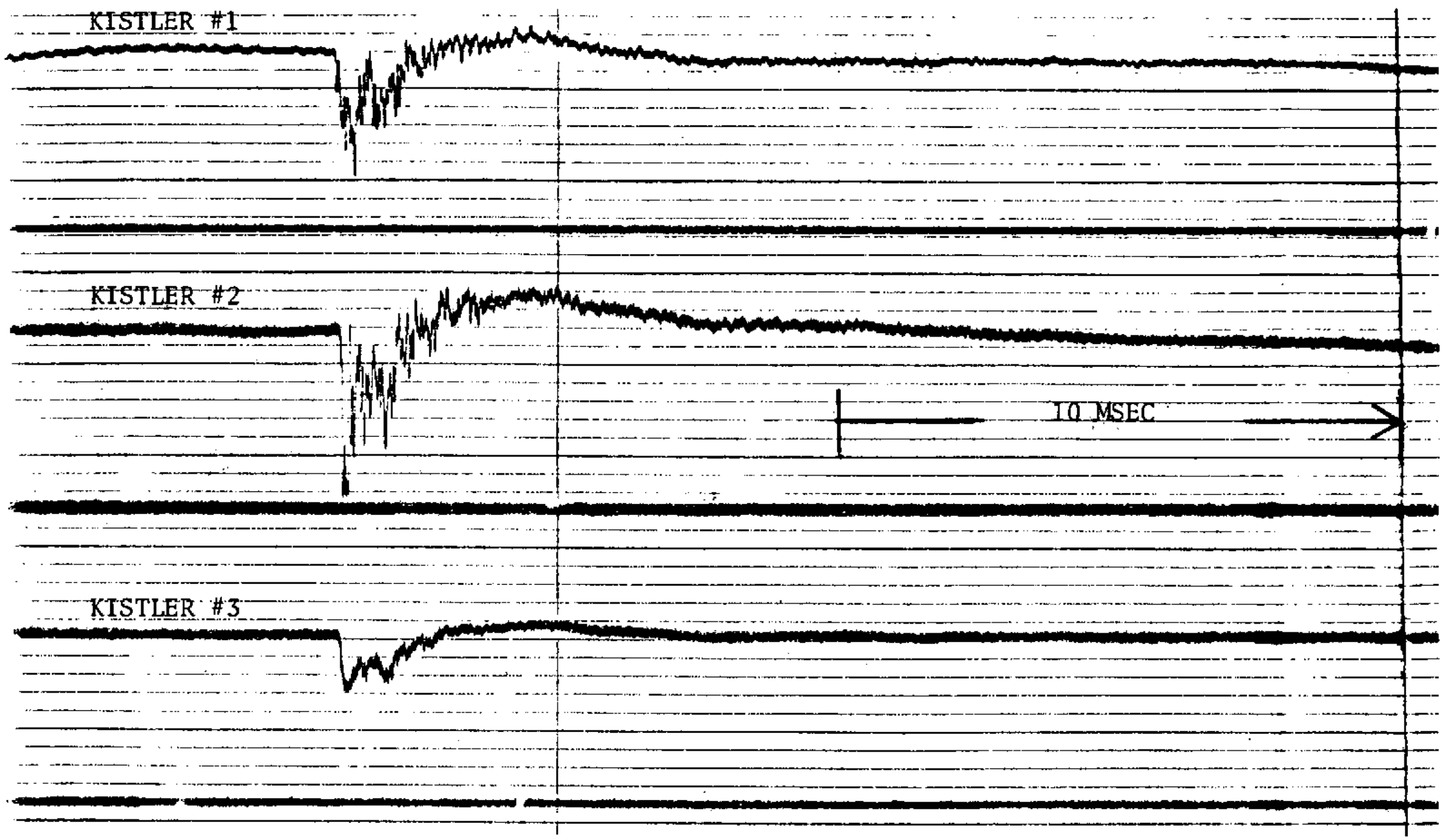


Figure 14. High Frequency Pc Traces At Bomb Detonation On Test 12

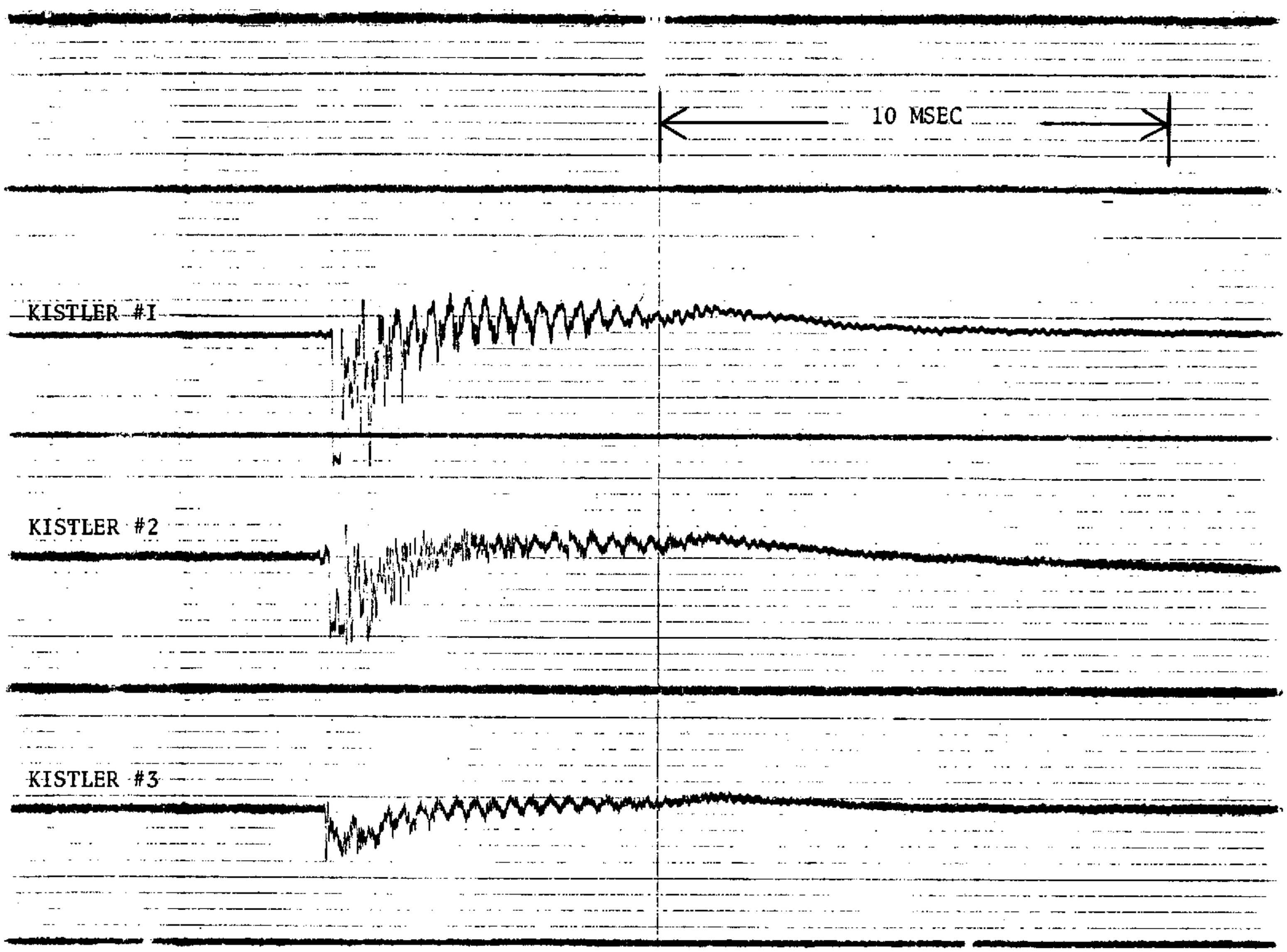


Figure 15. High Frequency Pc Traces At Detonation Of First Bomb On Test 13

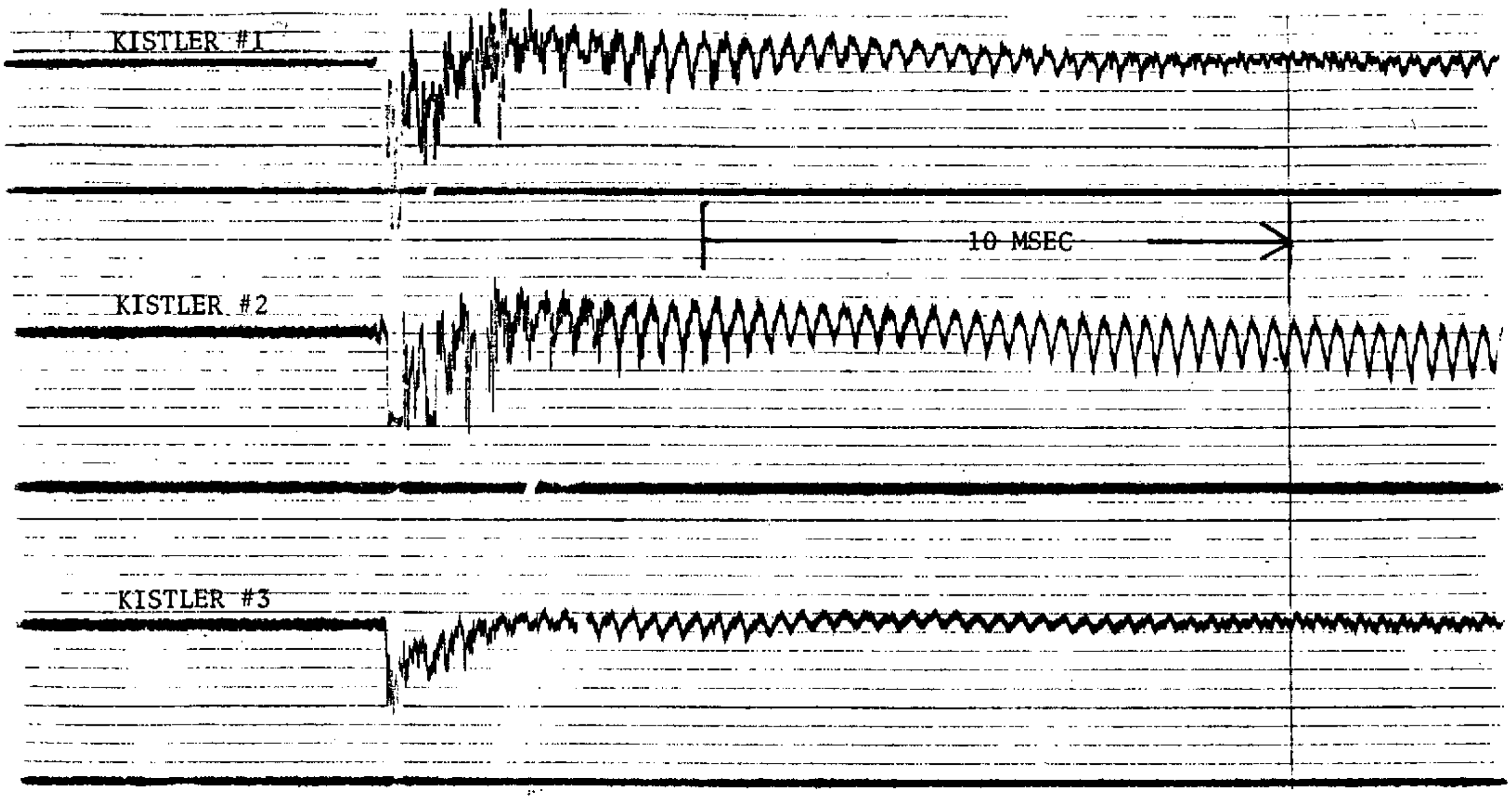


TABLE 3

ACOUSTIC CAVITY TEMPERATURES, F

	MEASUREMENTS							
	1		2		3		5	
	@BOMBS	@C.O.	@BOMBS	@C.O.	@BOMBS	@C.O.	@BOMBS	@C.O.
TEST 1	2140	2370			2240	2340	3500	2730
TEST 2	1960							
TEST 3	1740							
TEST 4	2370	2690						
TEST 5	2310	2530						
TEST 6	1990	2200						
TEST 7	2560	2290	2400	2550	3240	3130	3140	2910
TEST 8					2660	2770	2280	
TEST 9					1200	1770		
TEST 10					1170	1660		
TEST 11					1850	2230		
TEST 12					2240	2100		

The temperatures are plotted against mixture ratio in Fig. 16. The data indicate a trend of generally decreasing temperature with increasing mixture ratio. Similar results were reported in Ref. (a). The average temperature at nominal conditions was 2200 F and 2500 F for thermocouples #1 and #3 which are located at depths of 0.54 and 0.04 inches from the injector face, respectively. These temperatures agree, within the data scatter, with values obtained in Ref. (a).

The measured cavity temperatures provide an indication of the acoustic velocity existing in the cavity, which affects cavity tuning and instability suppression. Had the temperatures been different from those obtained previously, adjustments in cavity depth may have been needed to stabilize the engine. The fact that the temperatures are roughly consistent with those obtained previously, suggests the difference in method of injecting film coolant does not affect the required cavity tuning.

CONCLUSIONS

The results of the tests with the three configurations indicate that stability in the 2600-2800 hz region depends upon the injector hydraulics as well as the chamber acoustics. A like-doublet injector with boundary layer coolant injected at the periphery of the injector (2.7 percent of total propellant flow) was stabilized by radial dams in the fuel manifold and acoustic cavities having 14.8 percent open area and 1.75-inch effective depth. The injector was marginally unstable with full depth (1.75 inches effective depth) 1T cavities having an open area of 12 percent of the chamber cross-sectional area. Tuning these cavities or adding injector ring dams was not attempted but could result in a stable configuration with these cavity areas.

Figure 16. Acoustic Cavity Temperature