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NASA CR 62070

GPO PRICE $ ______

CFSTI PRICE(S) $ ______

Hard copy (HC) [redacted]

Microfiche (MF) ______

ff 653 July 65

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R-7060-1

A STUDY OF IGNITION PRESSURE SPIKING IN ATTITUDE CONTROL ENGINES

VOLUME I

EVALUATION OF THE USE OF CATALYTIC SURFACES TO ELIMINATE IGNITION PRESSURE SPIKING

By

R. N. Gurnitz
T. R. Mills
G. L. Falkenstein

Prepared For

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

May 1967

Contract NAS9-6134

Rocketdyne
A Division of North American Aviation, Inc.,
6633 Canoga Avenue, Canoga Park, California

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MAY 1968

FACILITY FORM 602

N68-23694 (ACCESSION NUMBER)

110 (PAGES)

NASA-CR #62070 (NASA CR OR TMX OR AD NUMBER)

(THRU)

1 (CODE)

28 (CATEGORY)

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Volume I

EVALUATION OF THE USE OF CATALYTIC SURFACES TO ELIMINATE IGNITION PRESSURE SPIKING

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FOREWORD

This report has been prepared in compliance with National Aeronautics and Space Administration Contract NAS9-6134.

The effort reported herein was conducted during the 10-month period from 1 July 1966 to 30 April 1967 by the Rocketdyne Research Division.

ACKNOWLEDGMENTS

The work described in this report was conducted by the Research Division of Rocketdyne under the program management of R. B. Lawhead and E. V. Zettle.

Mr. N. H. Chaffee of NASA-MSC was the Technical Monitor. His interest and assistance were appreciated.

Thanks are due to Mr. W. E. Devereux for his aid in the design of the experimental apparatus and his help and perseverance in the experimental portion of the program.

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ABSTRACT

A study was conducted to evaluate the effect on ignition pressure spiking of the incorporation of catalytic surfaces into the injector of a nominally 91-pound-thrust Apollo Command Module RCS engine. Test firings at a simulated altitude of 150,000 feet over a range of propellant and chamber temperatures (0 to 160 F) and a range of relative valve timings (+20 to -20 milliseconds) with both blank (unmodified) and catalytically modified splash plate injectors were made for N_2O_4/MMH, N_2O_4/50-50, and N_2O_4/N_2H_4 propellant combinations. It was determined that the catalytic concepts employed did not eliminate or supress the spiking. Effects on spiking levels of propellant combination, temperature, and valve timing were noted and are discussed.

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SUMMARY

Under conditions of high altitude, the ignition of hypergolic nitrogen tetroxide/hydrazine-type fuel propellant combinations is sometimes accompanied by pressure spikes of sufficient magnitude to result in thrust chamber and/or injector destruction. Under single-pulse type of operation, the spikes are thought to be due to a multiphase detonation of propellants collected in the thrust chamber during the period of ignition delay.

The present study was undertaken to evaluate the effect on ignition characteristics of catalytic modifications to the injector of a nominally 91-pound-thrust Apollo Command Module RCS engine. It was thought that if catalytic sites for the exothermic decomposition of the hydrazine-based fuels could be provided, the ignition delay, and thus raw propellant accumulation, could be reduced. The net result could be a reduction or possible elimination of ignition pressure spiking. Preliminary testing had shown that the technique appeared feasible and thus warranted further consideration.

A series of test firings with both blank (unmodified) and catalytically modified splash plate injectors was made. The propellant combinations employed were N_2O_4/MMH, N_2O_4/50 weight percent UDMH-50 weight percent N_2H_4, and N_2O_4/N_2H_4. The catalyst employed in the firings was Shell 405, a hydrazine decomposition catalyst. The tests were carried out at a simulated altitude of approximately 150,000 feet over a range of propellant and chamber temperatures (0 to 160 F) and a range of relative valve timings (+20 to -20 milliseconds).

The primary data for characterization of the ignition process were obtained from high-response pressure transducers. In addition, some high-speed photographic data were taken.

It was found that the catalytic concepts employed did not eliminate or suppress the ignition pressure spiking. For the N_2O_4/MMH and N_2O_4/50-50 propellant combinations, a catalytic concept in which the Shell 405 pellets were bonded to the injector splash plate at the 16 propellant impingement points with a high-temperature adhesive was found to be durable. However, with the N_2O_4/N_2H_4 combination, only one or two of the original catalyst pellets remained after a firing. Thus with the N_2O_4/N_2H_4 propellants, the possibility remains that spiking could be eliminated if a bonding concept capable of containing the pellets during a run were employed.

It was found that at the primary temperature of interest, 40 F, the spiking levels were greatest for the N_2O_4/N_2H_4 combination, less for the N_2O_4/50-50 combination, and least for the N_2O_4/MMH combination.

Increases in propellant and chamber temperatures resulted in decreases in ignition pressure spiking for all propellant combinations tested. The largest temperature effect occurred for the N_2O_4/50-50 combination, where, at the propellant temperature/chamber temperature conditions of 100 F/160 F, the spiking was virtually eliminated.

A broad distribution of ignition pressure spike values was found to exist for a given propellant combination at fixed-temperature and valve-timing conditions.

Trends in the data with respect to the effect of valve sequencing on ignition pressure spiking were noted. For the N_2O_4/MMH combination, maxima in ignition pressure spiking were noted in the vicinity of simultaneous valve action. For the N_2O_4/50-50 combination, spiking levels reached large values for the long (20 milliseconds) oxidizer lead conditions. Not enough data were taken with the N_2O_4/N_2H_4 combination for trends to be observed.

INTRODUCTION

Under conditions of high altitude, the ignition of hypergolic nitrogen tetroxide/hydrazine-type fuel propellant combinations is sometimes accompanied by a large chamber pressure spike. Thses spikes can be of a magnitude sufficient to result in destruction of the thrust chamber and/or injector.

At present, an incomplete understanding of the spiking process exists. From what has been observed, however, it is believed that two distinct types of ignition pressure spiking occur.

One type of spiking is usually attributed to condensed phase material which is accumulated during a previous engine shutdown. During ignition it is thought that this material is ignited explosively by the freshly injected hypergolic propellants. The condensed phase material has actually been observed, and work has been carried out at the Bureau of Mines (Ref. 1) to evaluate the adjunct from both chemical and stability standpoints. This type of spiking is associated with pulse-mode or multiple-restart operation.

The second type of spiking is associated with single-pulse or first-start ignition as well as multiple-restart operation. This is thought to be due to a multiphase detonation of the propellants collected in the thrust chamber during the period of ignition delay.

A number of programs have been directed toward elimination of this last mode of spiking. These have ranged from rather empirical approaches in which propellant additives were employed to more sophisticated approaches in which it was attempted to evolve design criteria from basic studies of the ignition process (Ref. 2 through 8). Although the use of a precup combustion chamber has shown utility in reducing the severity of the ignition spike, no real solution or understanding of the phenomenon has been achieved.

Because of the importance of the spiking problem, Rocketdyne evaluated novel spike suppression techniques. The most promising concept evolved was one in which catalyst pellets were employed in an injector splash plate at the impingement points of the unlike doublet elements. The rationale behind this concept was that the catalyst would reduce the ignition delay and thus reduce the raw propellant accumulation by providing sites for the exothermic decomposition of the hydrazine-based fuels.

A Rocketdyne IR&D experimental program was undertaken. Shell 405 catalyst pellets, a catalyst of superior quality for decomposition of neat hydrazine (Ref. 9 through 11), were incorporated into an injector splash plate at the propellant impingement points. The injector was similar to the 91-pound-thrust Apollo Command Module RCS design with 16 unlike doublet elements. The chamber was also similar to the Apollo design. The propellants were N_2O_4/50 weight percent N_2H_4-50 weight percent UDMH.

The results of the firings seemed to indicate that improved ignition characteristics, i.e., spining suppression, had occurred, and that a more extensive investigation was warranted to evaluate the concept.

The present investigation was therefore undertaken to more fully evaluate the effects of catalytic surfaces incorporated into the injector on the suppression of ignition pressure spiking for N_2O_4/hydrazine-base propellants. The ultimate aim was the development of design criteria for eliminating attitude control engine pressure spiking through the use of catalysts.

Two catalysts were to be considered: Shell 405, and uranium dioxide, UO_2. For the test-firing effort, a 91-pound-thrust engine similar to the Apollo Command Module RCS engine was to be used.

The experimental program was designed to systematically examine the effects of the following parameters under noncatalytic splash plate conditions to establish a baseline for comparison with the results obtained with catalytic surfaces incorporated into the splash plate:

1. Valve timing: +20, 0, -20 milliseconds oxidizer lead*
2. Propellant temperature: 40 F, 100 F
3. Hardware temperature: 0 F, 40 F, 160 F
4. Propellants: N_2O_4/N_2H_4, N_2O_4/MMH, N_2O_4/50 weight percent N_2H_4-50 weight percent UDMH

Other parameters were to be controlled throughout the experimental effort to the following nominal values:

1. Preignition altitude: 1 mm Hg (~ 150,000 feet)
2. Weight mixture ratio (o/f): 2.1
3. Engine chamber pressure: 150 psia

The tests with the catalytic surfaces incorporated in the splash plate were to cover the more severe operating conditions in terms of the spiking results.

Chamber pressure measurements with high-response transducers were to provide the primary data for characterization of the ignition process. In addition, high-response photographic data were to be taken.

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*Valve timing refers to the elapsed time between the electrical signals to the oxidizer and fuel fast-acting valves.

The original program objectives also included an evaluation using an impinging stream injector without a splash plate (flat-face injector). However, this effort was eliminated when the program was redirected following the conclusion that pressure spike suppression would not result from the incorporation of catalytic surfaces in splash plate injectors. As part of the program redirection, efforts were turned to a short comparison of the ignition pressure spiking characteristics of the hydrogen perioxide (98 percent)/monomethylhydrazine and nitrogen tetroxide/monomethylhydrazine propellant combinations. The results of that study are reported in Volume II (R-7060-2) of this report.

EXPERIMENTAL APPARATUS AND PROCEDURES

EXPERIMENTAL HARDWARE

Thrust Chambers

A reaction control engine configuration, similar to that of the Apollo Command Module RCS engine, was used for the program. In place of the ablative Apollo chamber, uncooled (including a transparent chamber) and cooled thrust chambers, built to the Apollo Command Module engine internal dimensions, were used. Photographs of the thrust chambers are presented in Fig. 1 through 3; assembly drawings are shown in Fig. 4 and 5. Thurst chamber design parameters were:

Throat diameter, inches	0.710
Contraction ratio	3.2
Contraction half angle, degrees	20
Characteristic length, inches	11.3
Nozzle expansion ratio	15

Uncooled Thrust Chamber. A two-piece thrust chamber assembly was used for the short-duration, N_2O_4/MMH tests. A solid-wall chamber segment was used except when photographic coverage was desired, when a transparent chamber segment was used.

The cylindrical solid-wall chamber section and converging-diverging nozzle section were fabricated from copper. A photograph and an assembly drawing of these sections are presented in Fig. 1 and 4. Copper tubing for temperature-conditioning coils was wrapped around and brazed to the outside of both segments. One fast-response pressure transducer port was located near the injector in the chamber segment, and two other ports were located on each side of the throat in the nozzle section. Prerun, steady-state, chamber temperature measurements were obtained from a thermocouple attached directly to the outside of the copper chamber. The transparent thrust chamber shown in Fig. 2 had a Plexiglas shell lined with 5/32-inch-wall Pyrex tubing. The converging-diverging nozzle segment is again shown.

Water-Cooled Thrust Chamber. A water-cooled thrust chamber was used for all of the long-duration tests. In addition, it was utilized for the short-duration N_2O_4/50-50 and N_2O_4/N_2H_4 tests. A photograph and an assembly drawing of the chamber are presented in Fig. 3 and 5.

The thrust chamber consisted of an integral copper-walled chamber and nozzle section which was drilled with internal cooling passages. It was encased in a stainless-steel sheath. For the short-duration tests, temperature conditioned fluids, instead of high-pressure cooling water, were pumped through the coolant passages. Prerun steady-state chamber temperature measurements were obtained from a thermocouple attached directly to the outside of the copper chamber.

A pressure transducer port was located in the chamber wall just upstream of the start of nozzle convergence. The port accepted a water-cooled Kistler pressure transducer. For the long-duration tests, high-pressure cooling water was used to cool the pressure transducer. For the short-duration tests, the same temperature-conditioned fluids as were used for the chamber were pumped through the transducer cooling passages.

Splash Plate Injector

A splash plate injector configuration similar to that of the Apollo Command Module RCS engine was used for the experimental effort. The stainless-steel injector assembly (Fig. 1 and 2) was in two pieces; an injector and a splash plate.

Injector. The injector was obtained by machining the splash plate from an Apollo injector. The face pattern was composed of 16 unlike impinging doublets equally spaced in a circle, with the fuel and oxidizer orifices placed on 0.48- and 0.36-inch radii, respectively. The integral Apollo valves were removed from the injector and the valves were connected in a close-coupled manner by a mechanical fitting. A photograph of the injector is shown in Fig. 6.

Splash Plate-Catalyst Incorporation Techniques. Two types of splash plates were used for comparative evaluation: one type included a catalytic surface and another type was identical except that the splash plates were of solid metal. The latter type (blank splash plates) was similar to the Apollo splash plate configuration. The one difference was that instead of being integral with the injector, as in the Apollo design, the splash plate was a separate segment positioned in front of the injector.

Several methods of incorporating the catalytic surfaces in the splash plate design were employed, including both mechanical and adhesive bonding techniques of Shell 405 catalyst pellets. A detailed drawing of the type of splash plate used for adhesively-bonded pellets is presented in Fig. 7. The blank splash plate configuration was identical except that no holes were drilled for the catalyst pellets. A detailed drawing of the type of ring holder used for the mechanically bonded pellets is presented in Fig. 8. The ring insert for the ring holder is shown in Fig. 9. Photographs of the finished splash plate hardware are presented in Fig. 10.

With both mechanical and adhesive bonding techniques, the catalyst pellets were held in 16 holes drilled through a splash plate. Splash plate indexing provisions were included to position these holes either directly at the point of propellant impingement, or halfway between adjacent impingement points.

Two high-temperature potting compounds were used with the adhesive technique, Sauereisen[1] and Eccoceram QC[2]. To ensure a smooth splash plate surface, the catalyst pellets were machined flush with the splash plate surface. In the mechanical technique, the catalyst pellets were held, without adhesive, in either tapered or stepped relief holes drilled through from the downstream side of the splash plate. A small retaining ring was used to hold the pellets in place (Fig. 9).

In addition to the Shell 405 efforts, flame spraying of UO_2 catalyst coatings on the face of a blank splash plate was evaluated. Initial Urania deposition attempts were unsuccessful due to the use of undersized UO_2 particles (< 10 microns). Subsequent attempts with a larger particle size feed (30 microns)resulted in reasonably uniform UO_2 coatings. Urania-coated splash plates were not used in any of the firings since laboratory tests showed the UO_2 to be noncatalytic with respect to N_2H_4, MMH, or 50-50 decomposition.

Main Valves

Apollo engine main valves (Fig. 11) were used. The valves were a common unit of two independently operated solenoid valves.

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[1] Manufactured by Sauereisen Cement Co., Pittsburgh, Pa.

[2] Manufactured by Emerson & Cumming, Inc., Gardena, Calif.

A metering orifice and a removable filter contained in the valve body were included with the valve. Each valve had two solenoid coils. Sequencing between the two valves was achieved by means of a solid-state, adjustable, delay circuit. The command signal was immediately fed to the leading valve. The time delay in the signal to the lagging valve was set by suitably adjusting a variable potentiometer in the RC delay circuit. Lead and lag valve sequence positions were controlled by changing the electrical connectors at the valve.

EXPERIMENTAL FACILITIES

The experimental firings were conducted at the flame laboratory test stand located at the Rocketdyne Santa Susana Field Laboratory. Photographs of the test stand are presented in Fig. 12 and 13.

Propellant Flow Systems

A schematic diagram of the propellant flow systems is shown in Fig. 14. The fuel and oxidizer flow systems are identical in design. Although the NTO system has been replaced with an H_2O_2 system in Fig. 12 and 13 (see Volume II, R-7060-2), its appearance is similar to that of the fuel system in the figures.

Helium was used as the pressurant gas for both 250-cubic-inch propellant tanks. Gaseous nitrogen purge systems and liquid flush systems were used to clear the propellant lines, main valves, and injector manifolds at the close of the firing day. The selection of the flush fluids, isopropyl alcohol and Freon TF for the fuel and oxidizer systems, respectively, was based on Apollo valve-cleaning standards.

A propellant recirculation system was included to allow recirculation of the propellants from the lines upstream of the main valves to the propellant tanks. This was to eliminate gas pockets in the propellant lines and to aid in propellant temperature conditioning.

Temperature conditioning of the propellants and thrust chamber was a program requirement. A schematic of the temperature-conditioning system employed is shown in Fig. 15. The conditioning system was capable of controlling temperatures in the range from -75 to +212 F. Low-temperature conditioning was obtained by circulating methyl alcohol through a low-temperature Dry Ice-alcohol bath to each of four conditioning tanks. Each conditioning tank was provided with a thermostatically controlled 500-watt heating element and an individual recirculation system to the test hardware. Separate conditioning tanks and hardware recirculation systems were used for (1) the thrust chamber, (2) the fuel and oxidizer propellant lines, (3) the fuel tank, and (4) the oxidizer tank. An intermediate tank was used for low-temperature oxidizer run tank conditioning. This was necessary because it was desired, from a safety standpoint, to use Freon TF as the oxidizer tank conditioning fluid instead of alcohol. Since the Freon TF would have frozen at the Dry Ice bath temperatures, an alcohol tank at an intermediate temperature was therefore employed.

For high-temperature conditioning, water was substituted for alcohol and Variac-controlled, higher-power (2- and 4-kilowatt) heating elements were used in addition to the thermostatically controlled 500-watt heaters.

Vaccum Chamber

Test conditions included firing at a simulated altitude of 150,000 feet. Altitude simulation was accomplished by firing the thrust chamber into a vacuum tank (21 cubic feet) which was evaculated by a large-capacity vacuum pump (Kinney Model No. KC 46). Vacuum pump oil (tricresylphosphate) compatible with the propellant exhaust products was employed. The vacuum tank and vacuum pump are identified in Fig. 13.

EXPERIMENTAL INSTRUMENTATION

A tabulation of the various measurements, together with the transducers and recorders used, is presented in Table 1.

Data Sensing Instrumentation

Pressure Measurements. Kistler and Statham pressure transducers were used for high- and low-response measurements of chamber pressure, respectively. Statham transducers were also used for propellant tank and line pressures.

Both Kistler Models 601H and 616A transducers were employed. Both models are similar except that the latter models were encased in a water-cooled jacket. The 601H transducers were used in the uncooled and transparent chambers. The 616A transducer was used in the long-duration, water-cooled chamber. Kistler Model 568 charge amplifiers were used with the transducers. Between the transducers and the charge amplifiers Kistler Model No. 131A25 ultralow-noise extension cables were used. The ratios of transient spike pressure to steady chamber pressure were obtained from the Kistler measurements.

Simulated altitude pressure data were obtained with a MKS Instrument Baratron Pressure Head, Type 774-30, 0-30 mm.

Flowrate Measurements. Both Fischer-Porter turbine-type flowmeters and Rocketdyne-designed, deflection-wand-type flowmeters were used to measure propellant flowrates. The Rocketdyne deflection flowmeter, which provides a d-c output from a strain gage as the wand is deflected by the propellant flow, was used for high-response measurements. The turbine flowmeters were used for steady-flow measurements.

Temperature Measurements. Sheathed iron-constantan thermocouples were used to measure propellant line temperatures, propellant injection temperatures, and thrust chamber conditioning temperature.

Valve Actuation Measurements. Main valve opening and closing data were obtained by monitoring the induced voltage from the secondary solenoid coil (an inactive coil). During valve operation one of the solenoid coils of the valve energized the armature, while the other coil was used to monitor the valve operation. The monitoring coil picked up the magnetic flux from the operating coil when it was energized, and also detected the armature motion due to its effect on the magnetic field. Figure 13 shows a typical trace of the output of this monitoring coil. As the operating coil was energized, the voltage across the monitoring coil rose sharply to a peak, and began to decay toward zero since the energizing current was no longer changing. The movement of the armature changed the magnetic field strength and induced an additional voltage across the monitoring coil that appeared as a second peak (Fig. 16). Valve power signals, pressure responses, and flowmeter responses are also shown in Fig. 16. (Note the essentially simultaneous response of the two high-response flowmeters to a simultaneous valve opening.)

Data Recording Instrumentation

Data were recorded as noted in Table 1 on either one or a combination of the following recording instruments:

1. Hieland Model 712C, 60-channel oscillograph, 0-3 khz response, CEC-type 1-127 a-c amplifiers, Dana Model 3840 d-c amplifiers, Rocketdyne-designed solid-state emitter follower amplifiers for Rocketdyne flowmeters
2. Beckman Offner Type R Dynalog, 0-200 hz response, 8 channel
3. Tektronix Type 545 oscilloscope, 0.01 μsec rise time
4. Ampex Model 5-3459 Tape Recorder, 7-channel 0-10,000 hz response
5. MKS Instruments, Type 77 Baratron Pressure Meter (Baratron referenced to a Stokes McLeod Gage, Flosdorf-type range 0-500 microns)
6. Foxboro Cell Type Dynalog Recorder, Model 9420 TV
7. Foxboro EMF Type Dynalog Recorder, Model 9330A
8. Bailey Meter, Model EX00, circular chart-type recorder

Data Playback Instrumentation

The magnetic tape records of the Kistler pressure transducers, a 1000-Hz timing pulse, and the Rocketdyne high-response flowmeters, which were simultaneously made on the Ampex Model 5-3459 recorder/reproducer at 60 ips, were replayed at 7-1/2 ips on an Ampex FR 100-7 recorder/reproducer. The output from the FR 100-7 was recorded by a 7-inch, CEC, 18-channel oscillograph. The paper speed on the latter was 27 ips.

The system playback response was limited by the oscillograph galvanometers which were rated at 5 KHz. Since the data were played back at 1/8 original speed, the overall limiting response in the whole tape recording/reproducing system was the real time 0-10 KHz response of the Model 5-3459 recorder.

EXPERIMENTAL PROCEDURES

The experimental test procedures are discussed in three parts: prerun checkout, testing, and posttest stand shutdown.

Prerun Checkout

The prerun checkout procedure was performed to ready the stand for testing. This included hardware assembly, flow system checks, instrumentation checks, and conditioning system activation and adjustment.

The hardware was assembled between the vacuum chamber and main valves. This included the injector, splash plate, and chamber sections. Following this, a complete flow system check was made, including a systematic check of the valves. Propellant was added to the run tanks if required.

The conditioning system was actuated and adjusted. For low-temperature operation (0 or 40 F), the cold bath was filled with Dry Ice and methyl alcohol and the other low-temperature baths were filled with alcohol. The baths used for high-temperature conditioning were filled with water. Adjustments to the system were made to keep the conditioned temperatures within desired ranges.

Instrumentation checks were made on all pressure and flowmeter transducers. The Kistler transducers were calibrated with a vacuum tube voltmeter each day and were calibrated on tape periodically. Other pressure transducers were zeroed and an electrical calibrate throw (80 percent of range signal) was obtained. (The pressure transducers were normally calibrated about once a month.) The thermocouples were checked for continuity and the flowmeters checked for operation, when the propellants were recirculated just prior to the countdown. The tape channels, oscillograph channels and galvanometers, and the direct inking oscillograph channels were checked for correct operation. The oscilloscope used to display the leading valve trace and a Kistler trace was also checked for correct operation.

Motion picture camera equipment was also set up for the transparent chamber firings during this time period.

Testing Procedure

Immediately prior to each test, the vacuum chamber was evacuated and final adjustments were made to the propellant and chamber conditioning systems. The main valves-actuation circuits were connected and the valve lead-lag control adjusted to give the proper valve.

The steps taken immediately prior to a firing were as follows:

1. The propellant prevalves were opened.
2. The propellant tanks were pressurized.
3. The propellant line and injection and chamber temperatures were read from a Leeds and Northrup millivolt potentiometer.

4. The test-pit fire-extinguishing system and sequencer were armed.
5. The altitude chamber vacuum conditions were read.
6. The oscilloscope camera shutter was opened.

A four-step countdown and firing sequence was made as follows:

One	-	the tape recorder was turned on
Two	-	(count only)
Three	-	(count only)
Fire	-	The Eagle sequencer was actuated

Also, at the command of "Fire," the oscillographs and circular recording charts were started. Approximately 2 seconds later the main valves were opened. The Eagle sequencer was used to control the test duration to between 450 and 750 milliseconds.

Following a test, the oscilloscope camera shutter was closed, the propellant tank pressures run down, the prevalves closed, and the fire and sequence systems were put in a standby condition.

Between tests the vacuum chamber was purged with nitrogen and then re-evacuated. After several tests it usually became necessary to change the vacuum pump oil because of contamination by the propellants. System operation was checked between tests by checking the parameters displayed by the on-line oscillograph and the photograph of the Kistler and valve trace taken with the oscilloscope camera.

Preliminary spiking data were obtained by simultaneously monitoring the leading valve and a Kistler transducer on an oscilloscope. Both the individual valve voltage and the pressure traces were recorded by a Polaroid camera. The camera lens was set on a time exposure and both traces were triggered to sweep across the oscilloscope by the electrical signal to the leading fast-acting propellant valve. Ignition delay times were obtained from the Polaroid recordings and simultaneous recordings of the two valve signatures (induced voltage) on a high-response oscillograph (Fig. 16).

During a test series, the above procedure was initiated immediately following attainment of the desired altitude conditions. When high-speed camera coverage was used, the pretest and test sequences were the same. The sequencer, however, controlled the camera operation: the low-speed (64 frames/second) camera was turned on immediately, the high-speed cameras (frame and streak) were turned on approximately 1 second before ignition; power to all cameras was removed after the main valves were closed.

Posttest Procedure

The hardware was separated at the injector-splash plate interface so that the splash plate coule be removed and inspected. The main propellant valves were purged and flushed with solvents (isopropyl alcohol and Freon TF for fuel and oxidizer, respectively) prior to securing the stand for the day.

DATA REDUCTION AND ANALYSIS PROCEDURE

The data reduction included both the slow-to-medium response data of system parameters such as propellant flowrate and chamber pressure, and the high-response data. In all cases, the propellant temperatures used to compute flowrates were taken from the precountdown thermocouple readings. The flowrates were calculated using the steady-state turbine meter spin frequency recorded on the galvanometer oscillograph, and the propellant density was determined from the line temperature; the mixture ratio was then calculated. Steady-state chamber pressure was also calculated from the deflection recorded on the galvanometer oscillograph. The final chamber pressure was calculated by dividing the steady-state deflection by the prerun calibrate throw. A calibration table was used to translate this reduced reading to the chamber pressure. The direct inking and circular chart recorders were used primarily for backup to the galvanometer oscillograph or when the prerun readings were questioned.

The high-response pressure spiking data were obtained from the Kistler pressure transducer output recorded on an FM tape recorder, speed reduced, and reproduced on a galvanometer oscillograph. Actual valve leads and lags were obtained directly on the galvanometer oscillograph traces in conjunction with the valve and Kistler traces photographed (Polaroid) on the oscilloscope.

PROPELLANT COMPOSITONS

Chemical analyses were performed on the propellants used for testing by the Analytical Chemistry section of the Research Division. These analyses are presented below:

N_2O_4 (Green NTO)

99.2 percent	N_2O_4
0.65 percent	NO
0.004 percent	NOCl
0.08 percent	H_2O

Density = 1.459 g/ml at 60 F

Conforms to MSC PPD-2A for
Components Analyzed

$N_2H_3CH_3$ (Monomethylhydrazine-MMH)

99.6 percent	MMH
0.2 percent	H_2O
0.1 percent	NH_3
0.1 percent	Other soluble impurities

Trace CH_3NH_2

Density = 0.870 g/ml at 77 F

Conforms to Mil P-27404 for Components Analyzed

50-50 (50 weight percent Hydrazine-50 weight percent Unsymmetrical Dimethylhydrazine)

50.9 percent	N_2H_4
48.1 percent	UDMH
1.0 percent	H_2O and other soluble impurities

Density = 0.908 g/ml at 60 F

Conforms to Mil P-27402 to Components Analyzed

N_2H_4 (Hydrazine)

98.6 percent	N_2H_4
0.6 percent	H_2O
0.8 percent	NH_3

Trace other soluble impurities

Density = 1.013 g/ml at 60 F

Conforms to Mil H-26536 for components analyzed

RESULTS AND DISCUSSION

The objectives of the present investigation were to evaluate the use of catalysts as a means for the elimination or suppression of pressure spiking which occurs during the altitude ignition of some hypergolic propellant combinations, and to establish design criteria for the incorporation of catalytic surfaces in bipropellant RCS engines. Results were obtained with three propellant combinations:

1. Nitrogen tetroxide/monomethylhydrazine
2. Nitrogen tetroxide/50 weight percent hydrazine-50 weight percent unsymmetrical dimethylhydrazine
3. Nitrogen tetroxide/hydrazine

A short preliminary laboratory effort was carried out to evaluate the two catalysts to be considered in this program, Shell 405 and uranium dioxide. The major portion of the program effort was directed at determining the catalytic effectiveness and durability of selected design concepts for the three propellant combinations. This was accomplished by first establishing a noncatalytic baseline of pressure spiking characteristics and then determining the corresponding characteristics with catalytic surfaces incorporated into the engine.

PRELIMINARY CATALYTIC LABORATORY STUDIES

A laboratory-scale experimental effort was carried out to evaluate the catalytic activity and durability of the two catalysts considered for use in the thrust chamber firing portion of the program. These two catalysts were Shell 405 and UO_2. Whole Shell 405 pellets (1/8-inch by 1/8-inch cylinders), pulverized pellets, UO_2 powder, and stainless-steel surfaces flame sprayed with UO_2 were tested. Catalytic activity was investigated with respect to the decomposition of the three hydrazine fuels of interest; neat hydrazine, monomethylhydrazine (MMH), and a 50 weight percent hydrazine-50 weight percent unsymmetrical dimethylhydrazine (UDMH) blend.

Catalytic Activity

For the Shell 405 and powdered UO_2 the tests consisted of the introduction of one pellet (or its pulverized or powder equivalent) into 1/2 milliliter of a hydrazine compound which was contained in a 25-milliliter graduate. For the tests with the flame-sprayed UO_2, the hydrazines were put on the UO_2 surfaces in drops. All tests were conducted under ambient (room) temperature conditions.

No gas evolution (with concurrent evaporation) was found for any of hydrazines when tested with either the powdered or flame-sprayed forms of the UO_2. It was therefore concluded that the UO_2 was not effective as an agent for the catalytic decomposition of hydrazine-type fuels of interest.

The most reactive fuel-catalyst combination found was that of hydrazine and pulverized Shell 405. The decomposition of 1/2 milliliter of hydrazine took place within about 2 seconds with a bright orange flame present. With the whole pellet, decomposition took place in about 50 seconds.

The decomposition of 1/2 milliliter of the 50-50 mixture with pulverized Shell 405 took place in about 15 seconds. A spark-type flame was present. With the whole pellet, the decomposition took place in about 100 seconds.

The MMH decomposition was found to be almost noncatalyzed by either the pulverized Shell 405 catalyst or the whole pellet. Liquid was found to remain in the graduate 1 hour after adding the catalyst.

It was concluded that the Shell 405 was very effective as a catalytic agent for the decomposition of hydrazine, but that it was practically ineffective for the decomposition of MMH. It was inferred that the reason for the moderate reactivity of the 50-50 mix was due to the presence of the hydrazine.

Catalyst Durability

An indication of catalyst durability was obtained by dropping hydrazine onto a flat end of a catalyst pellet. Immediate decomposition of the hydrazine took place, with the heat evolved causing the pellet to glow red for about 1/4 of its length. The pellet was allowed to cool and the experiment was repeated with the same results. The catalyst was then turned over and the two experiments were repeated with the same results. From the experiments it was concluded that the pellets had reasonable durability with respect to thermal stress.

After each series of runs with a given splash plate, the catalytic activity of the pellets was normally checked under laboratory conditions with neat hydrazine. A drop of neat hydrazine was placed on each of the pellets which was still bonded into the splash plate. This technique did not allow quantitative measurements of the catalyst's activity. Although the reactions were not as vigorous as pre-test, some reaction was evident in each case.

NITROGEN TETROXIDE/MONOMETHYLHYDRAZINE

Although the preliminary laboratory tests had shown MMH decomposition to be almost noncatalyzed by the Shell 405, a small portion of the engine testing was devoted to the N_2O_4/MMH propellant combination. This decision was made because of the extreme practical importance of the N_2O_4/MMH propellants and because there was at least a small chance of success. It was felt that only by actual ignition spiking tests could this small possibility be evaluated. Further, the noncatalytic testing with the N_2O_4/MMH would be useful as a baseline for comparison with the N_2O_4/50-50 propellants. Finally, a determination of the effects of valve timing and temperature on the N_2O_4/MMH spiking characteristics was considered important.

A summary of all the NTO/MMH tests is presented in Appendix A (Table A-1). The initial nonaltitude runs served to check out the system as well as to provide some data on the nonaltitude ignition characteristics of the NTO/MMH system. The remaining runs were designed to (1) establish a base of noncatalytic altitude ignition data, and (2) provide sufficient catalytic data from which to determine the effectiveness of the catalytic concepts employed. The altitude runs were carred out in a sequence designed for minimization of changes in the temperature-conditioning fluids.

Noncatalytic Altitude Tests

The noncatalytic test matrix was designed to produce ignition data for oxidizer leads of +20, 0, -20 milliseconds at propellant temperature-chamber temperature combinations of 40 F/0 F, 40 F/40 F, 40 F/160 F, and 100 F/0 F, 100 F/40 F, and 100 F/160 F. In addition, transparent chamber firings were made with 40 F propellants and ambient temperature (70 F) chambers.

A summary of the relevant data is presented in Table 2. Almost all of the conditioning temperatures were well within 5 F of the nominal temperatures shown. The oxidizer leads, times between oxidizer valve full open and fuel valve full open had maximum deviations of $^{+2}_{-0}$ milliseconds from the nominal values shown. The pressure spiking is reported as the ratio of the maximum spike pressure to the steady-state chamber pressure.

The most striking feature of the data is the apparent scatter in the ratios of the maximum spike to steady-state chamber pressure for fixed conditions. Continuous pre- and post-run checks of the Kistler pressure transducer measurement system precluded the scatter being due to experimental inaccuracies. Further, previous investigations have shown similar data scatter histories (Ref. 3). Therefore, although elimination of pressure spiking (the objective of the program) would be clearly revealed with a limited quantity of data, without a large number of tests the data scatter would preclude conclusions concerning a small degree of spiking suppression.

Effect of Valve Timing. Average spiking pressure ratios as a function of relative valve timings are presented in Fig. 17. Although the number of data points is certainly limited, there does appear to be maximum of the pressure ratios in the vicinity of zero oxidizer lead conditions. In Volume II, (R-7060-2) the results of 113 NTO/MMH firings, all with 100 F propellants and 100 F chamber temperature, are discussed. There, the large number of data points more clearly shows a maximum in pressure ratio in the vicinity of a zero oxidizer lead condition.

Effect of Temperature. A summary of the average of the pressure ratios for the various temperature combinations investigated is presented in Table 3. At a given propellant temperature, the averages of the pressure spike ratio generally decreased with increasing hardware temperature. Additionally, for a given hardware temperature, the averages of the pressure spike ratio generally decreased with increasing propellant temperature. The maximum pressure ratio for a given set of temperature conditions correlated well with an average temperature of the system, namely, the average of the propellant and chamber temperatures. A plot of the logarithm of the maximum pressure ratio vs the reciprocal of the average of the propellant and chamber temperatures for all of the noncatalytic N_2O_4/MMH data is presented in Fig. 18. It is seen that the data fits a straight line quite well. The fact that reciprocal temperature was found to be an important variable is consistent with the acknowledged dependence of the spiking process on propellant vapor pressure and/or reaction rate levels.

Photographic Observations. During five of the firings, photographic data were taken in addition to high-response Kistler pressure transducer data. Both framing and streak photographic techniques were employed. The framing photos were taken at about 3400 frames per second, the streaks at about 93 fps. Through use of a 1000-cps timing pulse, which was common to the Kistler and oscillograph recording systems and also common to timing lights employed on both the framing and streak cameras, the relative time positions of all data could be determined.

It was found that the first indication of ignition as determined photographically was coincident with the first indication of ignition as determined from the pressure transducer data. Accuracy in the determinations was within 1/3 millisecond.

The framing photographs, although of good clarity, failed to reveal any of the details of the spiking process. In one run in which the pressure spiked, then fell to a low preignition value, and then rose again, the framing photographs showed illumination, darkness, and then illumination, as should be expected.

All of the nontransparent chamber runs were made with the same splash plate, C1. For that plate, Eccoceram QC was used as the bonding agent. Prior to first time usage, all of the bonded catalyst pellets were spot checked with neat hydrazine and all appeared to be as active as unbonded pellets from the same catalyst batch. From these results, it was concluded that the pellets had not been contaminated during the bonding. After each set of tests, plate C1 was checked for pellet loss. No loss occurred in the test series 28-32 or 59-65. During the test series 70-75 2 of the original 16 pellets were lost. After test 75, the catalytic activity of the remaining 14 pellets was checked with neat hydrazine.

The transparent chamber firings were all made with another splash plate, C-2. For that plate, Sauereisen was used as the bonding agent. As with C-1, plate C-2 was tested with neat hydrazine prior to being fired, and was found to be uncontaminated. No pellet loss from plate C2 occurred in the test series 81-85.

Effect of Catalyst. The catalytic and noncatalytic data are presented in Fig. 14 and summarized in Table 3. The addition of the catalytic surfaces to the splash plate did not eliminate or reduce the spiking. These results confirmed the laboratory tests which had shown the Shell 405 to be almost noncatalytic with respect to MMH. The previously discussed broad distribution inherent in the ignition spike data is thought to be the cause of the increased average value and range of the spike pressure ratio for some of the catalytic run conditions.

Photographic Observations. Streak and framing photographic data were taken during five of the catalytic firings. During one of the catalytic firings, the streak photograph seemed to indicate that at the start of the ignition process, a sonic pressure wave began at the nozzle end of of the chamber and traveled toward the injector end. However, during the other catalytic firings which started with ignition pressure spikes, the

The streak photographs contained more basic data. The photographs were taken through an 0.002-inch slit which was parallel to the bulk flow movement of the gases. The recording was made with a high-speed, shutterless movie camera with the film moving perpendicular to the longitudinal axis of the slit. Thus, a luminous trace parallel to the direction of film travel would correspond to longitudinal velocity of zero while a luminous trace perpendicular to the direction of film travel would correspond to an infinite longitudinal velocity.

In those runs which started with an ignition pressure spike, the starts were characterized by luminous traces indicative of a velocity approximately equal to the speed of sound in the burned gases. These waves typically traveled from the injector region toward the nozzle region and then returned to the injector at about the same velocity. After reflecting from the injector, the waves typically seemed to decay before reaching the nozzle again. The entire process typically took about 1 millisecond. Following the first millisecond, the streak photographs usually exhibited a steady pattern, with streak slopes characteristic of velocities increasing from the injector end to the nozzle end of the chamber. The maximum measured velocities corresponded approximately to the predicted chamber Mach number. In addition, the streaks showed the flow to be directed toward the nozzle. A typical set of photographs is shown in Fig. 19. Also shown is the corresponding Kistler pressure transducer data.

Catalytic Altitude Tests

The catalytic altitude tests were carried out with oxidizer leads of +20, 0, and -20 milliseconds at propellant temperature-chamber temperature combinations of 40 F/0 F, 40 F/40 F, and 100 F/40 F. Also, some transparent chamber firings were made with 40 F propellants and ambient temperature (70 F) chambers. A summary of the runs is presented in Table 4.

sonic pressure waves at ignition started at the injector end, just as in all of the noncatalytic firings. Thus, in general, no differences were observed photographically between the noncatalytic and catalytic firings. These observations are consistent with the results of the pressure transducer data previously discussed.

NITROGEN TETROXIDE/50 WEIGHT PERCENT HYDRAZINE-50 WEIGHT PERCENT UNSYMMETRICAL DIMETHYLHYDRAZINE

A summary of all the NTO/50-50 tests is presented in Appendix A (Table A-2). As with the NTO/MMH tests, the runs were designed to (1) establish a base of noncatalytic altitude ignition data, and (2) provide sufficient catalytic data from which to determine the effectiveness of the catalytic concepts employed.

Noncatalytic Altitude Tests

The noncatalytic test matrix was designed to produce ignition data for oxidizer leads of +20, 0, and -20 milliseconds at propellant temperature-chamber temperature combinations of 40 F/0 F, 40 F/40 F, 40 F/160 F, 100 F/0 F, 100 F/40 F, and 100 F/160 F.

Table 5 presents a summary of the relevant data. As with the N_2O_4/MMH data, the maximum to steady-state pressure ratios, P_s/P_c, for a given set of conditions show a wide variation.

Effects of Valve Timing. The variations of the spiking to steady-state pressure ratios, P_s/P_c, with respect to valve timings are presented in Fig. 20. An unexplained difference in the pressure ratio characteristics as compared to NTO/MMH was noted. Whereas maxima in the spiking ratio occurred almost consistently at the zero oxidizer lead condition for the NTO/MMH propellant combination, for the NTO/50-50 propellant combination minima seemed to occur at the zero oxidizer lead condition. Additionally for the NTO/50-50 combination, spiking levels reached large values for the long (20 milliseconds) oxidizer lead conditions.

Effect of Temperature. A summary of the averages of the maximum to steady-state pressure ratios for various propellant and hardware temperatures is presented in Table 6. For all hardware temperatures, increases in propellant temperatures from 40 to 100 F resulted in lower spiking ratios. Similarly, increases in hardware temperature from 40 to 160 F resulted in lower spiking ratios at both the 40 and 100 F propellant temperature levels.

The high average spiking ratio of 7.6 which was observed for 40 F/40 F conditions was due primarily to two seemingly out-of-line ratios of 23.8 and 33.0. If the average is taken without those two tests, an average of 3.8 results. Employing that value, the temperature effects become entirely monotonic.

The two high spiking ratios of 23.8 and 33.0 are not thought to be due to experimental error. Rather, they are thought to be due to a type of spiking mechanism different from that accounting for the more commonly encountered, moderately valued spikes. For the 101 firings with N_2O_4/50-50 the two aforementioned spikes were the only ones with pressure ratios greater than 12.0.

The most striking effect of temperature occurred for the 100 F propellant/160 F chamber combination. Not only was the average value low, but the range of values was small. The total pressure ratio variation was from 1.2 to 1.9 for the seven firings. Therefore, it appears that through temperature manipulation alone, spiking could be held within tolerable limits for the N_2O_4/50-50 propellant combination. The minimum temperature seems to lie between 40 and 160 F for the chamber and between 40 and 100 F for the propellants.

Examination of plate C-5 after the next set of firings showed that 14 of the original 16 pellets still remained and it was concluded that no further catalytic testing at the 40 F/40 F temperature conditions was necessary. Catalyst plates C-6, C-7, and C-8 were all previously unfired, prerun hydrazine checked, Eccoceram QC bonded plates. No pellet loss occured with plate C-6. After the six tests with plate C-7, 14 of the original 16 pellets still remained. The condition of plate C-8 after its seven tests was similar to that of plate C-7 after its six tests.

Effect of Catalyst. Plots of both the catalytic and noncatalytic data are presented in Fig. 20. For reasons previously discussed, the results of those tests employing only plates C-4 and C-5 were used in 40 F/40 F plots. It can be seen that for all temperature conditions studied, the catalyst did not serve to eliminate the spiking.

While the catalytic and noncatalytic data in Fig. 20 appear reasonably close for the 100 F propellant temperature runs, a wide diversity exists for the set of runs with the 40 F propellants. Part of this can be explained. The high average spike value of 13.5 for the 40 F/40 F runs at the +20-millisecond oxidizer lead condition was mainly due to two runs with spike ratios of 23.8 and 33.0. If those are eliminated from the average for reasons discussed previously, an average value of 3.7 results. That compares quite favorably with the average catalytic value of 3.9.

Table 6 presents a summary of the catalytic and noncatalytic data. The results presented in this manner also show that the catalytic techniques were not effective in eliminating the spiking. Owing to the small number of data points relative to the broadness of the distribution of observed spiking levels at a given condition, the small reductions in spiking levels are not thought to be statistically significant.

Catalytic Altitude Tests

Catalytic altitude tests were carried out for oxidizer leads of +20, 0, and -20 milliseconds for propellant temperature-chamber temperature combinations of 40 F/40 F, 100 F/0 F, 100 F/40 F, and 100 F/160 F. A summary of the data is presented in Table 7.

Four sets of firings were carried out at the main temperature combination of interest, 40 F/40 F. In the first set of firings, catalytic splash plate C-2 was employed. This was a plate which had previously been used in a series of N_2O_4/MMH firings. As seen in Table 7, the catalyst did not serve to eliminate the spiking. A check of plate C-2 after test 97 revealed that only one pellet was lost.

Since plate C-2 could possibly have been contaminated in its use during the MMH firings, another set of firings was accomplished with a new plate. The new plate, C-3, contained mechanically bonded catalyst pellets, i.e., no bonding agent was employed. Before using C-3, all of the bonded pellets were tested with neat hydrazine to ensure that they were not contaminated during machine shop handling. The pellets were found to be as reactive as unbonded ones from the same catalyst batch. Again, during the test firings no spike elimination was found. However, examination of the splash plate after the seven firings showed that 14 of the original 16 pellets had been blown out.

The third set of firings was carried out with another previously unfired plate, C-4. This plate, which was also pretested with neat hydrazine, contained 16 pellets bonded with Eccoceram QC. The plate was examined after the second firing and all pellets were found to be in place. However, one pellet was loose so it was decided to use a new plate (activity checked with hydrazine) for the final set of 40 F/40 F firings.

NITROGEN TETROXIDE/HYDRAZINE

Preliminary laboratory tests had shown the Shell 405 catalyst to be considerably more reactive with respect to hydrazine decomposition than with respect to either 50/50 or MMH decomposition. Therefore, as a final test of the catalytic suppression concept, a limited number of both noncatalytic and catalytic N_2O_4/hydrazine firings were made. A summary of all the N_2O_4/N_2H_4 data is presented in Appendix A (Table A-3).

Noncatalytic Altitude Tests

The noncatalytic tests were conducted for oxidizer leads ranging from -20 to +20 milliseconds primarily at the propellant temperature/hardware temperature combinations of 40 F/40 F and 100 F/40 F. One successful test was also conducted at a 100 F/0 F condition. However, after hydrazine freezing occurred in a subsequent test, no more tests at that condition were attempted. A summary of the data is presented in Table 8.

Effect of Valve Timing. The variations of spiking pressure with respect to valve timings are shown in Fig. 21. For the 40 F/40 F temperature condition, a spiking maximum seems to occur in the vicinity of the zero oxidizer lead condition. For the 100 F/40 F condition, a minimum seems to occur in the vicinity of a +10-millisecond oxidizer lead. It is noted that maxima were typically found near the 0-millisecond lead-lag condition for the N_2O_4/MMH propellants while minima were found for the N_2O_4/50-50 propellants.

Effect of Temperature. A summary of the maximum to steady-state pressure ratios for the various propellant and hardware temperatures is presented in Table 9. As with the other propellant combinations, decreases in the average of the maximum to steady-state pressure ratios were found for both increasing propellant and chamber temperatures.

Catalytic Altitude Tests

Catalytic altitude tests were made at both the 40 F/40 F and 100 F/40 F propellant temperature-chamber temperature combinations.

Table 10 presents a summary of the runs for which pressure data were available. Each catalytic run was carried out with a previously unfired splash plate. Each splash plate contained 16 Eccoceram QC-bonded Shell 405 pellets. Prior to firing, they were laboratory checked with hydrazine and were found to be as catalytically active as unbonded pellets from the same catalyst batch.

It was necessary to use new catalyst plates for each run since after a run only 1 or 2 of the original 16 pellets remained. Such a pellet loss did not occur with either the N_2O_4/MMH or N_2O_4/50-50 propellant combinations. The fact that Shell 405 is significantly more catalytic with respect to N_2H_4 than with respect to MMH or 50-50 is consistent with the above. The increased decomposition rates would have the effect of increasing the gas evolution rates and combustion levels around the pellets. They would result in increased temperature and pressure buildups and therefore a greater potential for pellet loss.

Effect of Catalyst. Plots of both the catalytic and noncatalytic data are presented in Fig. 21. In addition, a comparative summary of the catalytic and noncatalytic data is given in Table 8 . It can be seen that the spiking was not eliminated. For the 100 F/40 F condition the spiking does not appear to have been reduced. At the 40 F/40 F condition, the two catalytic runs had lower spikes than the two corresponding noncatalytic runs. However, if the spread in spiking ratios at the zero oxidizer lead condition is assumed to be indicative of what the spread might have been at +20 and -20 milliseconds oxidizer lead conditions if more data had been taken, there really is no significance to the catalytic reduction observed.

The loss of catalyst pellets during each run still allows for the possibility that the spiking might have been eliminated if a bonding concept which was capable of containing the catalyst pellets during the whole run had been employed. However, the point in time at which the pellets were lost is not known and it is possible that the pellets remained in place during the spiking portion of each run and were lost during the latter portion of each run. If the latter is true then employment of a superior bonding concept would have been of no help.

CONCLUDING REMARKS

The concept of incorporating catalytic surfaces in splash plate injectors to eliminate ignition pressure spiking was unsuccessful with the three propellant combinations tested, N_2O_4/MMH, N_2O_4/50 wt. % N_2H_4-50 wt. % UDMH, and N_2O_4/N_2H_4. A design concept of bonding Shell 405 pellets into a splash plate with a high temperature adhesive was found to be durable under N_2O_4/MMH and N_2O_4/50 wt. % UDMH firing conditions. However, with the N_2O_4/N_2H_4 propellant combination only one or two of the original sixteen catalyst pellets remained after a short firing ($<$ 1 second duration). Thus, the possibility remains that the ignition spiking with N_2O_4/N_2H_4 could be eliminated with a suitable design concept for retaining the catalytic surface. However, interest in this propellant combination is relatively low.

A broad distribution of peak ignition pressure values was found for a given propellant at fixed temperature and valve timing conditons. Thus, although the use of catalytic surfaces was unambiguously not found to eliminate ignition pressure spiking, only through large amounts of data could possible moderating effects, if any, if the catalyst be clearly exhibited. Such large amounts of data were not obtained in the present program.

At the primary temperature of interest, 40 F, the ignition pressure spiking was most severe for the N_2O_4/N_2H_4 propellant combination, less severe for the N_2O_4/50 wt % N_2H_4 - 50 wt % UDMH combination, and least severe for the N_2O_4/MMH combination.

Increases in propellant chamber temperatures resulted in decreases in ignition pressure spiking for all propellant combinations tested. The largest temperature effect occurred for the N_2O_4/50-50 combination where at the propellant temperature/chamber temperature conditions of 100 F/160 F the spiking was virtually eliminated. Therefore, it would appear that maintaining the engine and propellants above some minimum temperature may be a viable solution to ignition pressure spiking with N_2O_4/50 wt % N_2H_4-50 wt. % UDMH propellants. The minimum temperature levels must be experimentally determined.

The effect of valve timing on ignition overpressure values was found to differ between the N_2O_4/MMH and N_2O_4/50 wt. % N_2H_4-50 wt. % UDMH combinations. The maximum ignition pressure values were found at near simultaneous actuation of the two propellant valves for the N_2O_4/MMH combination. Conversely, minima in the ignition pressure values were found for the N_2O_4/50 wt. % N_2H_4-50 wt. % UDMH combination. The causes of these different characteristics are not known.

TABLE 1

TABULATION OF MEASURED PARAMETERS AND INSTRUMENTATION

Measurement	Steady-State or Transient	Location	Instrument	Recorder
Flow	Steady-State	Fuel Line	Turbine Meter	Osc
Flow	Transient	Fuel Line	Vane Meter	T and Osc
Flow	Steady-State	Oxidant Line	Turbine Meter	Osc
Flow	Transient	Oxidant Line	Vane Meter	T and Osc
Temperature	Steady-State	Fuel Line	Thermocouple	Dyn and OF
Temperature	Steady-State	Oxidant Line	Thermocouple	Dyn and OF
Temperature	Steady-State	Fuel Storage	Thermocouple	Dyn
Temperature	Steady-State	Oxidant Storage	Thermocouple	Dyn
Temperature	Steady-State	Chamber Wall	Thermocouple	Dyn
Pressure	Steady-State	Oxidant Tank	Statham	Dyn
Pressure	Steady-State	Fuel Tank	Statham	Dyn
Pressure	Steady-State	Oxidant Line	Statham	OF and Osc
Pressure	Steady-State	Fuel Line	Statham	OF and Osc
Pressure	Steady-State	Injector	Statham	OF and Osc
Pressure	Transient	Nozzle	Kistler	T
Pressure	Transient	Nozzle	Kistler	T
Pressure	Transient	Chamber	Kistler	T and Scope
Pressure	Steady-State	Vacuum Tank	Baratron	Dyn and OF
Valve Signature	Transient	Fuel Line		Osc, Scope
Valve Signature	Transient	Oxidizer Line		Osc, Scope
Valve Signal	Transient	Fuel Line		Osc
Valve Signal	Transient	Oxidizer Line		Osc

Notes:
Osc - Oscillograph
T - F-M Tape 0-20KC
Dyn - Dynalog Charts
Scope - Oscilloscope
OF - Beckman Offner

TABLE 2

SUMMARY OF NONCATALYTIC N_2O_4/MMH ALTITUDE FIRINGS

(Nominal Altitude of 150,000 Feet)

Nominal Propellant Temperature, F	Nominal Chamber Temperature, F	Nominal Oxidizer Lead, milliseconds	P_s/P_c	Run Number
40	0	+20	3.26	21
		+20	1.73	27
		0	1.62	22
		0	6.21	24
		-20	1.20	26
	40	+20	2.03	14
		+20	2.88	18
		+20	1.19	20
		0	5.24	17
		0	3.68	19
		-20	1.54	15
		-20	2.32	16
	70	+20	2.08	78
		0	4.25	76
		0	4.20	77
		0	3.37	80
		-20	1.36	79
	160	+20	2.97	33
		+20	1.38	36
		0	1.54	34
		-20	2.72	35
100	0	+20	1.50	52
		+20	1.78	66
		+20	3.14	67
		+10	3.79	58
		0	3.95	53
		0	2.56	57
		-10	4.28	56
		-20	3.81	68
		-20	3.54	69

TABLE 2
(Concluded)

Nominal Propellant Temperature, F	Nominal Chamber Temperature, F	Nominal Oxidizer Lead, milliseconds	P_s/P_c	Run Number
100	40	+20	1.53	46
		+20	1.83	49
		0	3.00	45
		0	3.35	50
		-20	2.50	47
	160	+20	1.42	37
		+20	1.64	40
		0	1.59	38
		0	2.20	41
		0	2.02	42
		-20	2.60	39

Notes: Oxidizer Lead = time between oxidizer valve full open and fuel valve full open; (+) and (-) indicate oxidizer and fuel leads, respectively.

P_s/P_c = ratio of maximum or spiking pressure to steady-state chamber pressure

Nominal Steady-State Chamber Pressure = 150 psia

TABLE 3

SUMMARY OF THE MAXIMUM TO STEADY-STATE PRESSURE RATIOS FOR N_2O_4/MMH PROPELLANTS

(Nominal Steady-State Pressure of 150 psia)

A. Blank Splash Plate

	Hardware Temperature			
Propellant Temperature	0 F	40 F	70 F	160 F
40 F				
Average	2.8	2.7	3.1	2.2
Range	1.2-6.2	1.2-5.2	1.4-4.2	1.4-3.0
(Number of Tests)	5	7	5	4
100 F				
Average	3.0	2.4		1.9
Range	1.5-4.3	1.5-3.4		1.4-2.6
(Number of Tests)	10	6		6

B. Catalytic Splash Plate

Propellant Temperature				
40 F				
Average	6.18	3.6	2.7	
Range	1.6-15	1.7-10.6	1.7-4.5	
(Number of Tests)	5	6	5	
100 F				
Average		2.5		
Range		1.5-4.5		
(Number of Tests)		5		

TABLE 4

SUMMARY OF CATALYTIC N_2O_4/MMH ALTITUDE FIRINGS

(Nominal Altitude of 150,000 Feet)

Nominal Propellant Temperature, F	Nominal Chamber Temperature, F	Nominal Oxidizer Lead, milliseconds	P_s/P_c	Run Number	Splash Plate
40	0	+20	1.58	31	C-1
		+20	15.00	73	C-1
		0	8.29	32	C-1
		0	3.92	74	C-1
		-20	2.11	75	C-1
40	40	+20	1.32	28	C-1
		+20	2.17	70	C-1
		0	1.95	29	C-1
		0	10.61	71	C-1
		-20	3.68	30	C-1
		-20	1.66	72	C-1
40	70	+20	1.69	84	C-2
		0	3.64	81	C-2
		0	4.47	82	C-2
		0	1.70	83	C-2
		-20	1.85	85	C-2
100	40	+20	1.47	59	C-1
		+20	1.82	64	C-1
		0	4.50	60	C-1
		0	2.70	62	C-1
		-20	1.89	61	C-1

Notes: Oxidizer Lead = time between oxidizer valve full open, and fuel valve full open; (+) and (-) indicate oxidizer and fuel leads, respectively.

P_s/P_c = ratio of maximum or spiking pressure to steady-state chamber pressure

Nominal Steady-State Chamber Pressure = 150 psia

All tests made with Shell 405 Catalyst

TABLE 5

SUMMARY OF NONCATALYTIC N_2O_4/50-50 FIRINGS
(Nominal Altitude of 150,000 Feet)

Nominal Propellant Temperature, F	Nominal Chamber Temperature, F	Nominal Oxidizer Lead, milliseconds	P_s/P_c	Run Number
40	0	+20	1.70	133
		+20	10.00	136
		+20	12.75	139
		+20	2.56	140
		0	1.58	134
		0	1.50	137
		-20	1.67	135
		-20	3.12	138
40	40	+20	23.75	87
		+20	33.00	90
		+20	3.84	93
		+20	4.82	113
		+20	2.36	116
		0	2.50	86
		0	1.07	89
		0	1.24	112
		0	9.34	115
		-20	4.75	88
		-20	5.34	91
		-20	1.43	92
		-20	4.25	114
40	160	+20	5.05	142
		+20	1.62	144
		+20	1.50	147
		0	1.33	143
		0	1.97	146
		-20	1.45	145

TABLE 5

(Concluded)

Nominal Propellant Temperature, F	Nominal Chamber Temperature, F	Nominal Oxidizer Lead, milliseconds	P_s/P_c	Run Number
100	0	+20	5.62	178
		+20	5.69	181
		0	1.74	180
		-20	1.57	179
		-20	2.58	182
100	40	+20	4.95	167
		+20	2.11	170
		+20	1.88	173
		+20	2.31	176
		+20	2.14	198
		0	1.41	166
		0	2.94	169
		0	1.89	172
		0	2.39	175
		0	2.14	197
		-20	3.35	168
		-20	3.06	171
		-20	2.39	174
100	160	+20	1.50	148
		+20	1.60	151
		+20	1.89	154
		0	1.23	149
		0	1.35	152
		-20	1.50	150
		-20	1.47	153

Notes: Oxidizer Lead = time between oxidizer valve full open and fuel valve full open; (+) and (-) indicate oxidizer and fuel leads, respectively.

P_s/P_c = ratio of maximum or spiking pressure to steady-state chamber pressure

Nominal Steady-State Chamber Pressure = 150 psia

TABLE 6

SUMMARY OF THE MAXIMUM TO STEADY-STATE PRESSURE RATIOS FOR N_2O_4/50 WEIGHT PERCENT N_2H_4-50 WEIGHT PERCENT UDMH PROPELLANTS

(Nominal Steady-State Pressure of 150 psia)

A. Blank Splash Plate

	Hardware Temperature		
Propellant Temperature	0 F	40 F	160 F
40 F			
Average	4.4	7.6	2.15
Range	1.5-12.8	1.2-33.0	1.3-5.0
(Number of Tests)	8	13	6
100 F			
Average	3.4	2.6	1.5
Range	1.6-5.7	1.4-5.0	1.2-1.9
(Number of Tests)	5	13	7

B. Catalytic Splash Plate

Propellant Temperature	0 F	40 F	160 F
40 F			
Average		7.3	
Range		1.6-9.3	
(Number of Tests)		12	
100 F			
Average	2.2	2.2	1.4
Range	2.0-3.2	1.4-3.8	1.2-1.8
(Number of Tests)	7	6	11

TABLE 7

SUMMARY OF CATALYTIC N_2O_4/50-50 FIRINGS
(Nominal Altitude of 150,000 Feet)

Nominal Propellant Temperature, F	Nominal Chamber Temperature, F	Nominal Oxidizer Lead, milliseconds	P_s/P_c	Run Number	Splash Plate
40	40	+20	8.18	95	C-2
		+20	8.48	96	C-2
		0	2.12	94	C-2
		-20	4.92	97	C-2
40	40	+20	3.25	99	C-3
		+20	6.21	102	C-3
		0	2.32	98	C-3
		0	11.75	101	C-3
		0	3.94	104	C-3
		-20	3.19	100	C-3
		-20	5.46	103	C-3
40	40	+20	1.58	119	C-4
		0	5.00	118	C-4
40	40	+20	4.46	125	C-5
		+20	4.43	128	C-5
		+20	2.14	131	C-5
		+20	9.01	132	C-5
		0	4.94	124	C-5
		0	9.30	127	C-5
		0	6.25	130	C-5
		-20	8.35	123	C-5
		-20	8.45	126	C-5
		-20	4.84	129	C-5

TABLE 7

(Concluded)

Nominal Propellant Temperature, F	Nominal Chamber Temperature, F	Nominal Oxidizer Lead, milliseconds	P_s/P_c	Run Number	Splash Plate
100	0	+20	3.20	193	C-8
		0	1.95	189	C-8
		0	2.66	190	C-8
		0	2.68	192	C-8
		0	2.00	195	C-8
		-20	2.45	191	C-8
		-20	2.90	194	C-8
100	40	+20	1.39	184	C-7
		+20	1.95	187	C-7
		0	3.76	183	C-7
		0	2.05	186	C-7
		-20	1.90	185	C-7
		-20	2.10	188	C-7
100	160	+20	1.24	155	C-6
		+20	1.44	158	C-6
		+20	1.84	161	C-6
		+20	1.58	164	C-6
		0	1.33	156	C-6
		0	1.39	159	C-6
		0	1.29	162	C-6
		0	1.26	165	C-6
		-20	1.44	157	C-6
		-20	1.26	160	C-6
		-20	1.22	163	C-6

Notes: Oxidizer Lead = time between oxidizer valve full open, and fuel valve full open; (+) and (-) indicate oxidizer and fuel leads, respectively.

P_s/P_c = ratio of maximum or spiking pressure to steady-state chamber pressure

Nominal Steady-State Chamber Pressure = 150 psia

TABLE 8

SUMMARY OF NONCATALYTIC N_2O_4/N_2H_4 FIRINGS
(Nominal Altitude of 150,000 Feet)

Nominal Propellant Temperature, F	Nominal Chamber Temperature, F	Nominal Oxidizer Lead, milliseconds	P_s/P_c	Run Number
40	40	+20	6.60	214
		0	19.81	213
		0	11.62	216
		0	3.77	223
		-20	10.35	215
100	0	0	6.61	207
100	40	+20	3.52	203
		+20	3.54	210
		+10	1.97	200
		0	6.10	199
		-10	7.40	141
		-20	11.60	202

Notes: Oxidizer Lead = time between oxidizer valve full open, and fuel valve full open; (+) and (-) indicate oxidizer and fuel leads, respectively.

P_s/P_c = ratio of maximum or spiking pressure to steady-state chamber pressure

Nominal Steady-State Chamber Pressure = 150 psia

TABLE 9

SUMMARY OF THE MAXIMUM TO STEADY-STATE PRESSURE RATIOS FOR N_2O_4/N_2H_4 PROPELLANTS

(Nominal Steady-State Pressure of 150 psia)

A. Blank Splash Plate

Propellant Temperature	Hardware Temperature 0 F	Hardware Temperature 40 F	Hardware Temperature 160 F
40 F			
Average		10.3	
Range		3.8-19.8	
(Number of Tests)		5	
100 F			
Average	6.6	5.4	
Range	-	3.5-11.6	
(Number of Tests)	1	7	

B Catalytic Splash Plate

Propellant Temperature	
40 F	
Average	5.0
Range	4.7-5.3
(Number of Tests)	2
100 F	
Average	2.9
Range	-
(Number of Tests)	1

TABLE 10

SUMMARY OF CATALYTIC N_2O_4/N_2H_4 FIRINGS

(Nominal Altitude of 150,000 Feet)

Nominal Propellant Temperature, F	Nominal Chamber Temperature, F	Nominal Oxidizer Lead, milliseconds	P_s/P_c	Run Number	Splash Plate
40	40	+20	5.30	224	C-12
		-20	4.69	222	C-11
100	40	0	2.94	204	C-9
		-20	9.10*	205	C-9

Notes: Oxidizer Lead = time between oxidizer valve full open, and fuel valve full open; (+) and (-) indicate oxidizer and fuel leads, respectively.

P_s/P_c = ratio of maximum or spiking pressure to steady-state chamber pressure

Nominal Steady-State Chamber Pressure = 150 psia

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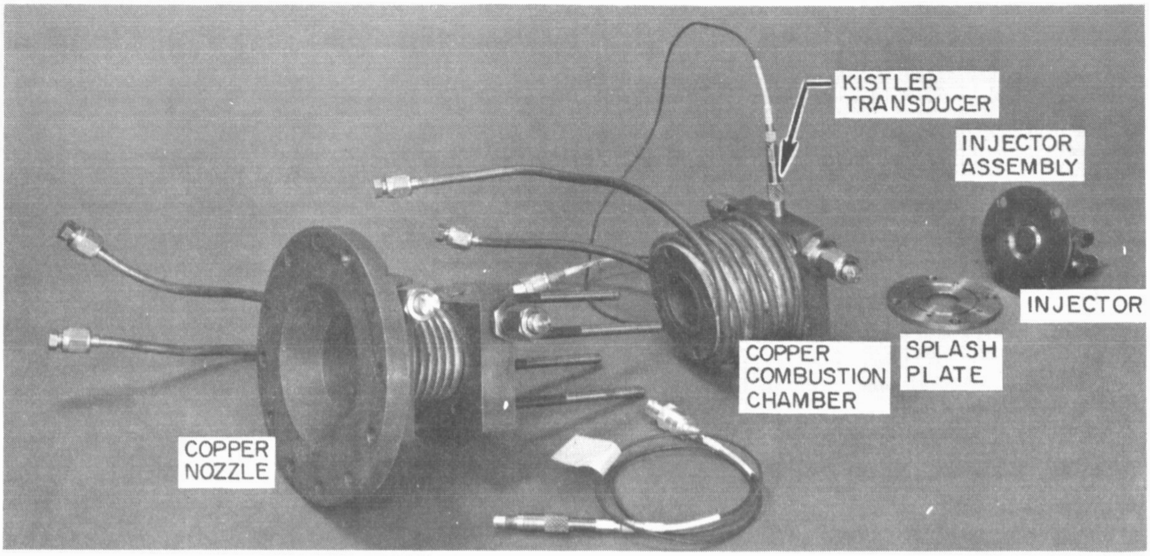
*Very probably most of the pellets were blown out of the splash plate in the previous test.



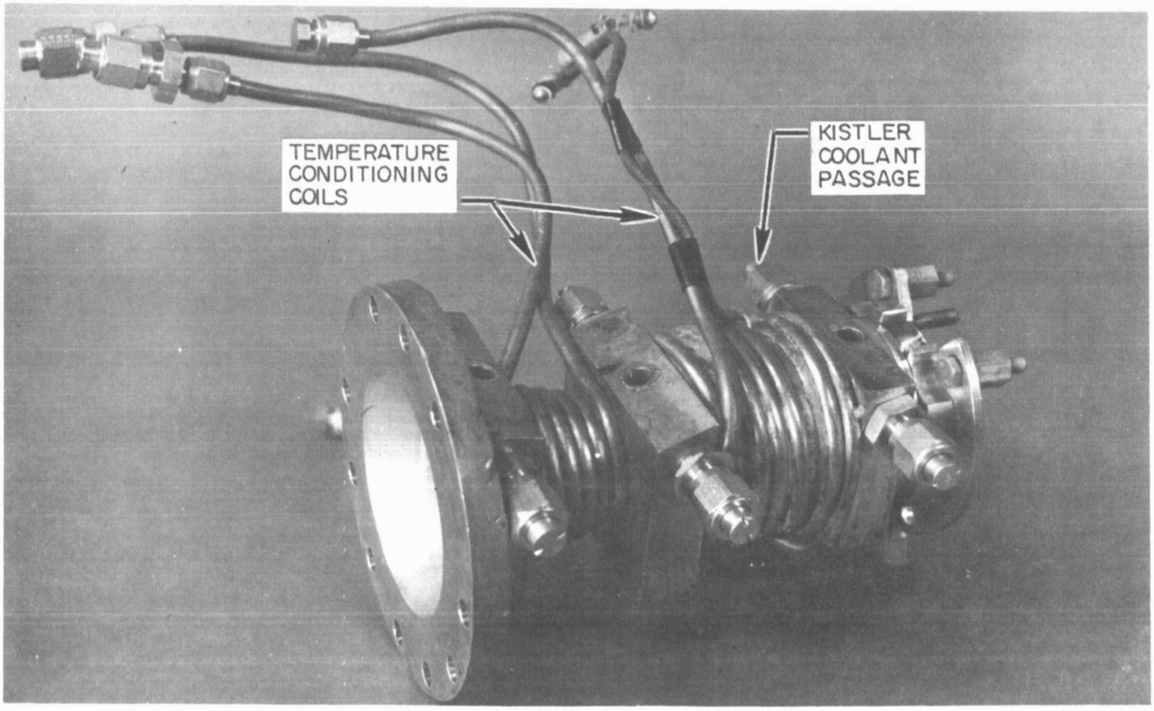
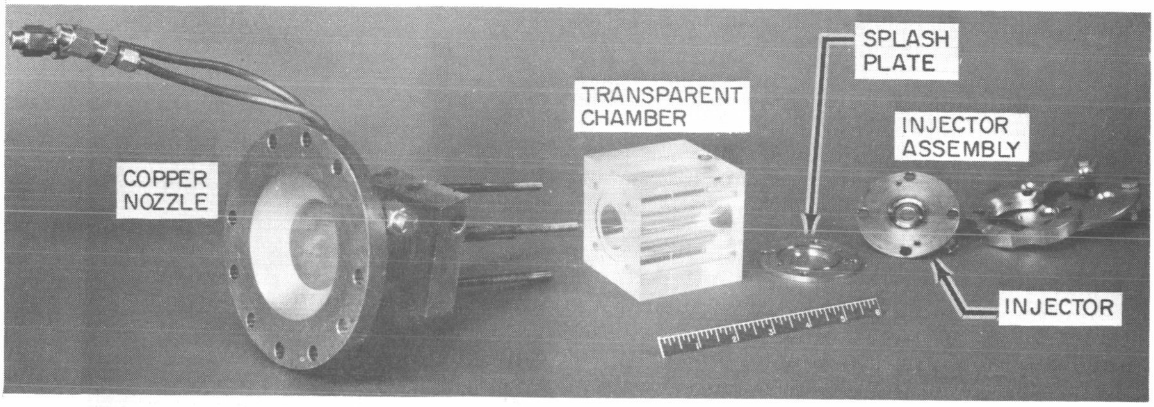


Figure 1. Solid Wall Combustion Chamber and Nozzle with Injector Assembly, Kistler Pressure Transducers and Temperature Conditioning Coils



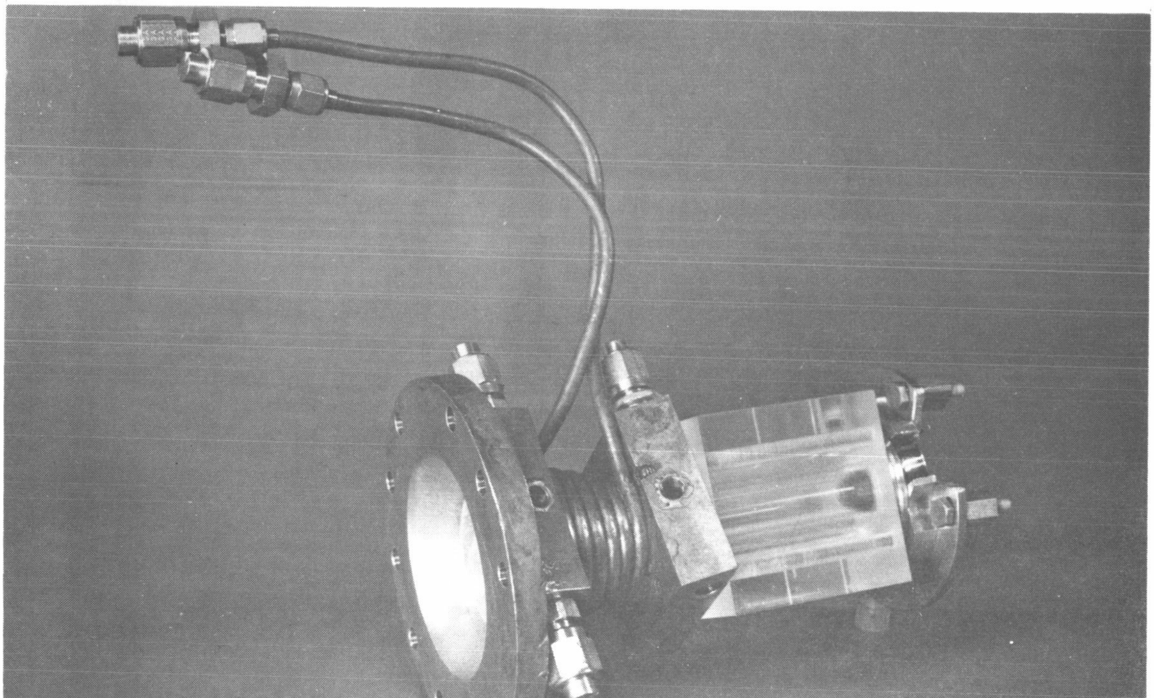
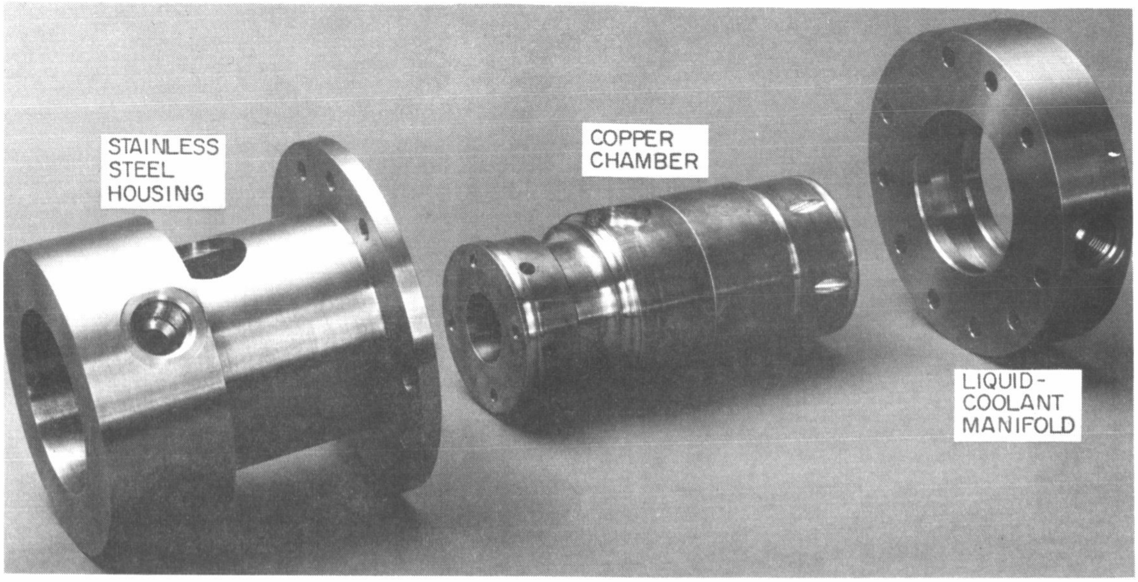


Figure 2. Solid Wall Nozzle and Transparent Chamber with the Injector Assembly



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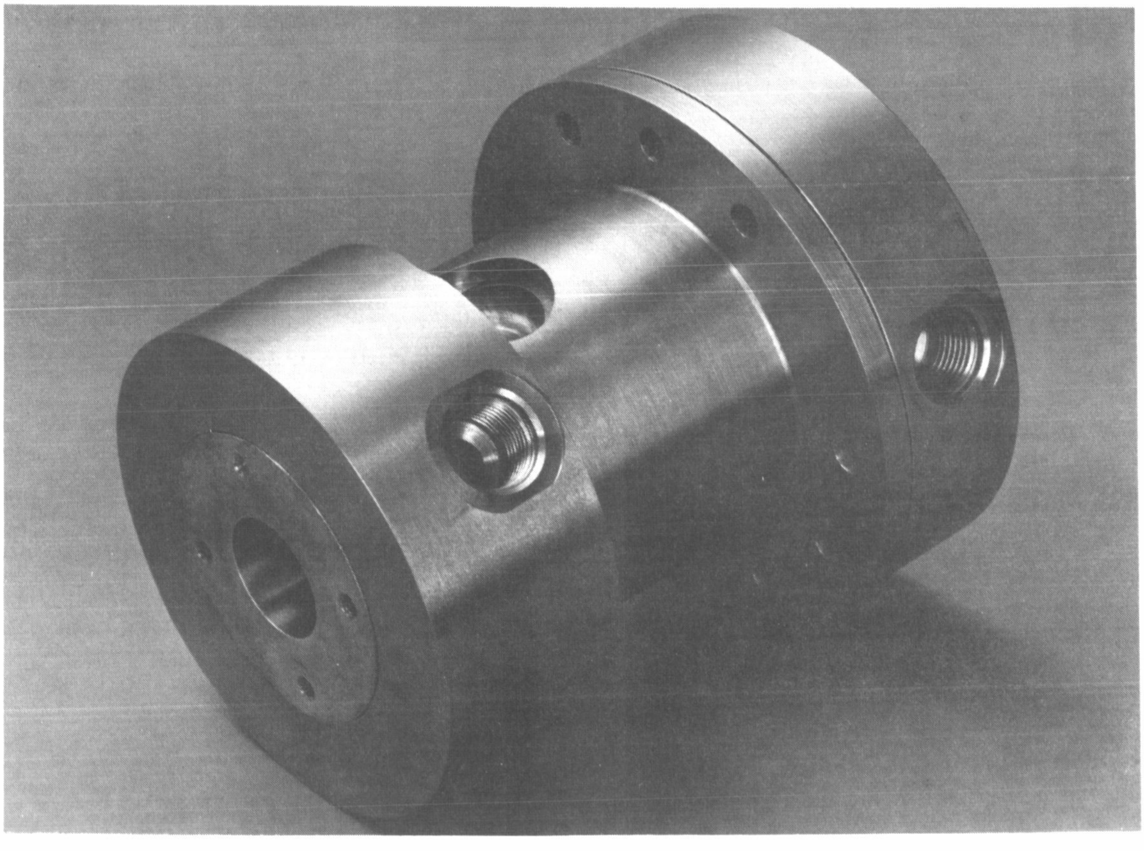


1XW31-11/17/66-S1A

Figure 3. Liquid-Cooled Combustion Chamber and Nozzle Assembly

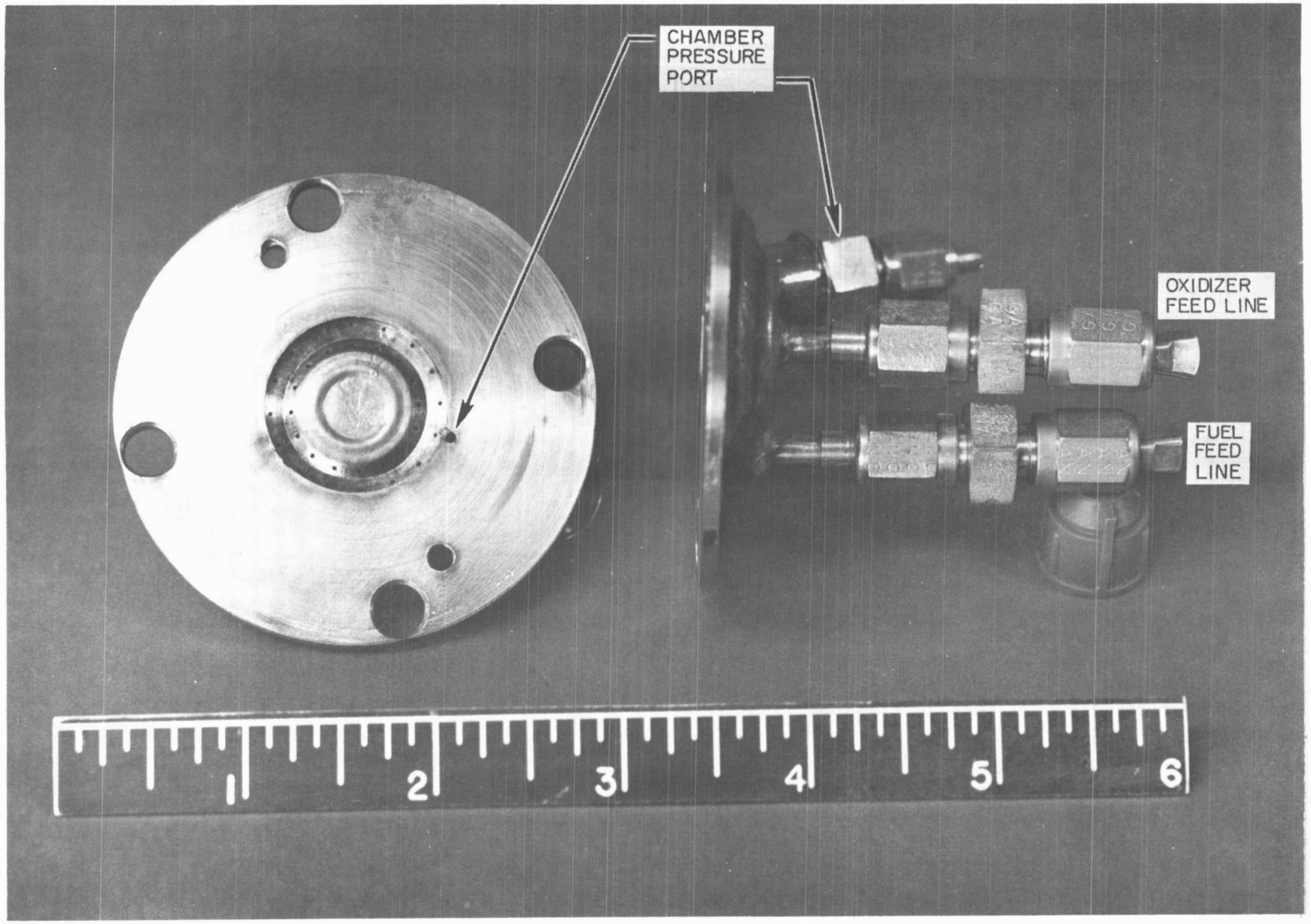


Figure 6. Sixteen Element Unlike Doublet Injector without Attached Splash Plate

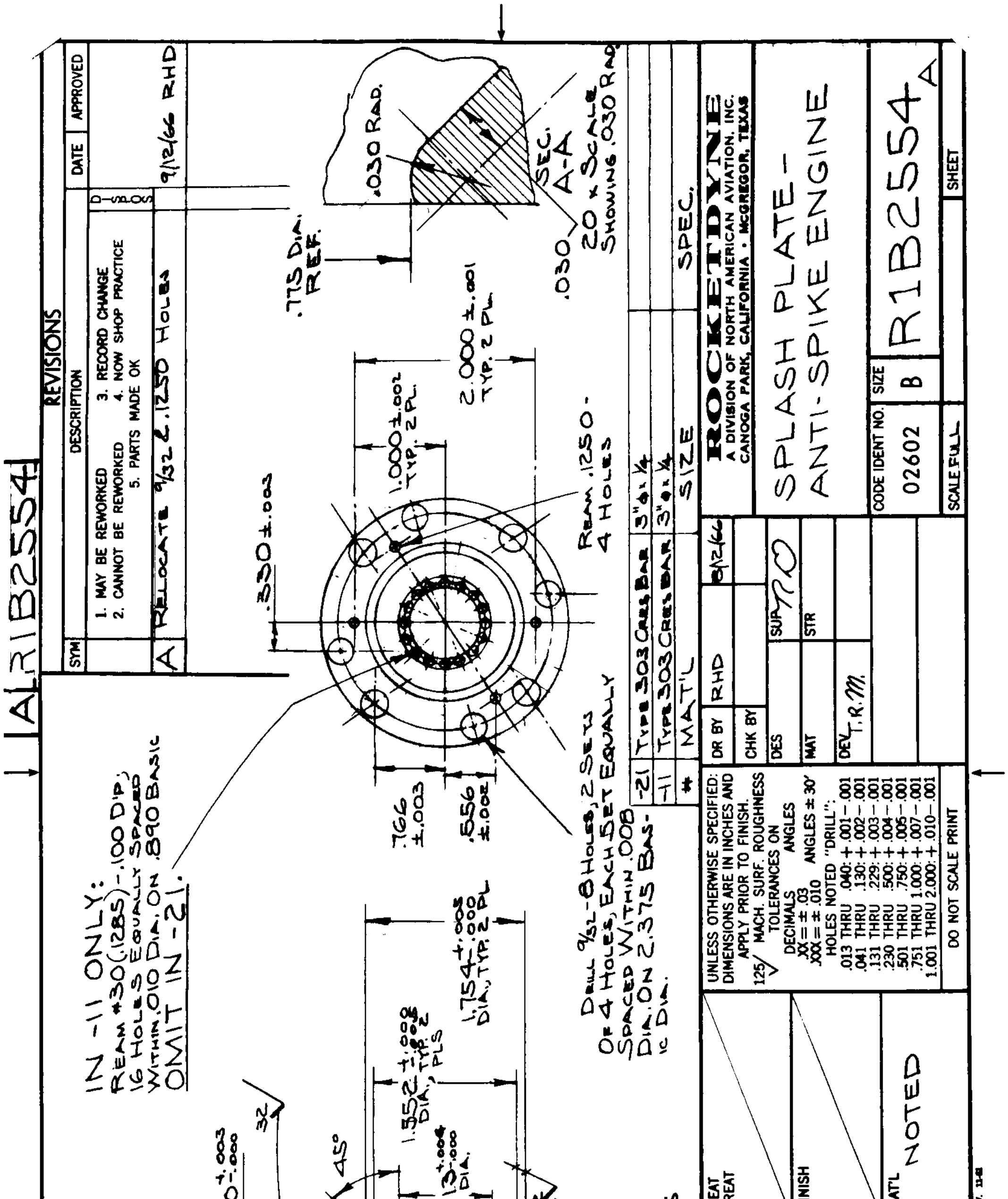
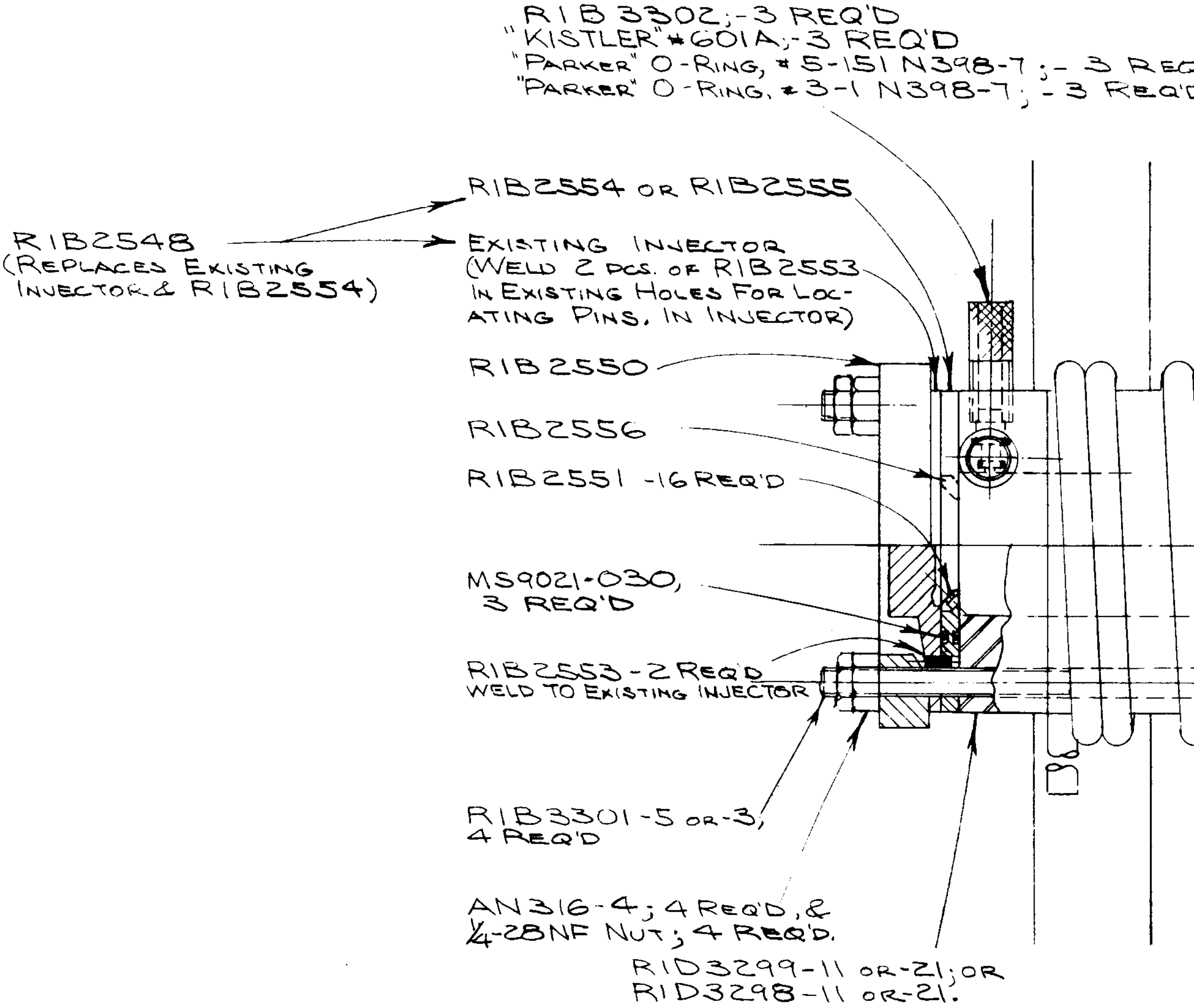


Figure 7. Splash Plate Used for Adhesively Bonded Pellets



HEAT TREAT

FINISH

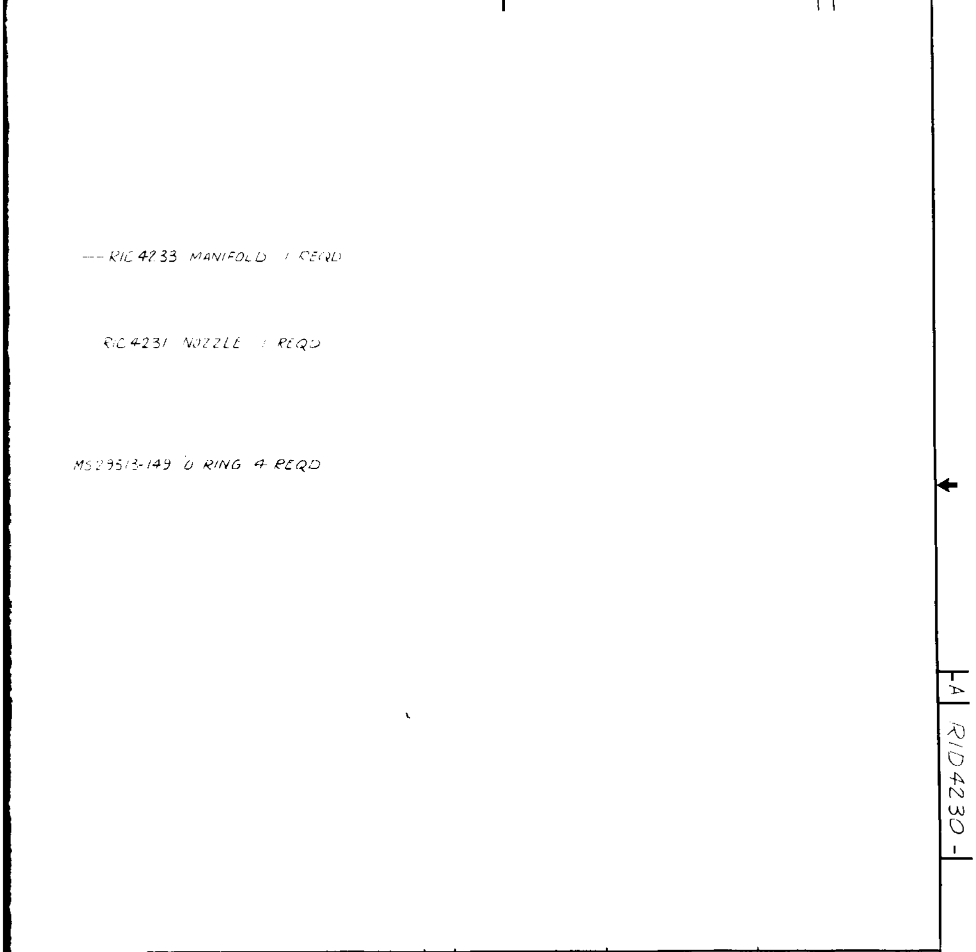
MAT'L

1. WELD PER RA0107-027, CLASS 2,

NOTE: UNLESS OTHERWISE SPECIFIED

FOLDOUT FRAME 1

SYM	DESCRIPTION	DISPOS	DATE	APPROVED
	1 MAY BE REWORKED 3. RECORD CHANGE 2. CANNOT BE REWORKED 4. NOW SHOP PRACTICE 5. PARTS MADE OK			
A	1 REMOVED M.9021 "O" RINGS 2 ADDED BRAZE NOTES		9/15/66	K.S. AU

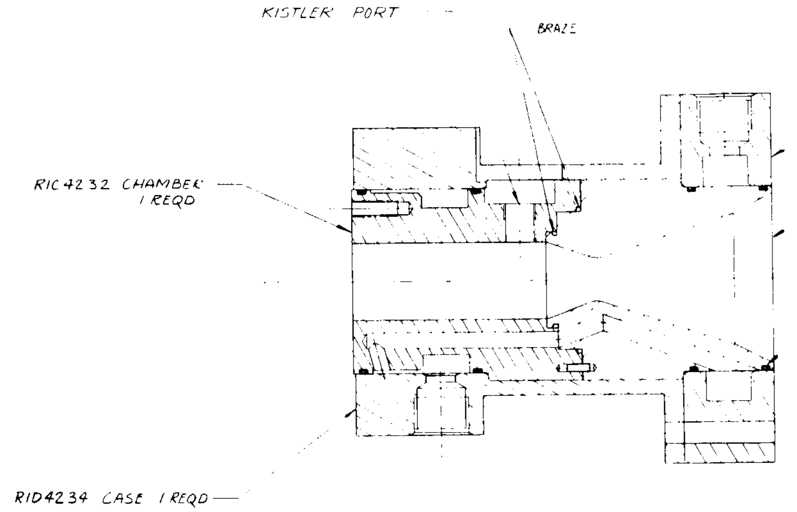


HEAT TREAT	UNLESS OTHERWISE SPECIFIED. DIMENSIONS ARE IN INCHES AND APPLY PRIOR TO FINISH. 125√ MACH SURF ROUGHNESS	DR BY K.S. AU	ROCKETDYNE A DIVISION OF NORTH AMERICAN AVIATION, INC. CANOGA PARK, CALIFORNIA - McGREGOR, TEXAS
FINISH	TOLERANCES ON DECIMALS ANGLES .XX = ± .03 .XXX = ± .010 ANGLES ± 30'	CHK BY	ANTI-SPIKE ENGINE WATER COOLED
MAT'L	HOLES NOTED "DRILL": .000 THRU .040 + .0015 .001 .041 THRU .130 + .003 .001 .131 THRU .229 + .0045 .001 .230 THRU .500 + .006 .002 .501 THRU .750 + .007 .002 .751 THRU 1.000 + .009 .001 1.001 THRU 2.000 + .012 .001	DES / SUP MAT / STR DEV	CODE IDENT NO. 02602 SIZE D RID4230
	DO NOT SCALE PRINT		SCALE 1/1 SHEET

FORM NO. 606-A-3 REV. 3-63

Figure 5. Anti-Spike Engine (Water Cooled)

FOLDOUT FRAME 2



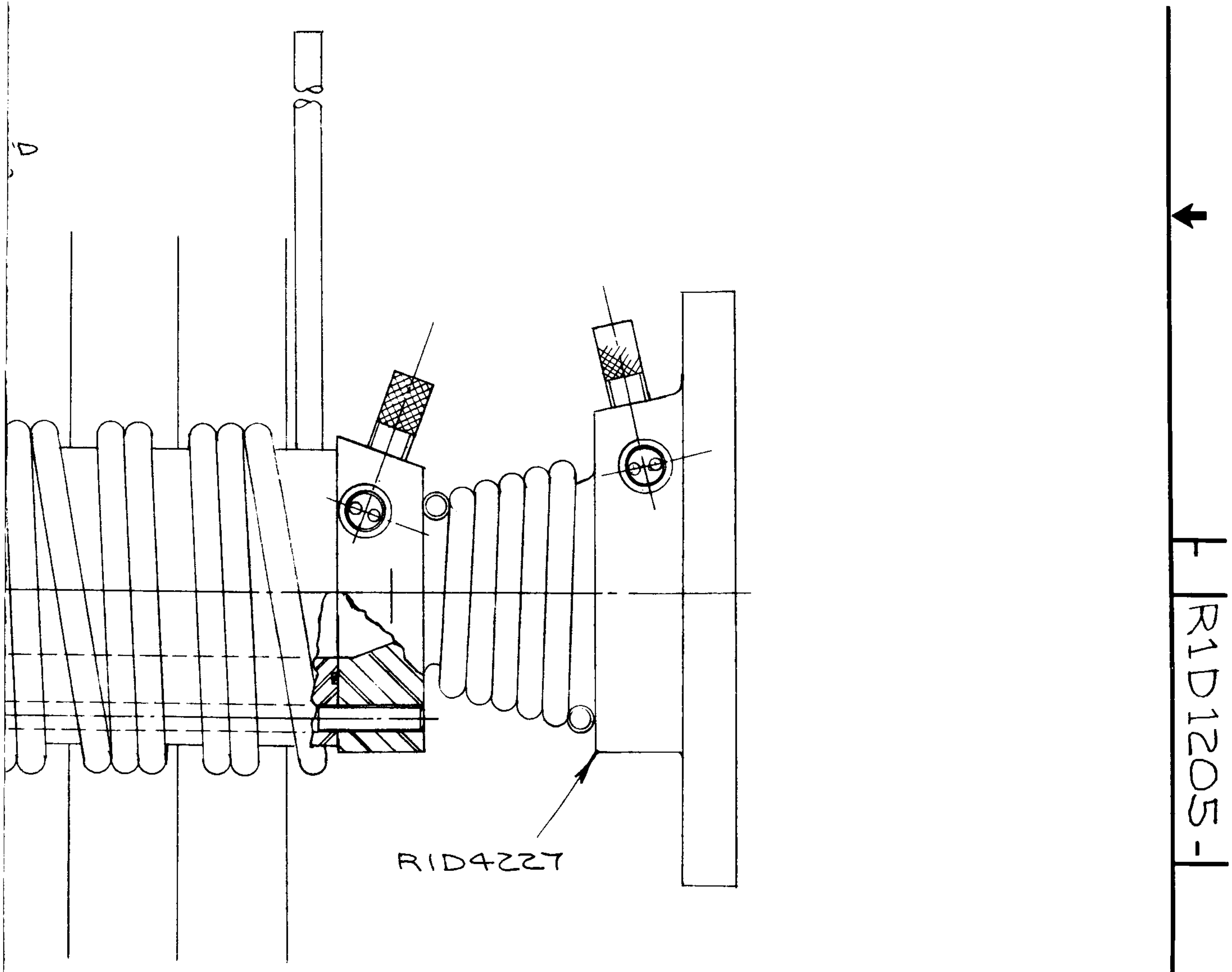
3 BRAZE ALLOY NO. 7
2 BRAZE PER RA0107 009
1. USE KISTLER PRES [illegible]

NOTE: UNLESS OTHERWISE SPEC

DIETZGEN CLEARPRINT

FOLDOUT FRAME

ROCKETDYNE • A DIVISION OF NORTH AMERICAN AVIATION, INC.



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES AND APPLY PRIOR TO FINISH.

125/ MACH. SURF. ROUGHNESS

TOLERANCES ON

DECIMALS	ANGLES
.XX = ± .03	ANGLES ± 30'
.XXX = ± .010	

HOLES NOTED "DRILL":

.000 THRU .040:	+.0015	−.001
.041 THRU .130:	+.003	−.001
.131 THRU .229:	+.0045	−.001
.230 THRU .500:	+.006	−.001
.501 THRU .750:	+.007	−.001
.751 THRU 1.000:	+.009	−.001
1.001 THRU 2.000:	+.012	−.001

DO NOT SCALE PRINT

DR BY	RHD		8/23/66
CHK BY			
DES		SUP TRD	
MAT		STR	
DEV T.R.M.			

ROCKETDYNE
A DIVISION OF NORTH AMERICAN AVIATION, INC.
CANOGA PARK, CALIFORNIA • McGREGOR, TEXAS

ANTI-SPIKE
ENGINE

CODE IDENT NO.	SIZE	
02602	D	R1D1205
SCALE Full		SHEET

FORM NO. 606-A-3 REV. 3-66

Figure 4. Anti-Spike Engine Schematic

FOLDOUT FRAME 2

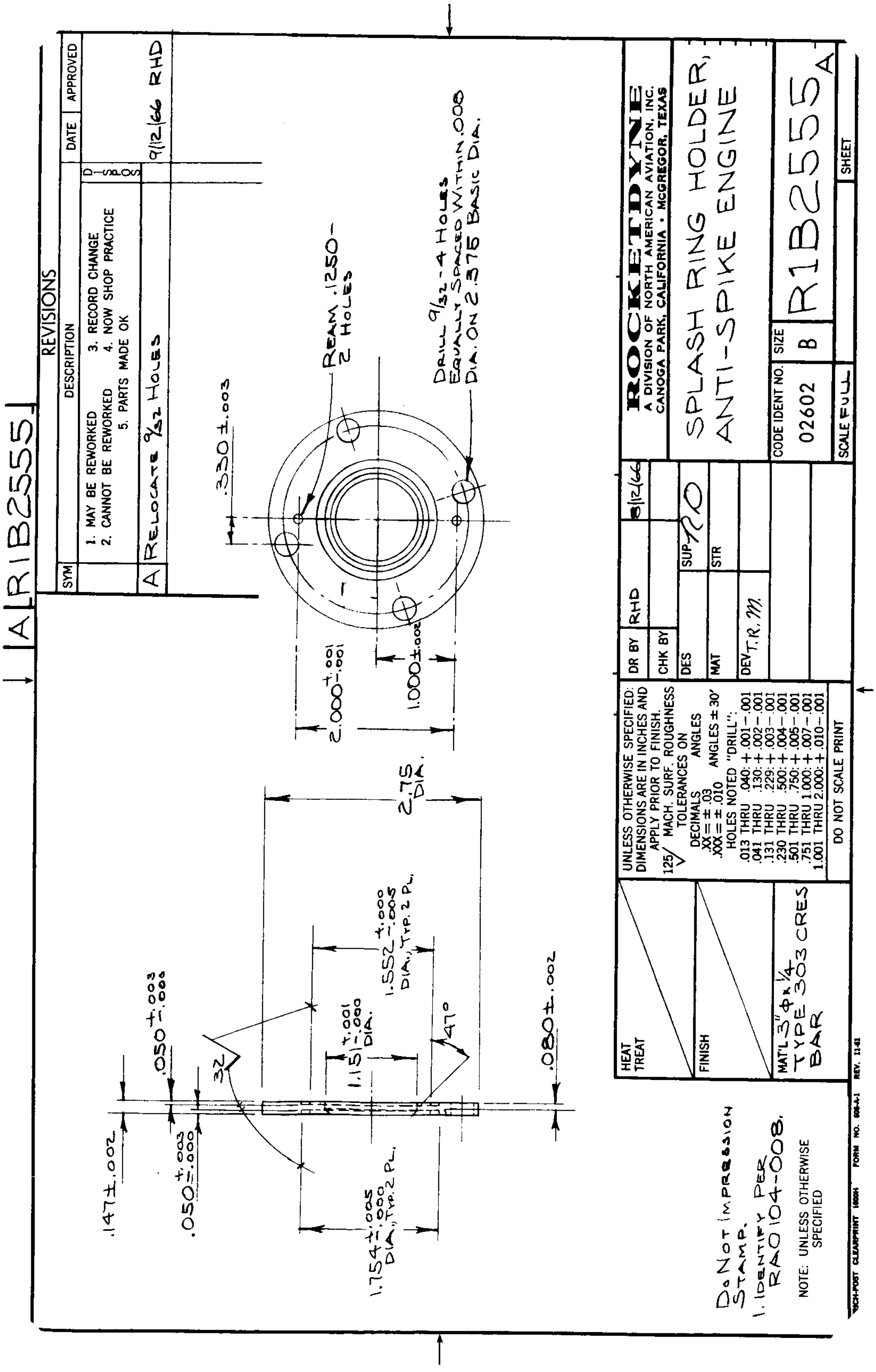


Figure 8. Splash Plate Used for Mechanically Bonded Pellets--Ring Holder

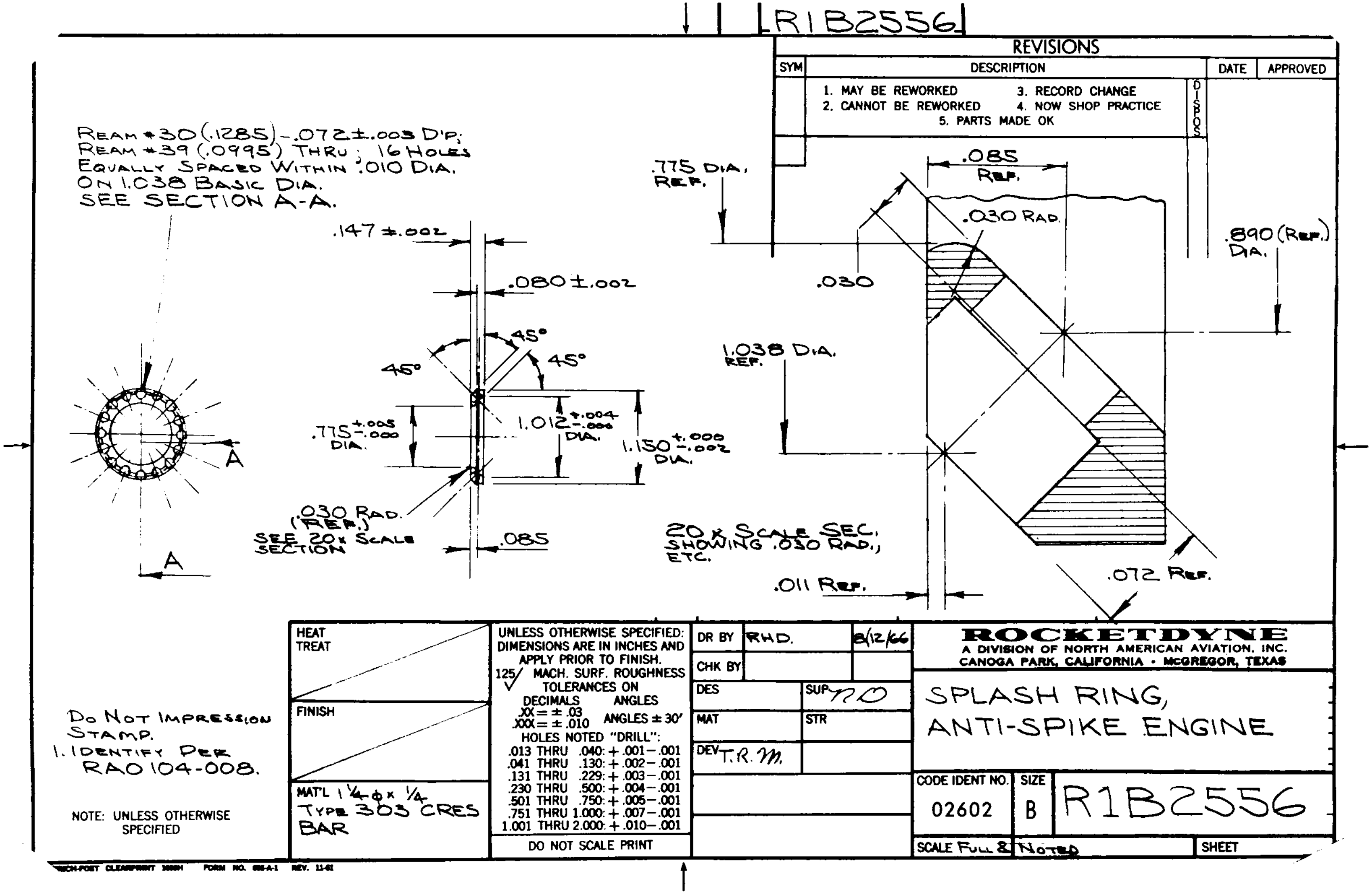


Figure 9. Splash Plate Used for Mechanically Bonded Pellets--Ring Insert

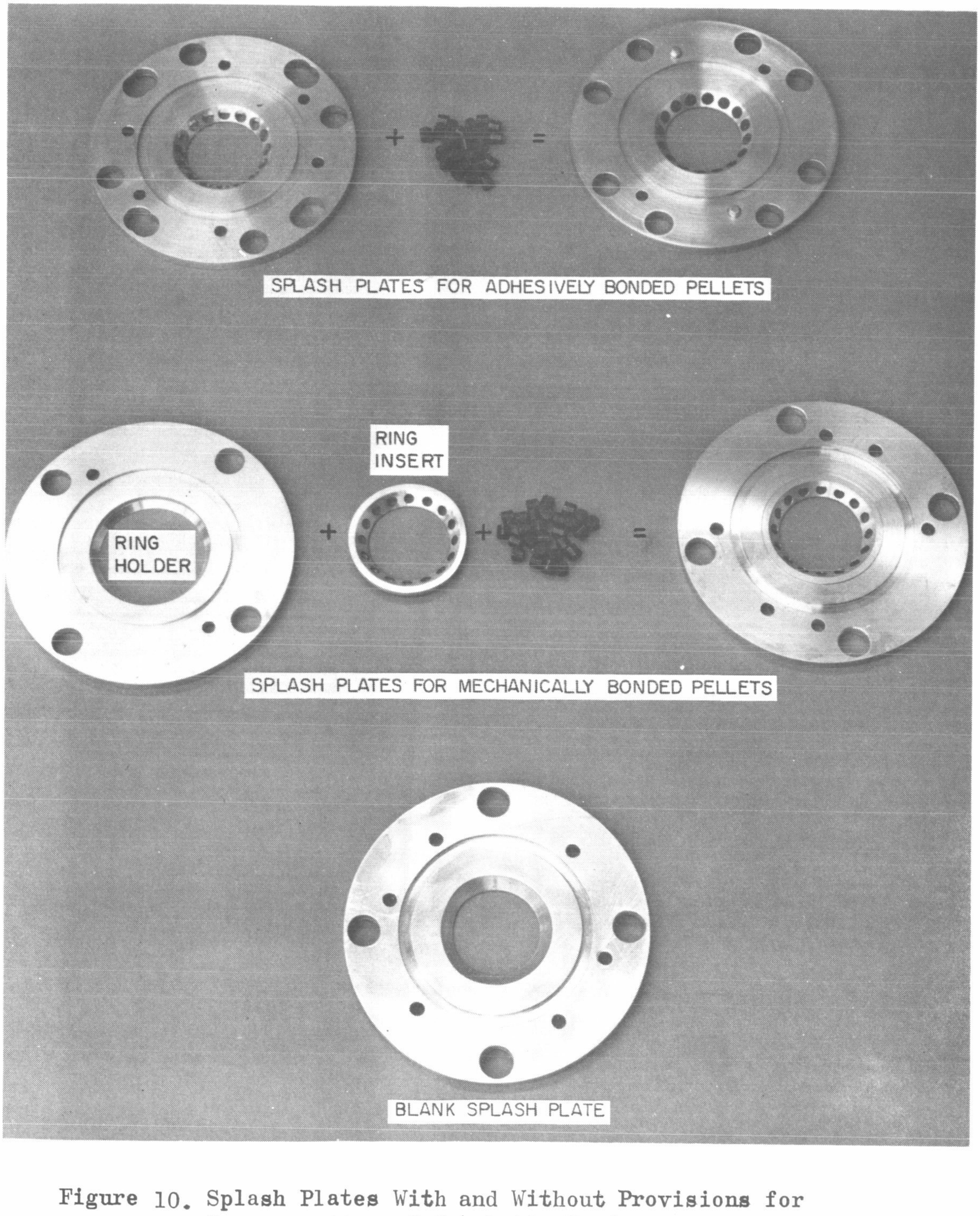


Figure 10. Splash Plates With and Without Provisions for Incorporation of Catalytic Surfaces

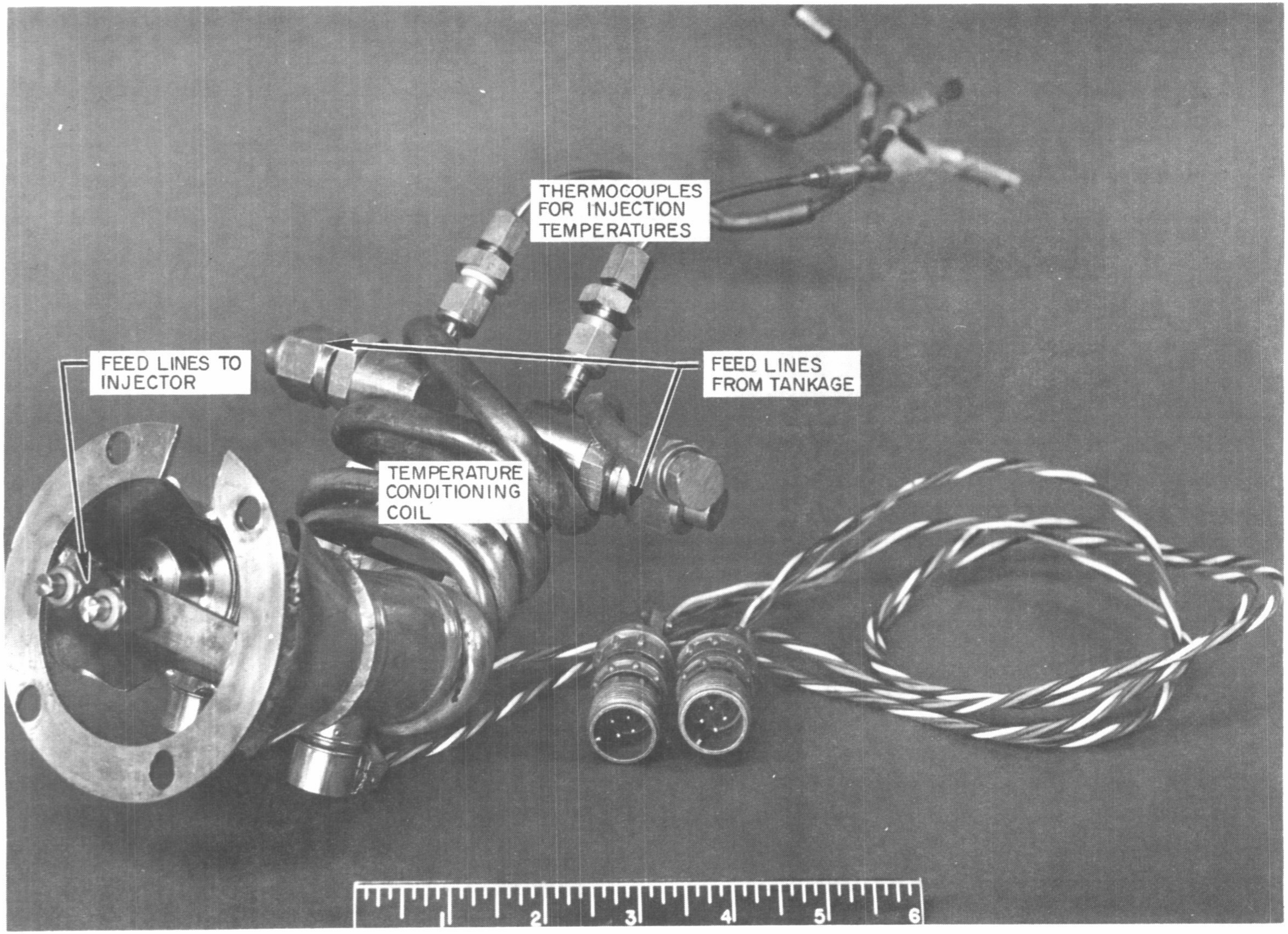


Figure 11. Main Propellant Valves—Solenoid Valves From an Apollo Command Module RCS Engine

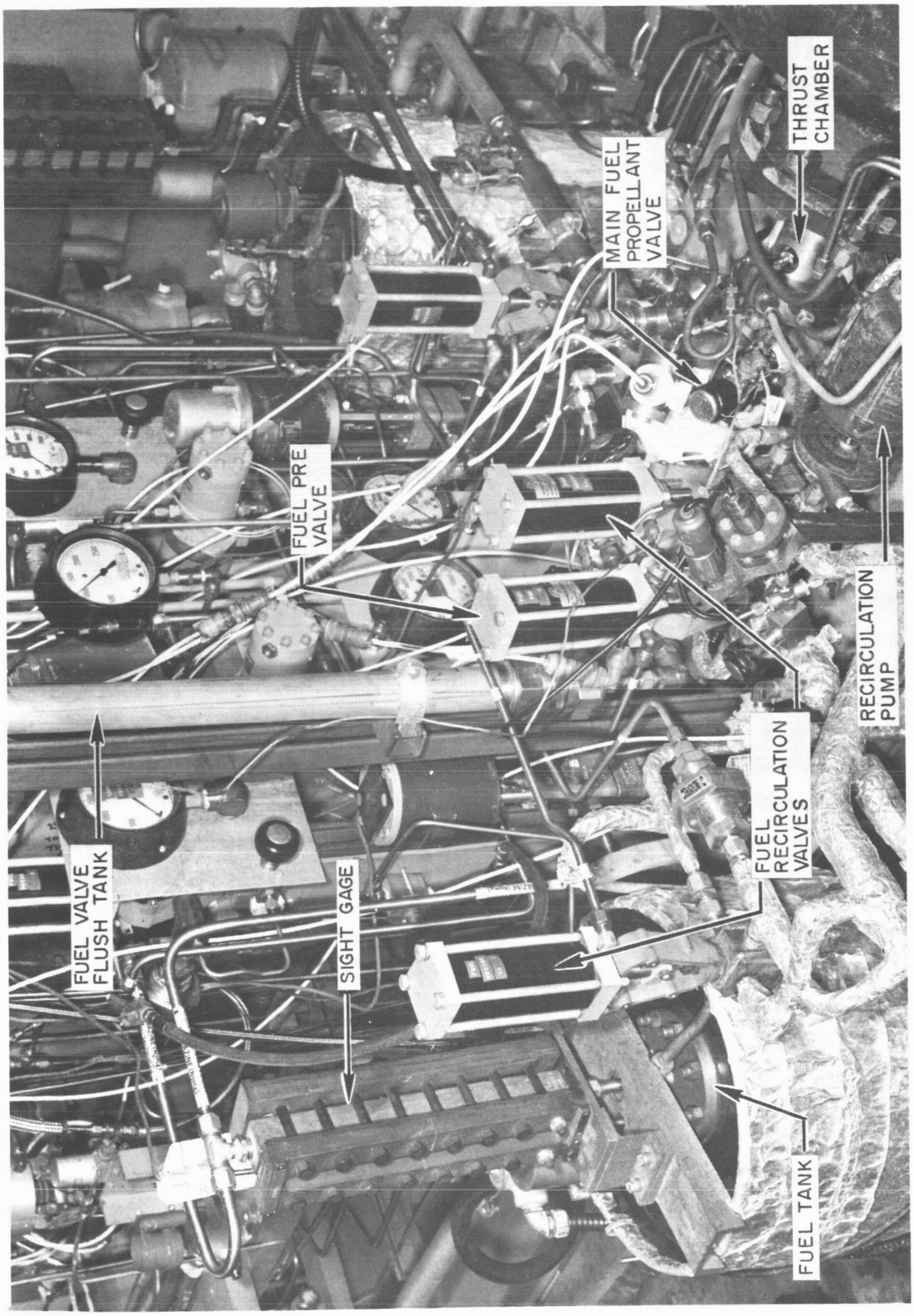


Figure 12. Propellant Feed Systems and Test Stand

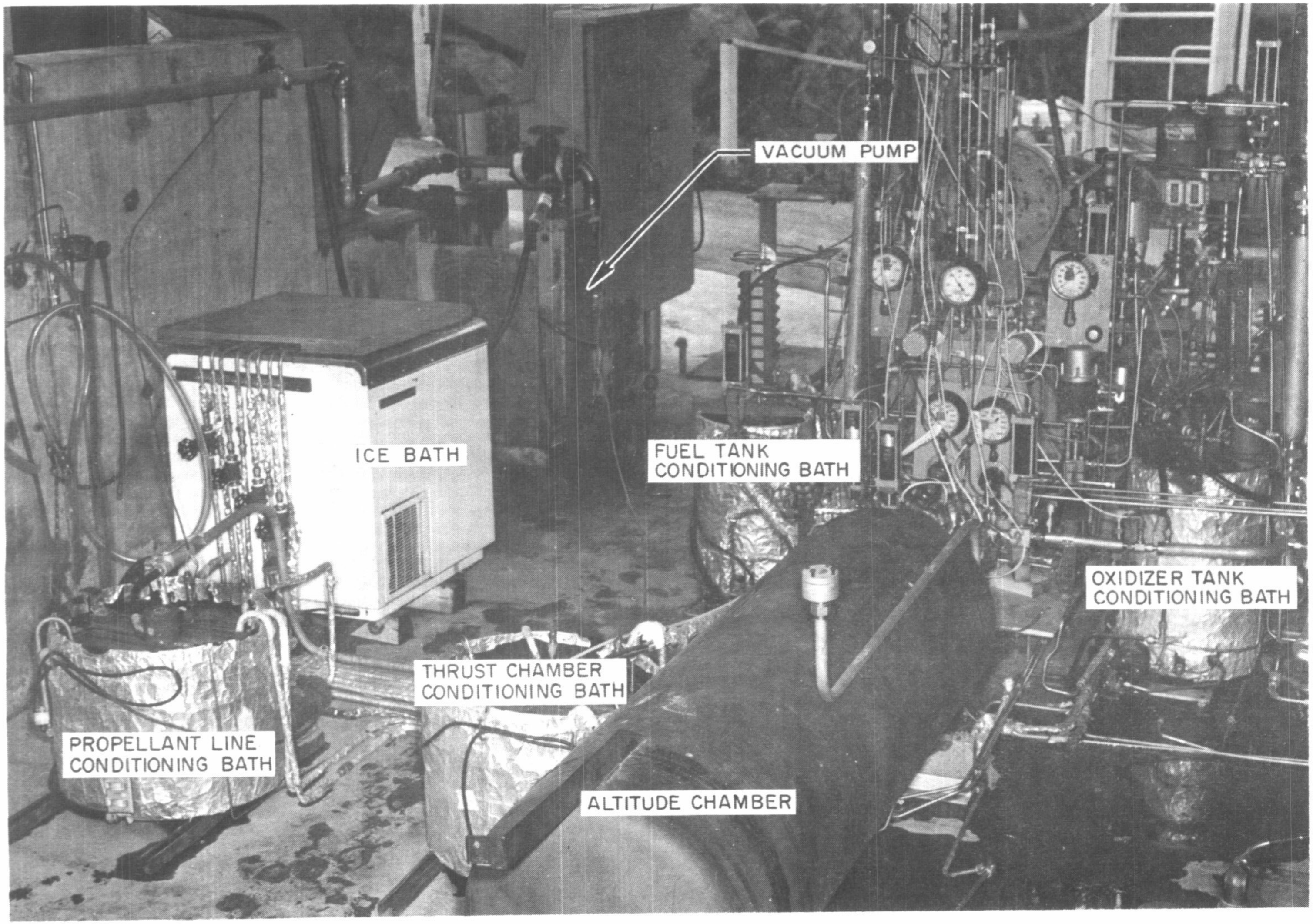


Figure 13. Conditioning System, Vacuum System and Chamber, and Test Stand

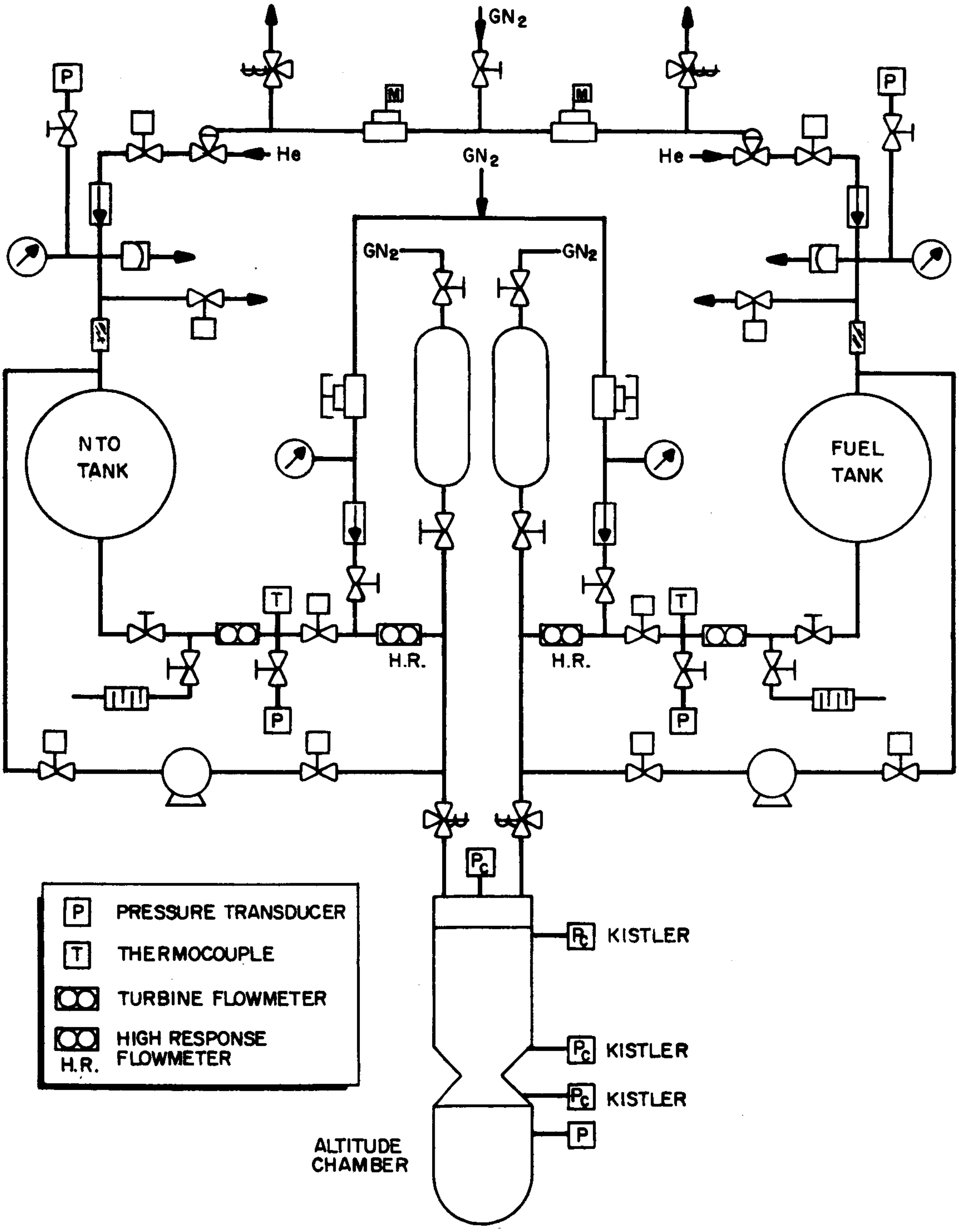


Figure 14. Schematic Representation of the Propellant Feed Systems and Test Engine Used for N_2O_4/Hydrazine-Type Fuel Tests

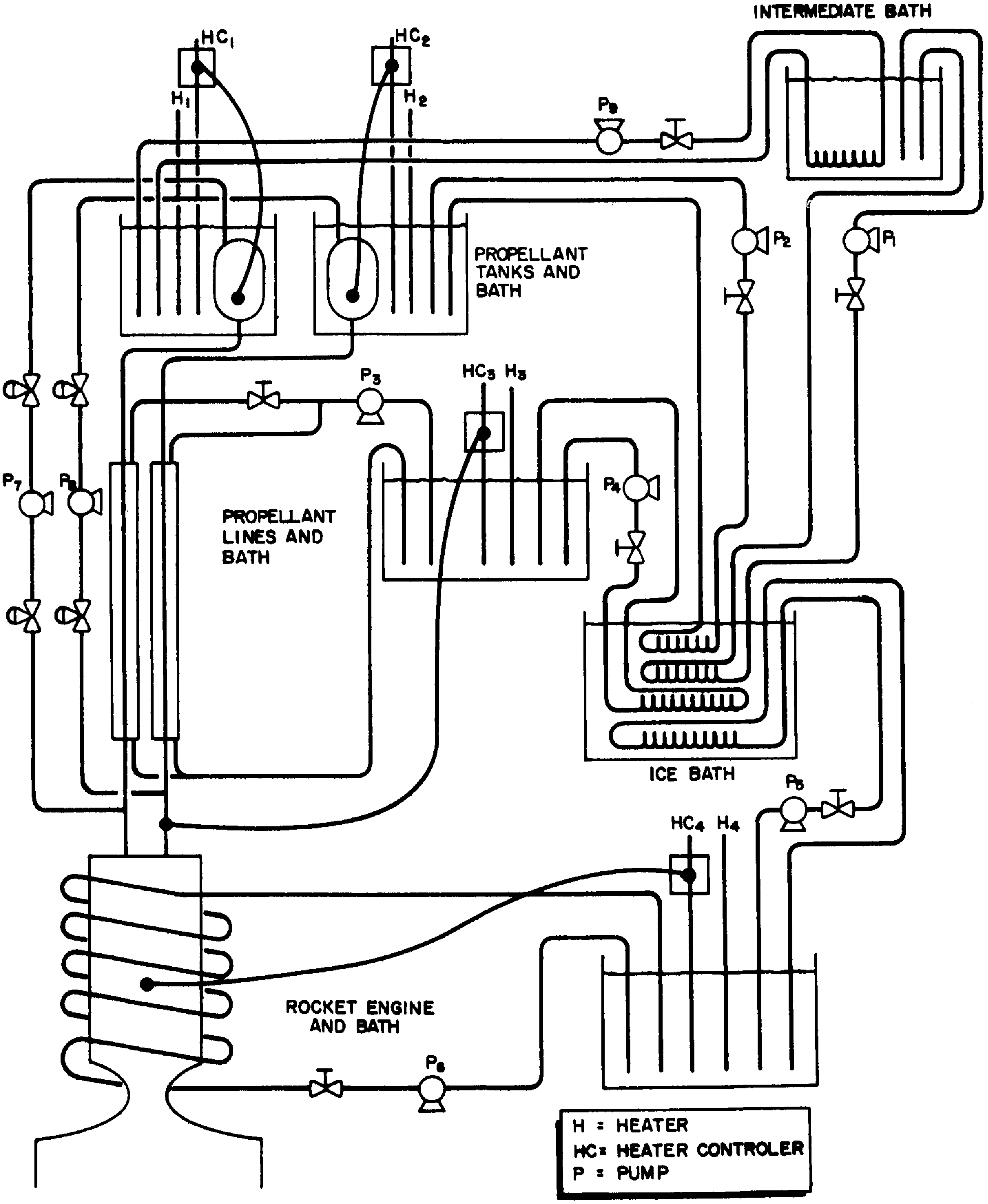
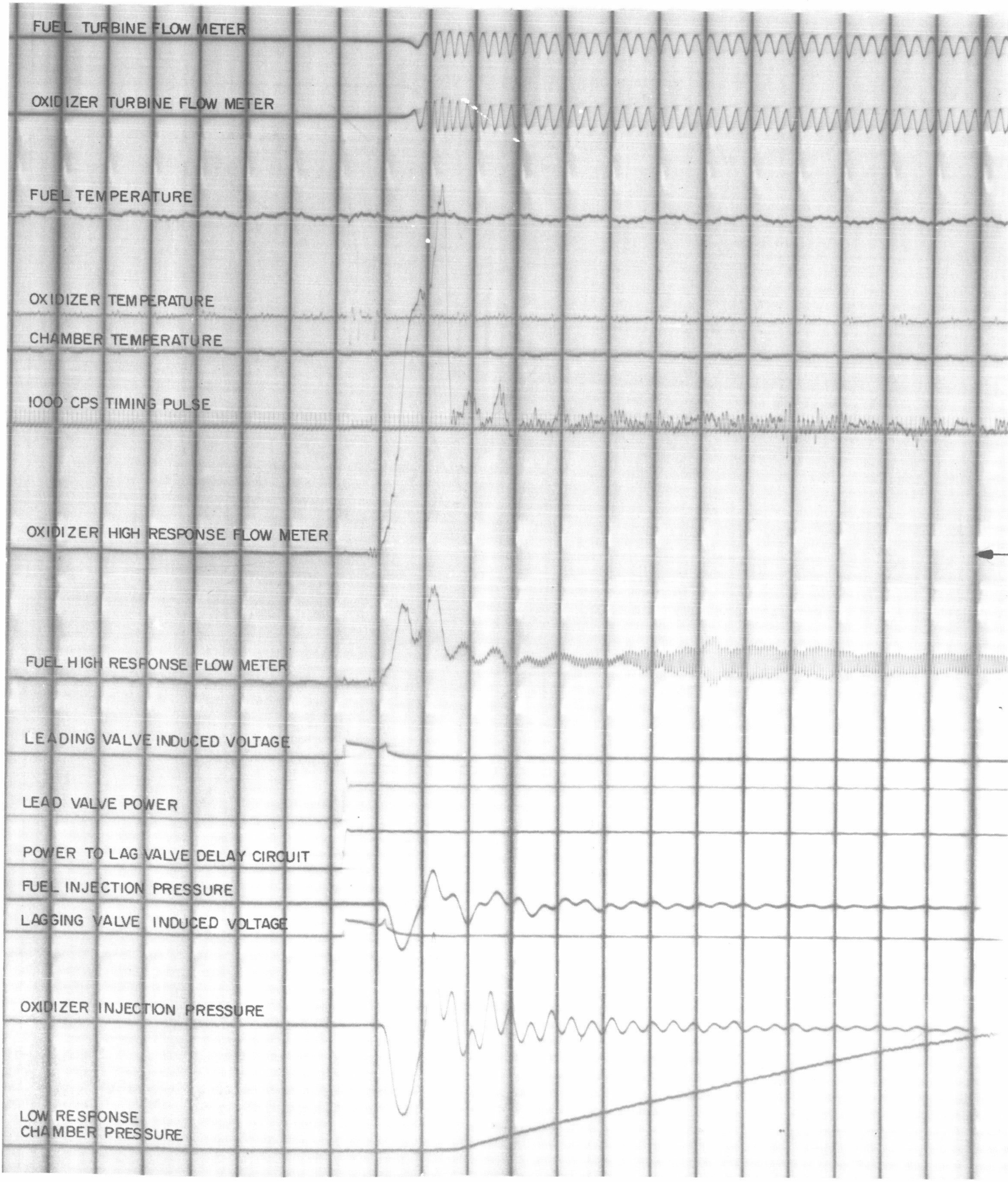
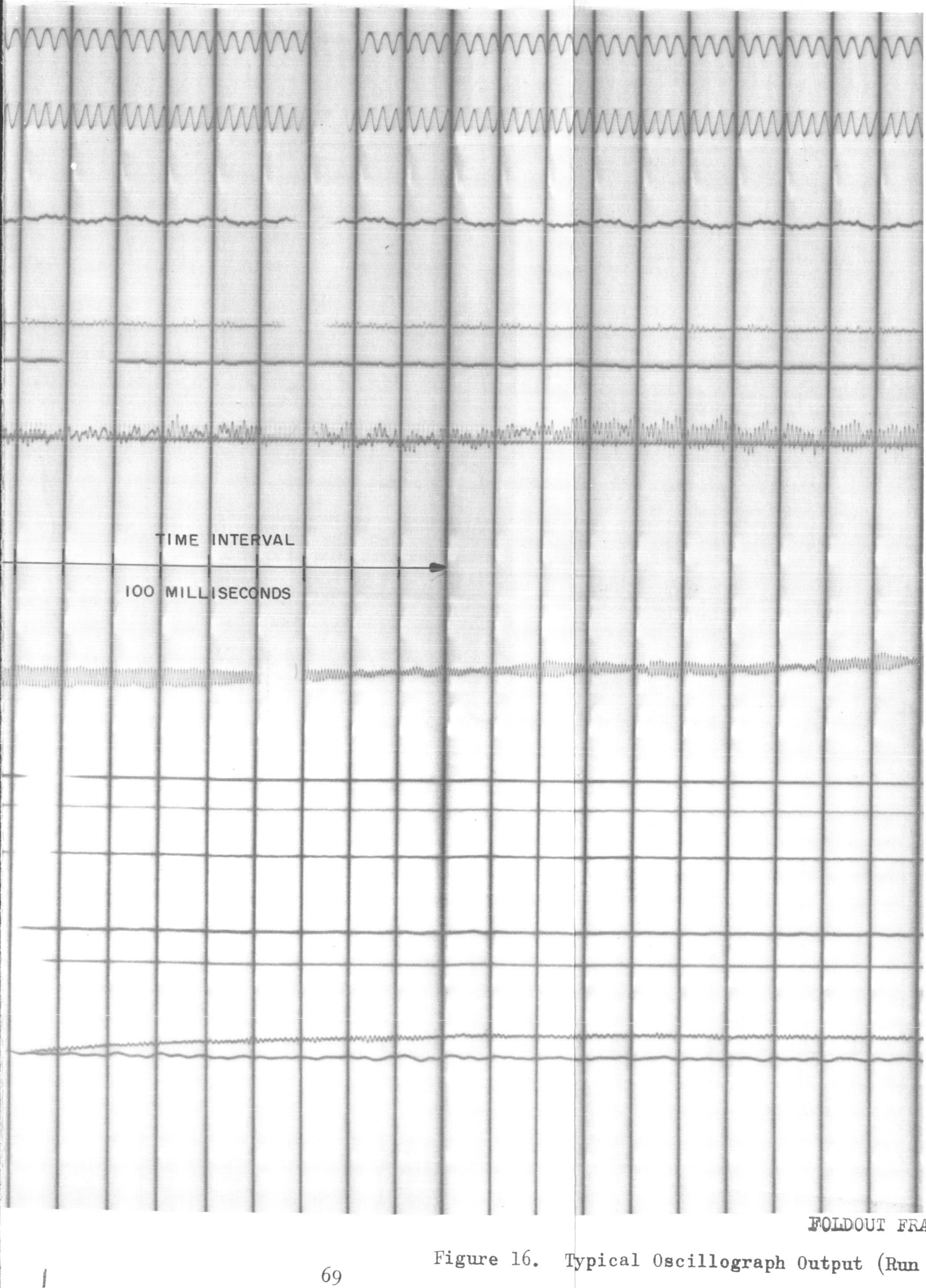


Figure 15. Schematic Representation of the Temperature Conditioning System



FOLDOUT FRAME 1



FOLDOUT FRAME 2

Figure 16. Typical Oscillograph Output (Run 94)

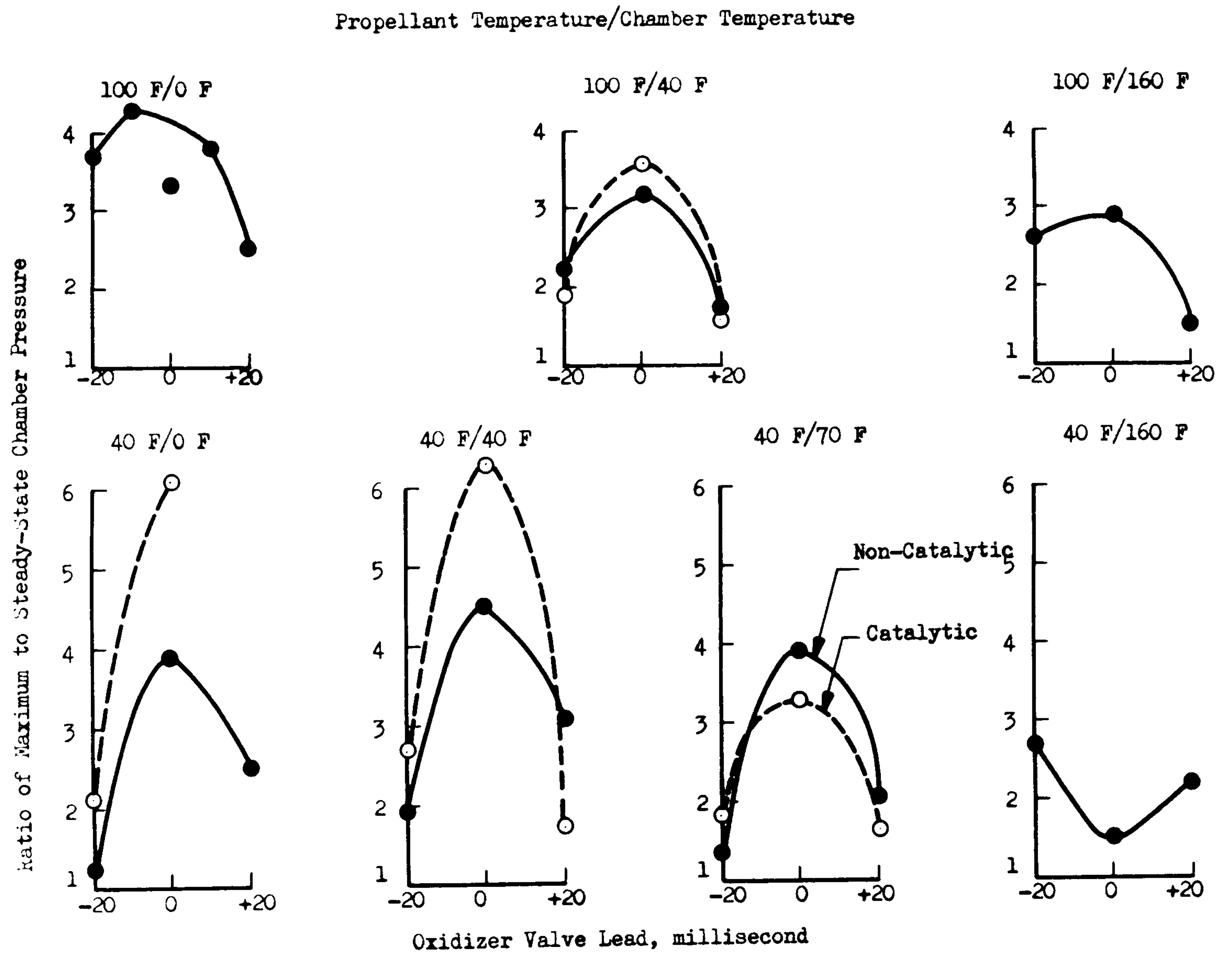


Figure 17. Effect of Oxidizer Valve Lead on Average Spiking Ratio for N_2O_4/MMH Propellants at Various Propellant Temperature/Chamber Temperature Combinations

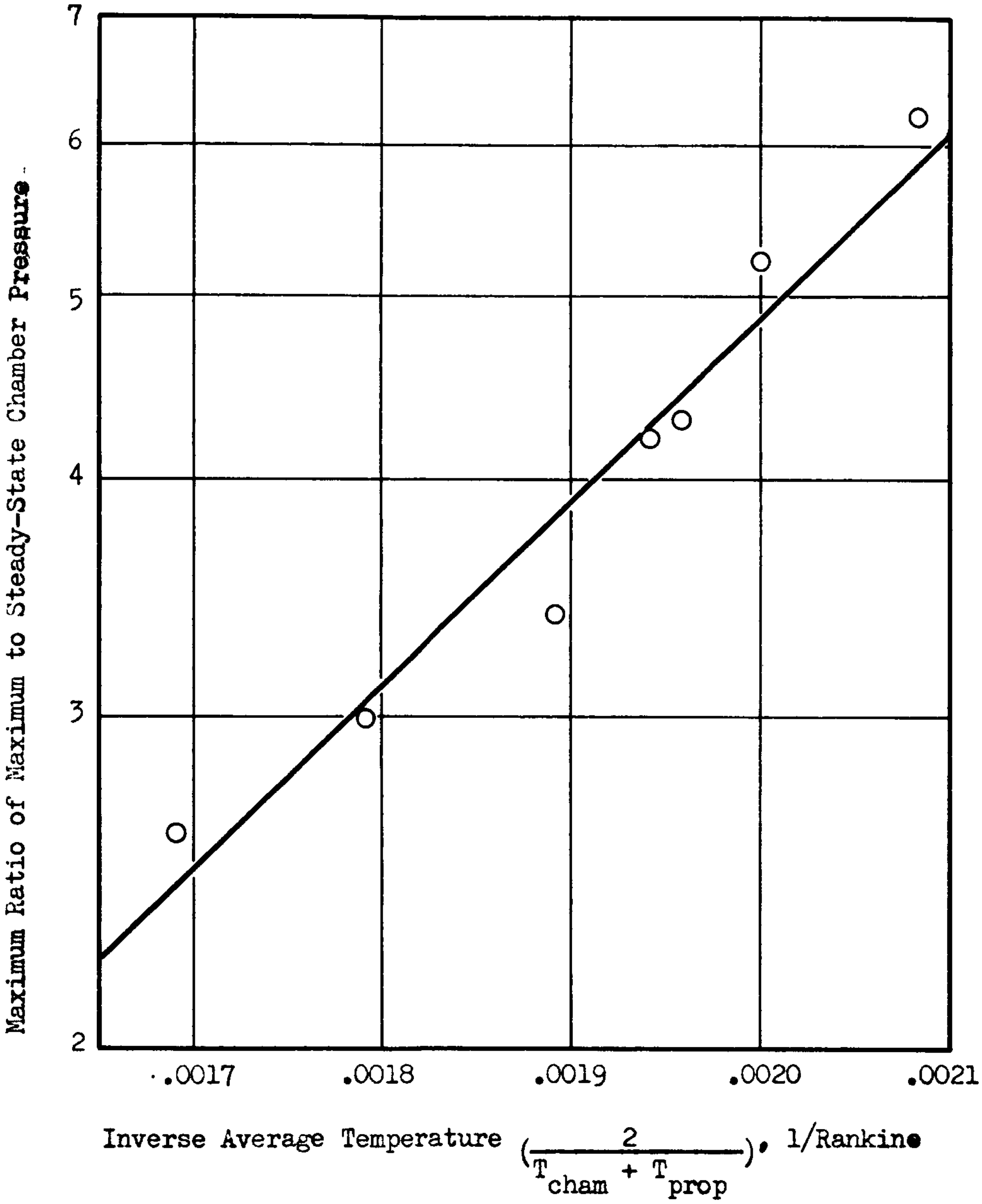
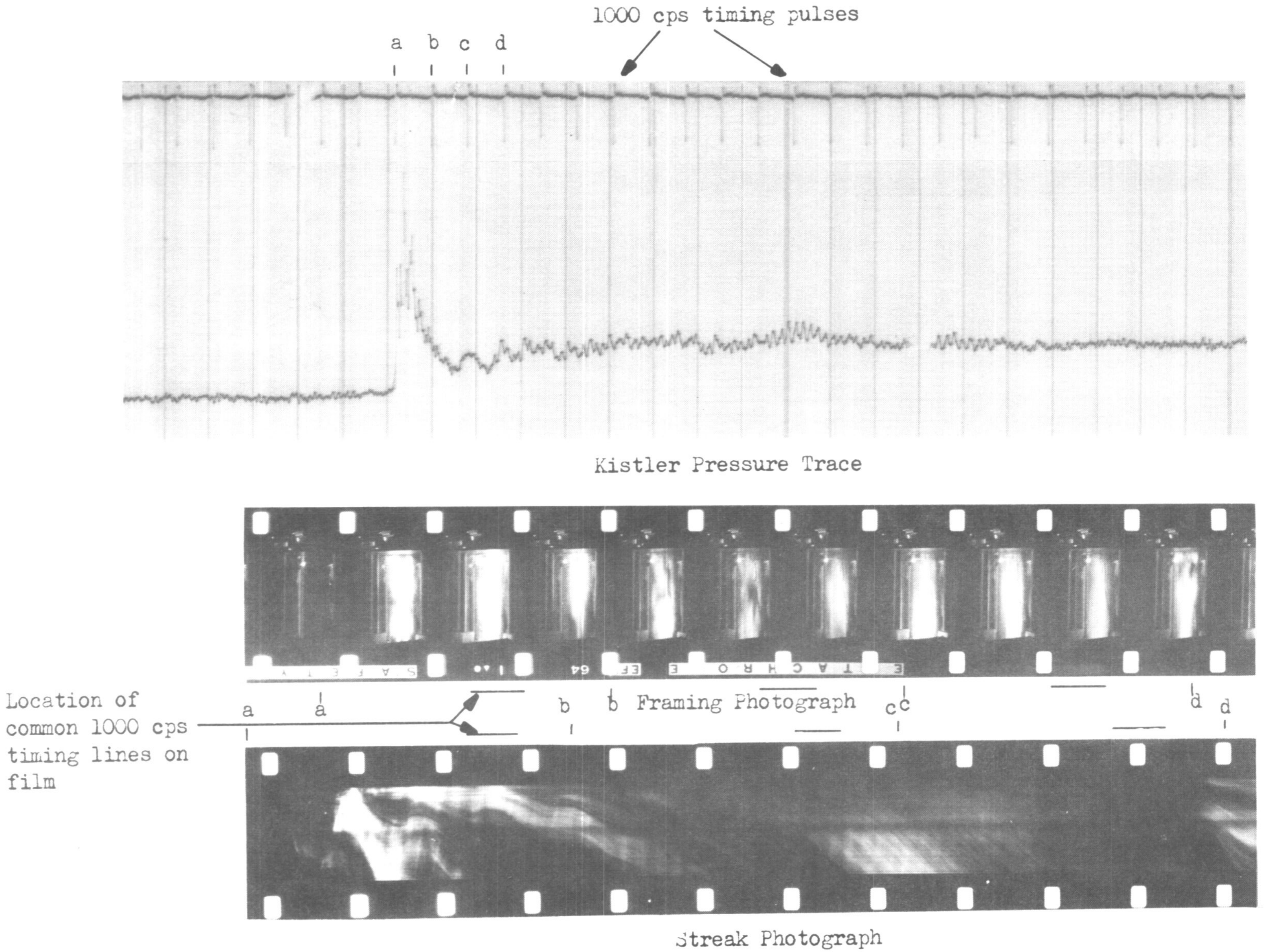


Figure 18. The Effect of Temperature on the Maximum Spiking Ratio for N_2O_4/MMH Propellants and Blank (Unmodified) Splash Plate Configuration



(Timing light in camera was located exactly 5 frames away from point of focus of image on film. Taking that into account, points a, b, c, and d were established as corresponding to simultaneous times.)

Figure 19. Typical Streak, Framing, and Kistler Pressure Traces (Run 77)

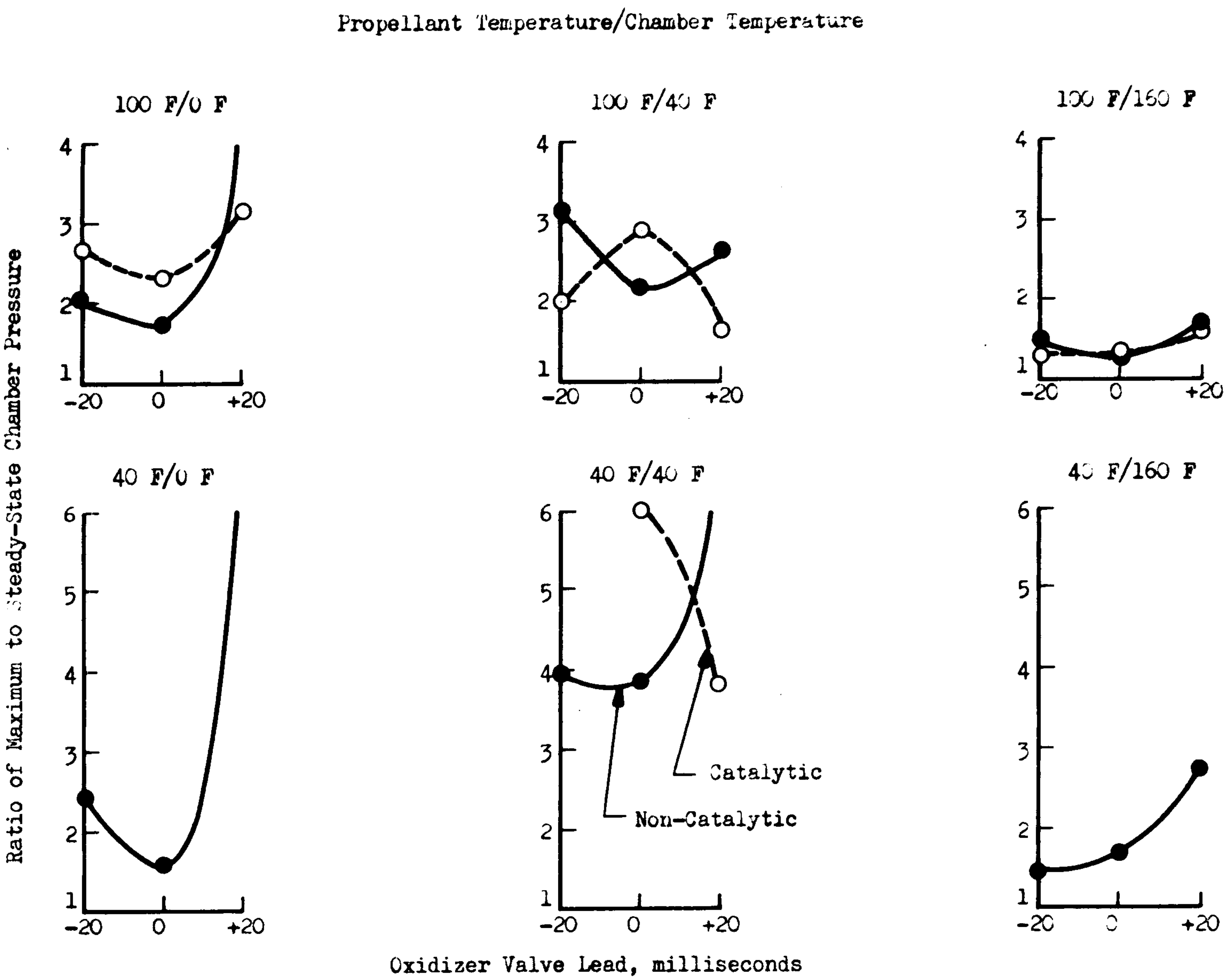


Figure 20. Effect of Oxidizer Valve Lead on Average Spiking Ratio for N_2O_4/50-50 Propellants at Various Propellant Temperature/Chamber Temperature Combinations

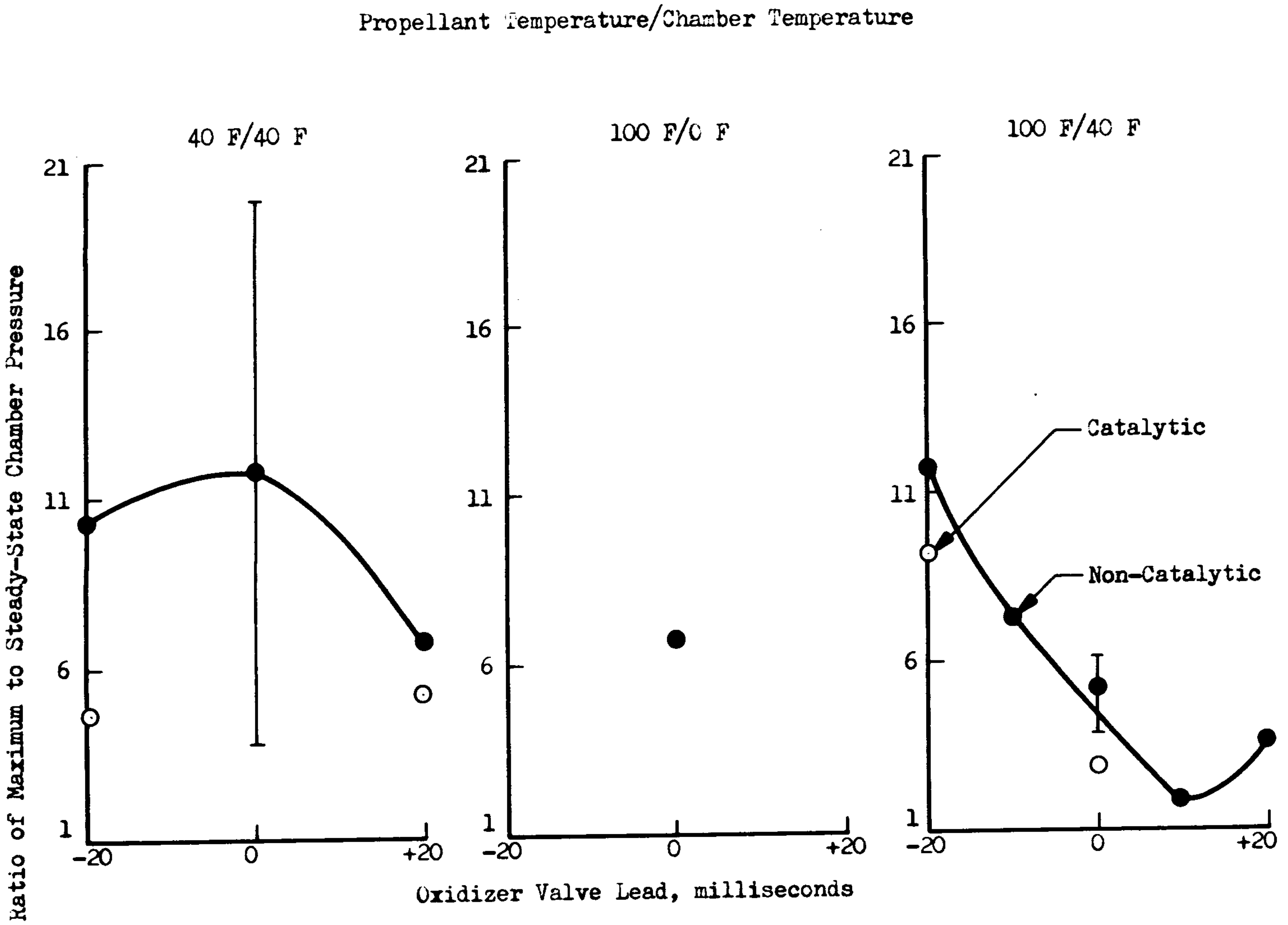


Figure 21. Effect of Oxidizer Valve Lead on Average Spiking Ratio for N_2O_4/N_2H_4 Propellants at Various Propellant Temperature/Chamber Temperature Conditions

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7. AFRPL-TR-65-105, "Hypergolic Ignition at Reduced Pressures," by A. D. Corbett, B. E. Dawson, T. G. Seamans, Thiokol Chemical Corporation, RMD, Denville, New Jersey, Contract AF04(t11)-9946, July 1965, CONFIDENTIAL.

8. AFRPL-TR-65-257, "Hypergolic Ignition at Reduced Pressures," by A. D. Corbett, B. E. Dawson, T. F. Seamans, M. M. Vanpee, Thiokol Chemical Corporation, RMD, Denville, New Jersey, Contract AF04(611)-9946, CONFIDENTIAL.

9. S-13864, "Development of Catalysts for Monopropellant Decomposition of Hydrazine, Part I-Engineering Calculations" (U) Contract NAS7-97, Final Report, January-September, 1962, Shell Development Company, Emeryville, California, CONFIDENTIAL.

10. S-13864, "Development of Catalysts for Monopropellant Decomposition of Hydrazine, Part II-Engineering Calculations" (U) Contract NAS7-97, Final Report, January-September, 1962, Shell Development Company, Emeryville, California, CONFIDENTIAL.

11. S-13947, "Development of Catalysts for Monopropellant Decomposition of Hydrazine" (U), Contract NAS7-97, Final Report April-December, 1964, Shell Development Company, Emeryville, California, CONFIDENTIAL.

APPENDIX A

TEST DATA

Summaries of the N_2O_4/MMH, N_2O_4/50 wt. % N_2H_4-50 wt. % UDMH, and N_2O_4/N_2H_4 firings are presented in TablesA-1 through A-3, respectively. For these tables the following definitions are applicable.

Oxidizer lead is defined as the time between full opening of the oxidizer and fuel main valves as monitored by the induced voltage in a secondary coil in close proximity to the valve solenoid. The monitored voltage was recorded and read from a galvanometer oscillograph. A + indicates an oxidizer lead and a - indicates a fuel lead.

Oxidizer, fuel, and chamber temperature are pretest temperatures monitored and read from a Leeds and Northrup millivolt potentiometer.

Altitude is defined as the pretest pressure in the altitude chamber monitored and read from the Baratron system.

P_{spike}/P_c is the ratio of the maximum pressure reached during ignition to the steady-state pressure as monitored by the Kistler pressure transducer, recorded on tape, and read from a galvanometer oscillograph playback of the tape.

Ignition delay is the time between the lagging valve full open position and first indications of chamber pressure. The time between the leading valve full open position and the Kistler's indication of chamber pressure was read from the oscilloscope photograph; the ignition delay was determined by subtracting the oxidizer lead time from the time between the leading valve full open position and the Kistler's indication of chamber pressure.

The following notations were used:

φ	Data not available due to lack of instrumentation
*	Data not available due to system malfunction
**	Data not available due to instrumentation malfunction
Amb	Ambient pressure (approximately 13.7 psia)
B	Blank Splash Plate
C-1	Pellets cemented in place by Eccoceram QC adhesive
C-2	Pellets cemented in place by Sauereisen (#29 Filler and Binder)
C-3	Pellets mechanically held in place
C-4	Pellets cemented in place by Eccoceram QC adhesive
C-5	Pellets cemented in place by Eccoceram QC adhesive
C-6	Pellets cemented in place by Eccoceram QC adhesive
C-7	Pellets cemented in place by Eccoceram QC adhesive
C-8	Pellets cemented in place by Eccoceram QC adhesive
C-9	Pellets cemented in place by Eccoceram QC adhesive
C-10	Pellets cemented in place by Eccoceram QC adhesive
C-11	Pellets cemented in place by Eccoceram QC adhesive
C-12	Pellets cemented in place by Eccoceram QC adhesive

For tests No. 12 through 75, the temperature conditionable chamber was employed. P_1 was located near the injector; P_2 was located just upstream of the converging section.

For tests No. 76 through 85 the transparent chambers were used. The Kistler tap was located near the injector.

For all other tests the water-cooled chamber was used. For that chamber the Kistler tap was located upstream of the converging section.

TABLE A-1

SUMMARY OF N_2O_4/MMH TEST DATA

Test Number	Total Propellant Flowrate, lb/sec	Mixture Ratio	Chamber Pressure, psia	Oxidizer Lead, msecs	Oxidizer Temperature F	Fuel Temperature F	Chamber Temperature F	Splash Plate	Altitude, mm Hg	$\frac{P_{spike}}{P_c}$ (Position 1)	$\frac{P_{spike}}{P_c}$ (Position 2)	Ignition Delay, msecs
1	φ	φ	160	+12	87	96	φ	B	Ambient	φ	1.23	φ
2	φ	φ	170	+19	89	100	φ	B	Ambient	φ	2.09	φ
3	φ	φ	147	+4	91	100	φ	B	Ambient	φ	1.52	φ
4	0.347	2.19	155	+14	89	98	φ	B	Ambient	φ	φ	φ
5	*											
6	0.349	2.14	153	+2	88	100	φ	B	Ambient	φ	φ	φ
7	0.382	2.14	167	+2	81	95	φ	B	Ambient	φ	φ	φ
8	0.333	2.30	145	+2	80	93	φ	B	Ambient	φ	φ	φ
9	0.344	2.03	154	+18	39	36	φ	B	Ambient	1.84	φ	φ
10	0.362	2.00	167	+18	32	42	φ	B	Ambient	1.66	φ	φ
11	0.323	2.02	145	+18	40	50	φ	B	Ambient	1.60	φ	φ
12	0.348	1.95	152	+19	39	40	37	B	0.8	φ	φ	φ
13	0.348	2.02	152	+18	37	37	32	B	1.0	φ	1.73	7
14	0.337	2.08	154	+22	38	37	38	B	0.8	2.03	2.31	8
15	0.338	2.07	150	-21	42	43	36	B	1.0	1.54	2.36	6
16	0.337	2.03	148	-22	46	45	37	B	0.9	2.32	2.70	φ
17	0.336	2.06	150	+0	44	45	37	B	0.9	5.24	φ	8
18	0.343	2.08	147	+21	42	43	40	B	1.0	2.88	φ	8
19	0.338	2.04	148	+1	39	39	39	B	0.9	3.68	φ	8
20	0.348	2.05	150	+22	42	44	1	B	0.8	1.19	1.31	φ
21	0.344	2.02	146	+21	41	42	0	B	1.0	3.26	φ	φ
22	0.346	2.04	147	+0	40	43	0	B	1.1	1.62	φ	7
23	**											
24	0.351	2.10	150	+0	40	42	4	B	0.8	6.21	6.21	10
25	0.350	2.07	147	-21	40	42	2	B	0.8	φ	φ	φ
26	0.354	2.10	147	-20	43	42	1	B	0.7	1.20	φ	4

TABLE A-1
(Continued)

Test Number	Total Propellant Flowrate, lb/sec	Mixture Ratio	Chamber Pressure, psia	Oxidizer Lead, msecs	Oxidizer Temperature F	Fuel Temperature F	Chamber Temperature F	Splash Plate	Altitude, mm Hg	$\frac{P_{spike}}{P_c}$ (Position 1)	$\frac{P_{spike}}{P_c}$ (Position 2)	Ignition Delay, msecs
27	0.357	2.10	146	+21	39	40	2	B	1.2	1.73	1.85	4
28	0.357	2.13	150	+22	39	40	43	C-1	1.1	1.32	1.38	10
29	0.354	2.10	148	+0	40	40	40	C-1	1.2	1.95	2.04	9
30	0.355	2.12	146	-21	40	41	42	C-1	1.0	3.68	4.50	6
31	0.353	2.07	145	+20	41	42	1	C-1	1.2	1.58	1.78	4
32	0.356	2.12	148	+0	42	42	1	C-1	1.0	8.29	12.39	10
33	0.357	2.13	146	+21	40	43	159	B	1.0	2.97	3.08	10
34	0.354	2.10	146	+0	41	43	160	B	1.0	1.54	2.82	0
35	0.355	2.08	144	-21	39	41	163	B	1.0	2.72		6
36	0.355	2.08	144	+20	44	45	164	B	1.0	1.38		8
37	0.361	2.16	149	+22	100	102	162	B	0.7	1.42	1.35	10
38	0.367	2.24	154	+2	98	98	163	B	1.0	1.59	3.05	8
39	0.365	2.23	152	-20	97	100	160	B	1.0	2.60		8
40	0.354	2.10	159	+22	101	104	161	B	0.9	1.64		8
41	0.355	2.08	147	+0	96	99	160	B	1.0	2.20		8
42	0.353	2.12	149	-0	98	99	165	B	1.0	2.02		8
43	*											
44	*											
45	0.358	2.12	148	+2	99	101	43	B	1.0	3.00	2.43	8
46	0.359	2.06	140	+21	100	101	36	B	1.1	1.53		8
47	0.358	2.08	146	-21	100	101	38	B	1.0	2.50		7
48	0.365	2.14	145	+21	106	107	43	B	1.0	0		5
49	0.360	2.10	143	+22	99	100	46	B	0.8	1.83		8
50	0.357	2.16	151	+0	101	102	44	B	0.9	3.35		8
51	0.357	2.13	146	-20	104	104	40	B	1.0	1.91		0
52	0.365	2.06	134	+20	103	104	-1	B	0.7	1.50		12
53	0.359	2.18	151	+0	107	109	5	B	0.8	3.95		0
54	0.361	2.14	150	+2	100	101	-3	B	0.8	0		0
55	0.358	2.14	150	-9	103	104	-1	B	0.8	0		0

TABLE A-1
(Concluded)

Test Number	Total Propellant Flowrate, lb/sec	Mixture Ratio	Chamber Pressure, psia	Oxidizer Lead, msecs	Oxidizer Temperature F	Fuel Temperature F	Chamber Temperature F	Splash Plate	Altitude, mm Hg	$\frac{P_{spike}}{P_c}$ (Position 1)	$\frac{P_{spike}}{P_c}$ (Position 2)	Ignition Delay, msecs
56	0.356	2.12	150	-10	101	101	1	B	0.8	4.28		7
57	0.351	2.19	155	+0	99	100	2	B	0.9	2.56		9
58	0.354	2.10	146	+10	98	102	3	B	0.9	3.79		8
59	0.363	2.10	140	+22	103	102	43	C-1	0.8	1.47		5
60	0.355	2.14	151	+0	98	98	40	C-1	0.9	4.50		9
61	0.364	1.94	127	-20	99	100	42	C-1	0.9	1.89		7
62	0.363	2.18	150	+0	100	101	40	C-1	0.9	2.70		8
63	0.354	2.10	148	+22	102	101	41	C-1	0.8	9		9
64	0.356	2.07	145	+22	100	100	40	C-1	1.0	1.82		9
65	*											
66	0.361	2.11	145	+22	94	96	4	B	0.8	1.78		9
67	0.355	2.12	150	+22	98	100	5	B	1.0	3.14		8
68	0.366	2.21	147	-21	101	101	2	B	0.9	3.81		7
69	0.362	2.12	143	-21	100	100	5	B	0.3	3.54		7
70	0.342	2.19	144	+20	41	44	40	C-1	0.2	2.17		11
71	0.344	2.21	147	+0	40	41	40	C-1	0.6	10.61		10
72	0.348	2.13	148	-20	39	41	40	C-1	0.8	1.66		5
73	0.350	2.10	149	+20	41	42	1	C-1	0.7	15.00		8
74	0.352	2.11	150	+0	42	43	0	C-1	0.9	3.92		8
75	0.354	2.10	152	-20	41	43	-1	C-1	1.1	2.11		6
76	0.327	2.88	126	+0	42	45	70	B	0.8	4.25		14
77	0.329	2.72	137	+0	40	42	70	B	0.8	4.20		10
78	0.335	2.55	139	+21	40	40	69	B	1.0	2.08		9
79	0.341	2.54	139	-21	41	41	69	B	1.0	1.36		8
80	0.325	2.44	128	+0	38	39	68	B	1.0	3.37		10
81	0.339	2.93	136	+0	44	42	67	C-2	0.6	3.64		15
82	0.342	2.90	136	+0	42	43	73	C-2	0.6	4.47		12
83	0.339	2.81	135	+0	41	41	73	C-2	0.9	1.70		11
84	0.342	2.72	138	+21	41	44	72	C-2	1.0	1.69		12
85	0.346	2.84	128	-20	37	40	72	C-2	1.2	1.85		11

TABLE A-2

SUMMARY OF N_2O_4/N_2H_4-UDMH (50-50) TEST DATA

Test Number	Propellant Flowrate, lb/sec	Mixture Ratio	Chamber Pressure, psia	Oxidizer Lead, msecs	Oxidizer Temperature, F	Fuel Temperature, F	Chamber Temperature, F	Splash Plate	Altitude, mm Hg	$\frac{P_{spike}}{P_c}$	Ignition Delay, msecs
86	0.329	3.63	124	+0	44	42	40	B	0.5	2.50	11
87	0.334	2.98	129	+22	36	34	42	B	0.7	23.75	12
88	0.333	2.92	136	-21	42	42	41	B	1.0	4.75	5
89	0.336	2.90	136	+0	47	46	40	B	1.1	2.22	11
90	0.343	2.40	141	+21	38	41	42	B	0.7	33.00	11
91	0.346	2.46	141	-20	36	36	41	B	0.8	5.34	6
92	0.347	2.47	141	-21	38	38	37	B	0.8	1.43	9
93	0.345	2.38	140	+20	44	44	39	B	0.8	3.84	9
94	0.329	3.77	119	+0	42	42	40	C-2	0.6	2.12	φ
95	0.332	2.95	128	+21	34	33	41	C-2	0.8	8.18	14
96	0.335	2.95	131	+21	41	42	42	C-2	0.9	8.48	10
97	0.335	2.95	134	-21	38	37	38	C-2	0.8	4.92	7
98	0.333	4.55	104	+0	38	38	41	C-3	0.7	2.32	16
99	0.329	4.22	112	+21	38	36	40	C-3	0.8	3.25	13
100	0.333	3.38	126	-21	38	38	40	C-3	0.7	3.19	8
101	0.344	2.83	127	+0	39	38	39	C-3	0.8	11.75	13
102	0.345	2.79	128	+21	39	39	40	C-3	0.8	6.21	11
103	0.349	2.80	134	-21	40	40	43	C-3	0.9	5.46	7
104	0.351	2.78	128	-0	38	37	40	C-3	1.1	3.94	11
105	0.345	2.14	147	+0	44	39	4	B	0.6	φ	9
106	**	---	---	---	---	---	---	---	---	---	---
107	0.339	2.36	144	+21	42	41	2	B	0.7	φ	φ
108	0.332	2.82	134	+0	37	39	38	B	1.0	φ	φ
109	0.342	2.46	142	+0	41	39	43	B	0.9	φ	12
110	0.341	2.33	141	+0	41	39	37	B	1.0	φ	10
111	0.342	2.29	144	+0	42	40	35	B	1.0	φ	10
112	0.338	2.42	141	+0	41	38	38	B	0.8	1.24	11
113	0.340	2.44	128	+21	42	39	39	B	0.8	4.82	φ
114	0.337	2.50	137	-21	44	41	39	B	0.9	4.25	φ
115	0.337	2.48	131	+0	42	39	40	B	0.8	9.34	11

TABLE A-2
(Continued)

Test Number	Propellant Flowrate, lb/sec	Mixture Ratio	Chamber Pressure, psia	Oxidizer Lead, msecs	Oxidizer Temperature, F	Fuel Temperature, F	Chamber Temperature, F	Splash Plate	Altitude, mm Hg	$\frac{P_{spike}}{P_c}$	Ignition Delay, msecs
116	0.336	2.49	124	+21	41	39	41	B	0.8	2.36	11
117	*	---	---	---	---	---	---	---	---	---	---
118	0.338	2.55	135	+2	39	38	40	C-4	1.0	5.00	11
119	0.338	2.52	139	+23	41	40	41	C-4	1.1	1.58	φ
120	0.327	3.12	130	+1	59	60	61	C-5	0.7	φ	φ
121	0.332	2.60	135	+2	57	57	63	C-5	0.8	1.88	φ
122	0.343	2.17	142	+3	58	58	64	C-5	0.8	2.34	φ
123	0.345	2.06	144	-23	40	37	39	C-5	0.9	8.35	2
124	0.351	2.05	145	+1	43	41	42	C-5	0.3	4.94	φ
125	0.343	2.18	136	+19	43	41	42	C-5	0.7	4.46	φ
126	0.342	2.20	141	-19	43	42	41	C-5	1.0	8.45	φ
127	0.340	2.20	140	+0	44	43	41	C-5	1.0	9.30	φ
128	0.339	2.22	136	+19	44	42	40	C-5	0.5	4.43	φ
129	0.342	2.23	143	-19	39	37	40	C-5	0.5	4.84	7
130	0.342	2.21	140	+0	42	40	41	C-5	0.6	6.25	φ
131	0.344	2.16	139	+19	41	39	39	C-5	0.6	2.14	8
132	0.347	2.16	134	+19	43	41	38	C-5	0.8	9.01	φ
133	0.351	2.07	138	+19	42	42	1	B	0.3	1.70	9
134	0.351	2.06	146	+1	42	41	1	B	0.9	1.58	10
135	0.353	2.07	149	-18	42	40	0	B	1.0	1.67	11
136	0.350	2.02	146	+19	43	42	0	B	1.0	10.00	8
137	0.349	2.03	148	+1	41	40	-2	B	0.6	1.50	8
138	0.345	1.97	136	-18	43	42	-1	B	1.0	3.12	11
139	0.349	2.01	134	+19	43	42	-1	B	0.9	12.75	φ
140	0.349	2.01	149	+20	41	39	1	B	0.8	2.56	6
141	*	---	---	---	---	---	---	---	---	---	---
142	0.346	2.01	145	+19	42	39	4	B	0.7	5.05	7
143	φ	φ	φ	+1	42	42	161	B	0.4	1.33	φ
144	φ	φ	φ	+19	41	40	161	B	0.8	1.62	φ
145	φ	φ	φ	-18	42	40	160	B	1.0	1.45	φ
146	φ	φ	φ	+0	42	38	163	B	0.7	1.97	φ
147	φ	φ	φ	+19	42	40	162	B	0.7	1.50	φ
148	0.358	2.06	157	+19	97	100	160	B	0.5	1.50	9

TABLE A-2
(Continued)

Test Number	Propellant Flowrate, lb/sec	Mixture Ratio	Chamber Pressure, psia	Oxidizer Lead, msecs	Oxidizer Temperature, F	Fuel Temperature F	Chamber Temperature, F	Splash Plate	Altitude, mm Hg	$\frac{P_{spike}}{P_c}$	Ignition Delay, msecs
149	0.360	2.16	157	+1	98	101	161	B	0.7	1.23	φ
150	0.362	2.14	154	-18	95	98	160	B	0.8	1.50	7
151	0.357	2.19	154	+19	98	100	160	B	0.7	1.60	φ
152	0.361	2.14	156	+1	98	100	161	B	0.9	1.35	9
153	0.358	2.20	154	-18	99	102	160	B	0.9	1.47	φ
154	0.361	2.16	156	+19	99	102	161	B	0.7	1.89	6
155	0.360	2.12	156	+20	98	100	157	C-6	0.4	1.24	7
156	0.361	2.20	158	+1	98	102	159	C-6	0.8	1.33	9
157	0.360	2.16	156	-1	99	102	158	C-6	1.0	1.44	6
158	0.361	2.16	156	+19	101	104	161	C-6	0.6	1.44	φ
159	0.361	2.22	157	+1	100	103	162	C-6	0.9	1.39	9
160	0.362	2.22	158	-19	99	101	161	C-6	1.0	1.26	φ
161	0.360	2.21	157	+18	100	102	161	C-6	0.9	1.84	8
162	0.361	2.20	157	+1	99	102	161	C-6	0.8	1.29	8
163	0.359	2.22	157	-19	99	102	160	C-6	0.8	1.22	5
164	0.359	2.23	156	+19	99	102	161	C-6	0.8	1.58	φ
165	0.360	2.22	158	+1	98	102	159	C-6	0.8	1.26	8
166	0.359	2.13	153	+1	98	99	41	B	0.5	1.41	8
167	0.361	2.14	150	+19	96	101	42	B	0.8	4.95	8
168	0.363	2.21	151	-19	98	100	38	B	0.9	3.35	φ
169	0.365	2.22	154	+0	98	101	40	B	0.9	2.94	9
170	0.368	2.23	155	+19	100	103	39	B	0.8	2.11	8
171	0.366	2.20	155	-19	100	103	41	B	0.9	3.06	φ
172	0.364	2.21	154	+1	98	100	40	B	1.0	1.89	8
173	0.369	2.21	155	+19	99	102	41	B	0.9	1.88	9
174	0.363	2.24	155	-19	99	102	40	B	0.9	2.94	6
175	0.364	2.22	156	+0	97	98	40	B	0.9	2.39	9
176	0.366	2.20	151	+19	98	101	38	B	0.8	2.31	8
177	0.366	2.16	155	+0	100	100	1	B	0.5	φ	φ
178	0.368	2.21	150	+19	98	101	0	B	1.0	5.62	7
179	0.302	1.38	117	-19	98	100	1	B	0.9	1.57	13

TABLE A-2
(Concluded)

Test Number	Propellant Flowrate, lb/sec	Mixture Ratio	Chamber Pressure, psia	Oxidizer Lead, msecs	Oxidizer Temperature, F	Fuel Temperature, F	Chamber Temperature, F	Splash Plate	Altitude, mm Hg	$\frac{P_{spike}}{P_c}$	Ignition Delay, msecs
180	0.357	2.06	150	+0	99	101	0	B	0.9	1.74	12
181	0.364	2.12	151	+19	99	101	1	B	0.9	5.69	7
182	0.360	2.10	152	-18	99	101	2	B	0.8	2.58	13
183	0.361	2.14	155	+0	100	101	39	C-7	0.6	3.76	10
184	0.361	2.14	151	+19	99	101	40	C-7	1.1	1.39	φ
185	0.362	2.16	156	-19	98	102	39	C-7	0.8	1.90	6
186	0.361	2.21	156	+0	φ	102	40	C-7	0.8	2.05	8
187	0.362	2.22	156	+19	98	101	40	C-7	0.8	1.95	8
188	0.362	2.18	154	-19	99	100	38	C-7	0.5	2.10	φ
189	0.358	2.19	154	+0	99	102	4	C-8	0.8	1.95	9
190	0.323	1.72	137	+1	100	102	3	C-8	1.0	2.66	12
191	0.357	2.14	153	-19	99	101	2	C-8	0.6	2.45	11
192	0.357	2.14	152	+0	100	103	2	C-8	0.5	2.68	13
193	0.360	2.16	137	+19	99	102	1	C-8	0.6	3.20	7
194	0.362	2.15	154	-18	100	102	2	C-8	0.5	2.90	φ
195	φ	φ	φ	+0	98	100	0	C-8	0.4	2.00	8
196	**	---	---	---	---	---	---	---	---	---	---
197	φ	φ	φ	+1	92	95	36	B	0.3	2.14	9
198	φ	φ	φ	+20	95	99	35	B	0.5	2.14	8

TABLE A-3

SUMMARY OF N_2O_4/N_2H_4 TEST DATA

Test Number	Propellant Flowrate, lb/sec	Mixture Ratio	Chamber Pressure, psia	Oxidizer Lead, msecs	Oxidizer Temperature, F	Fuel Temperature, F	Chamber Temperature, F	Splash	Altitude,	$\frac{P_{spike}}{P_c}$	Ignition Delay, msecs
199	0.361	2.14	143	+0	98	100	44	B	0.4	6.10	13
200	0.364	2.17	142	+9	96	99	43	B	0.6	1.97	10
201	0.362	2.18	141	-9	95	98	43	B	0.5	7.40	8
202	0.362	2.16	143	-20	98	101	45	B	0.6	11.60	8
203	0.367	2.17	140	+19	100	102	44	B	0.6	3.52	10
204	0.363	2.08	139	+0	94	96	38	C-9	0.5	2.94	12
205	0.366	2.16	135	-20	94	92	41	C-9	0.4	9.10	8
206	φ	φ	φ	φ	98	102	38	C-9	0.4	2.74	φ
207	0.366	2.20	139	+0	87	100	3	B	0.5	6.61	11
208	**	—	—	—	—	—	—	—	—	—	—
209	0.370	2.24	140	+0	92	96	40	B	0.6	3.94	φ
210	0.365	2.18	135	+20	96	100	41	B	0.8	3.54	9
211	0.364	2.16	139	-19	97	101	39	B	0.6	φ	8
212	*	—	—	—	—	—	—	—	—	—	—
213	0.350	2.07	135	+0	44	40	38	B	0.3	19.81	11
214	0.348	2.10	134	+2	41	40	35	B	0.8	6.60	11
215	0.349	2.11	133	-19	45	42	36	B	0.9	10.35	9
216	0.348	2.11	136	+0	46	44	44	B	0.5	11.62	φ
217	**	—	—	—	—	—	—	—	—	—	—
218	**	—	—	—	—	—	—	—	—	—	—
219	0.367	2.48	142	+0	46	45	42	B	0.5	φ	φ
220	0.373	2.56	138	+1	44	47	39	C-10	0.6	φ	12
221	0.372	2.48	140	+20	45	47	39	C-10	0.8	φ	φ
222	0.367	2.42	138	-19	45	47	36	C-11	0.8	4.69	φ
223	0.372	2.45	141	+0	44	44	39	B	0.4	3.77	φ
224	0.376	2.48	137	+19	43	43	38	C-12	0.6	5.30	10

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1. ORIGINATING ACTIVITY *(Corporate author)* Rocketdyne, a Division of North American Rockwell Corporation, 6633 Canoga Avenue, Canoga Park, Calif.	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE
A STUDY OF IGNITION PRESSURE SPIKING IN ATTITUDE CONTROL ENGINES, VOLUME I EVALUATION OF THE USE OF CATALYTIC SURFACES TO ELIMINATE IGNITION CONTROL ENGINES

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Final Report (1 July 1966 to 30 April 1967)

5. AUTHOR(S) *(Last name, first name, initial)*
Gurnitz, R.N.; Mills, T.R.; Falkenstein, G.L.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
May 1967	99	11

8a. CONTRACT OR GRANT NO. NAS9-6134 b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) R-7060-1 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. AVAILABILITY/LIMITATION NOTICES

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY National Aeronautics and Space Administration

13. ABSTRACT

A study was conducted to evaluate the effect on ignition pressure spiking of the incorporation of catalytic surfaces into the injector of a nominally 91-pound-thrust Apollo Command Module RCS engine. Test firings at a simulated altitude of 150,000 feet over a range of propellant and chamber temperatures (0 to 160 F) and a range of relative valve timings (+20 to -20 milliseconds) with both blank (unmodified) and catalytically modified splash plate injectors were made for N_2O_4/MMH, N_2O_4/50-50, and N_2O_4/N_2H_4 propellant combinations. It was determined that the catalytic concepts employed did not eliminate or supress the spiking. Effects on spiking levels of propellant combination, temperature, and valve timing were noted and are discussed.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Attitude Control Engines						
Ignition Pressure Spiking						
N_2O_4/MMH						
N_2O_4/50-50						
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