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VACUUM IGNITION CHARACTERISTICS OF OXYGEN DIFLUORIDE/DIBORANE AND FLOX/DIBORANE

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Thiokol Chemical Corporation
Reaction Motors Division

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SPECIAL NOTICE

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FOREWORD

This report is the final report covering work performed by Thiokol Chemical Corporation, Reaction Motors Division, Denville, New Jersey, under National Aeronautics and Space Administration Contract NAS 7-660, Phase II.

The technical manager of the program was Mr. Robert W. Rowley, Liquid Propulsion Section, Jet Propulsion Laboratory, Pasadena, California 91103. The NASA Project Manager was Dr. Robert S. Levine, OART, NASA Headquarters, Washington, D. C.

The Phase II technical program described herein was conducted during the period 15 January 1969 through 14 December 1969. The Phase I technical program was conducted during the period 15 February 1968 through 15 October 1968 and the results are given in Interim Final Report RMD 5534-FI, "Vacuum Ignition Characteristics of Flox/Diborane and Oxygen Difluoride/Diborane", dated March 1969. The Phase I program stressed the Flox/B_2H_6 propellant combination whereas the Phase II program stressed the OF_2/B_2H_6 combination.

The Program Manager of the programs was Mr. Thomas F. Seamans and the Principal Investigator was Mr. George R. Mistler. Other contributors were Dr. Josephine D. Readio and Messrs. B. M. Fagan, H. W. Romaine and J. Taylor, Jr.

ABSTRACT

The vacuum ignition characteristics of OF_2/B_2H_6, primarily, and Flox/B_2H_6 have been investigated in 100 lbf thrust rocket engines to determine potential problem areas and define design concepts required to insure reliable vacuum starting of space engines. The engine and operating parameters investigated were design chamber pressure, dribble volume/injector configuration, propellant valve type, valve/injector coupling, run tank ullage, propellant lead/lag, oxidizer temperature, fuel temperature and hardware temperature. Ignition spikes occurred with the OF_2/B_2H_6 combination but only under conditions of an oxidizer lead. No ignition spikes were observed under any conditions with the Flox/B_2H_6 combination. Cocking of the solenoid valve poppets just prior to the start of normal poppet transfer allows a low "pre-flow" of the propellants into the chamber. Initial ignition is very fast and occurs in the vapor phase when one or both of the propellants is in the pre-flow period. Propellant concentrations, and temperature, are very low. The initial ignition produces a weak flame that acts as a pilot flame for the oncoming bulk flows. Main ignition occurs when the full mass flow of the lagging propellant occurs. Combustion residues are formed by both oxidizers with diborane. The residues contain amorphous elemental boron, H_2O and at least two other components one or both of which are borates though not B_2O_3 nor H_3BO_3.

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I. INTRODUCTION

The high energy propellant combination, oxygen difluoride/diborane, offers attractive characteristics for improving the mission capability of future spacecraft. These characteristics (high density, hypergolic ignition, excellent performance even at low chamber pressures, and storable in space for extended periods) are especially desirable for high response, low thrust reaction control system engines for interplanetary missions.

The program described in this report is concerned with the vacuum ignition characteristics of oxygen difluoride/diborane, primarily, and of Flox/diborane, secondarily. The less expensive 70 percent F_2/30 percent O_2 Flox mixture, whose overall composition closely matches that of OF_2, has been considered as a substitute for OF_2 in pre-flight hardware testing and evaluation.

The present program is a continuation of the initial study of vacuum ignition of these propellants conducted in 1968. Reference 1 is the final report covering that Phase I effort.

The purpose of the present twelve month technical program is to further define vacuum starting characteristics and potential problem areas in vacuum ignition of space engines using oxygen difluoride/diborane and Flox/diborane propellant combinations.

The program consists of three technical tasks as follows:

TASK I - VACUUM IGNITION OF OF_2/B_2H_6

The primary effort of the program and of this task was an experimental investigation of the vacuum ignition of 100-lbf thrust rocket engines using the OF_2/B_2H_6 propellant combination. The engine and operating parameters investigated were design chamber pressure, dribble volume/injector configuration, propellant valve type, valve/injector coupling, run tank ullage, propellant lead/lag, oxidizer temperature, fuel temperature and hardware temperature. A correlative effort to define the physical and chemical mechanisms which control starting under the test conditions and to define design concepts and operational procedures required to insure reliable vacuum starting of OF_2/B_2H_6 space engines was performed.

TASK II - INTERCHANGEABILITY OF OF_2 AND FLOX

This task consists of experimental and analytical studies to determine the effects on engine ignition characteristics when Flox is substituted for the OF_2. From the tests and supporting analyses, changes in design concepts and hardware required for reliable starting of space engines when Flox is substituted for OF_2 were determined.

TASK III - HIGH SPEED MOTION PICTURES

The purpose of this task was to investigate techniques for taking useful high speed motion pictures of the injection and ignition processes that would be adequate to allow engineering analysis of the physical/chemical processes involved. Preliminary sketches were prepared to show thrust chamber modifications to accept a viewing window. Requirements and procedures to obtain the desired motion pictures were defined.

It was intended at the program outset that the scope of work of this task would be extended to include the actual taking of the movies. However, due to a decision during the present program by Corporate management to phase out the Reaction Motors Division, a program extension to permit movie-taking was not possible. No further effort was expended in this area.

The results of Tasks I and II of the program are discussed in detail in the following sections.

II. SUMMARY

The purpose of the program reported herein was to define vacuum starting characteristics and potential problem areas in vacuum ignition of space engines using oxygen difluoride/diborane and Flox/diborane as propellants.

This report is the final report of a twelve-month program which consisted of three technical tasks as follows. The primary effort of the program and of Task I was an experimental investigation of the vacuum ignition characteristics of a 100 lbf thrust engine using the oxygen difluoride/diborane propellant combination. The engine and operating parameters investigated were design chamber pressure, dribble volume/injector configuration, propellant valve type, valve/injector coupling, run tank ullage, propellant lead/lag, oxidizer temperature, fuel temperature and hardware temperature. A correlative effort to define the physical and chemical mechanisms which control starting under the test conditions and to define design concepts and operational procedures required to insure reliable vacuum starting of OF_2/B_2H_6 space engines was performed.

Task II consisted of experimental and analytical studies to determine the extent to which results obtained using OF_2 may be applied to similar engines using Flox as oxidizer. From the tests and supporting analyses, changes in design concepts and hardware required for reliable starting of space engines when Flox is substituted for OF_2 were determined.

The purpose of Task III was to investigate techniques for taking useful high speed motion pictures of the injection and ignition processes that would be adequate to allow engineering analysis of the physical/chemical processes involved. Requirements and procedures were defined and preliminary sketches were prepared in anticipation of an increased scope of work which would provide for the necessary hardware rework and the actual taking of the movies. However, due to a decision during the program by Corporate management to phase out the Reaction Motors Division, a program extension to permit movie-taking was not possible.

Ignition tests were conducted with 100-lbf thrust engines at simulated altitudes in excess of 250,000 ft. The test hardware consists of two thrust chambers, two injectors, three types of propellant valves, two valve/injector couplings and two run tank ullages. The two thrust chambers differ primarily in design chamber pressure: 100 psia and 20 psia. Both chambers have a contraction ratio of 6.25 and an L* of 25 inches.

Two impinging stream injectors were used to evaluate effects of dribble volume. One injector is a nine element doublet injector

representative of flight-type hardware. The other is a single element doublet with about one-third the internal volume of the nine pair injector. Both injectors mate interchangeably with the two thrust chambers.

The bulk of the tests were conducted with light weight, straight through, solenoid operated, poppet type propellant valves with metal-to-metal sealing. A few tests were made with a flight-type torque motor operated, bipropellant valve and with light weight, positive sealing, explosively actuated valves.

Two types of valve/injector coupling were tested. In one, the valves (solenoid) were thermally conditioned with the respective propellant to assure conditioning of the initially flowing propellant to the desired temperature. Short stand-off tubes with drilled inserts to minimize internal volumes were used between the propellant valves and the injectors. In the second configuration, the line lengths were reduced to minimize dribble volume. In this case the valves were no longer conditioned with the respective propellant but rather with the injector/chamber.

Primary instrumentation consisted of an optical propellant entry detector, an optical ignition sensor, and high response, flush mounted piezoelectric pressure transducers in the thrust chambers and in each injector manifold. Frequency response was well in excess of 25 kHz.

Seventy-six vacuum ignition test runs were conducted during this Phase II program for a total of 124 tests including the Phase I effort. For the various tests, engine hardware was conditioned to 70°, 0°, -100°, -200° and -250°F. Propellant conditioning was as follows: OF_2 at -170°, -200° and -320°F, Flox at -250° and -320°F and B_2H_6 at -10°, -100°, -200° and -250°F. Propellant lead/lags (electrical) included a range from 13 msec fuel lead to 14 msec oxidizer lead.

With the solenoid propellant valves, the valve poppets cock as the magnetic flux builds up prior to the start of normal poppet transfer. With the metal-to-metal sealing, this cocking of the poppets opens small leakage paths through which propellants pass and then flash vaporize. A very low "pre-flow" results which, in the present case, has a duration of 4-8 msec prior to the start of normal poppet transfer.

Initial ignition is very fast. It apparently occurs in the vapor phase when one or both of the propellants is in the pre-flow period. Propellant concentrations at such times are very low as is temperature.

The initial ignition produces a weak pilot flame. The flame then increases in intensity as the mass input into the thrust chamber increases provided a reasonable balance between fuel and oxidizer is maintained.

When the mass input of one propellant lags markedly, the pilot flame remains weak and "main ignition" is delayed.

Main ignition, or the time when significant chamber pressure--and therefore thrust--begins to develop, occurs when the full mass flow of the lagging propellant occurs.

Ignition spikes were observed only with OF_2 as the oxidizer and, in these cases, only with an (electrical) oxidizer lead. No ignition spikes were indicated with fuel leads nor with simultaneous valve signals. With 70/30 Flox as the oxidizer with B_2H_6, no ignition spikes were observed under any conditions.

Solid combustion residues were found in the thrust chambers following each run with either OF_2/B_2H_6 or Flox/B_2H_6. In selected runs, samples of the residues were collected and maintained under an inert atmosphere until analyzed. In one run, the residue was exposed to air for two days before being examined. The samples were analyzed by infrared spectroscopy, X-ray diffraction and flame test. It was found that similar species are present in the residues formed by either OF_2 or Flox with B_2H_6. The residues consist of various concentrations of at least amorphous elemental boron, H_2O, and two other compounds one or both of which are borates ($BO_3^{\equiv}$, $B_4O_7^{=}$). Neither H_3BO_3 nor B_2O_3 is present in the residues but BN may be present. The composition of the residues depends to some extent on the lagging tail-off propellant.

The factors that promote short delays to main ignition are those factors that cause rapid, hard-liquid filling of the injector manifolds. These include flow control by system ΔP, high design chamber pressure, small injector dribble volumes and fast acting propellant valves. Temperature was found to have no significant effect on delays to main ignition.

The first test with the torque motor operated bipropellant valve ran normally. Ignition transients with OF_2/B_2H_6 were smooth as expected under the zero-lead condition. Although the bipropellant valve reached the full open position more quickly than the solenoid valves under the respective run conditions, the time to hard liquid filling of the injector manifolds was slightly longer and therefore the delay to main ignition was also slightly longer. In the second run, a malfunction occurred in the valve. Following the run, neither the oxidizer side nor the fuel side sealed properly. The symptoms and post-run findings are not fully explained.

A test with explosively actuated valves was made with the valves at below design-point temperatures. Although the fuel-side valve operated normally, the oxidizer-side valve failed due to reaction of the OF_2 with the fuel-rich squib combustion products which blew-by the shear ram into the downstream cavity of the valve.

In the midst of the many tests with the solenoid propellant valves, the oxidizer valve failed to open upon voltage application in two successive runs. The cause is attributed to a straw-colored material which froze during temperature conditioning causing the valve to hang up. The material was found only in the valve and was insufficient for analysis. After a thorough cleaning, no further incidents occurred. The nature and origin of the material is unknown but should be investigated so as to prevent any recurrence during a space mission.

III. EXPERIMENTAL SYSTEM

The experimental system for the work reported herein was basically the same as that used for the previous study which concentrated on the Flox/B_2H_6 propellant combination (Ref. 1). Several improvements to the system were made and additional test hardware was used. For completeness, a detailed description of the experimental system used in the present study follows. The experimental system consists of test hardware, test system and instrumentation system.

A. TEST HARDWARE

The test hardware includes two thrust chambers, two injectors, three types of propellant valves, two valve/injector couplings and two run tank ullages.

1. Thrust Chambers

Chambers and nozzles were designed for a thrust of 100 lbs under space conditions. At 100 psia chamber pressure, a Flox/B_2H_6 mixture ratio of 3 and an exit area ratio of 25, the vacuum specific impulse is approximately 410 sec. The engines were designed for a specific impulse of 400 which corresponds to a total flowrate of 0.25 lb/sec at an O/F of 3.

To evaluate the expected effect of design chamber pressure on ignition, two nozzle-chamber combinations were used: one designed for 100 psia and the second for 20 psia chamber pressure. Each has a contraction ratio of approximately 6.25 and an L* of approximately 25 inches. The nozzles have a 90 degree convergent angle. Throat diameters are approximately 0.8 and 1.75 in., respectively. The rounded throat contours are followed by only short expansion sections since thrust measurements and specific impulse were not required. The nozzle flange contains bolt holes and an O-ring groove to seal to the vacuum system. The upper chamber flange was designed to hold two Kistler pressure transducers flush-mounted in the chamber wall and to bolt to the injector.

For the present study, the two thrust chambers were modified to accept a "Propellant Entry Detection" system. Each chamber was re-worked at the injector end to mount two small-diameter, interchangeable windows which are diametrically opposed. One window permits light to be beamed across the injector face. The other permits a light guide to conduct the incident light beam to a light detector (see Sec. III. C below). Propellant entry is indicated when the beam intensity is attenuated by passage of the propellants through the beam.

The thrust chambers were also modified to contain probes to collect condensed-phase combustion residue. Two types of probes were fabricated. One provides a surface area of .062 square inches and mounts flush with the chamber wall. The other protrudes 0.8 inches into the chamber and provides twelve times the surface area.

Figure 1 shows an exploded view of the chamber/injector assemblies prior to the rework. Figure 2 is a composite sketch of the above rework.

2. Injectors

To define potential problem areas relative to dribble volume and flow paths, two injectors were used. Both injectors are doublets and they are interchangeable with the two chambers. One injector is a single element doublet to reduce injector dribble volume to a minimum. The second injector is also a doublet but it contains nine pairs of orifices and a larger distribution manifold more representative of flight hardware. A comparison of the data from the two injectors at the same design flowrates and temperature conditions indicates the extent to which flashing of the propellants within the injector must be considered in designing flight hardware. Detail drawings of the two injectors are given in Appendix A.

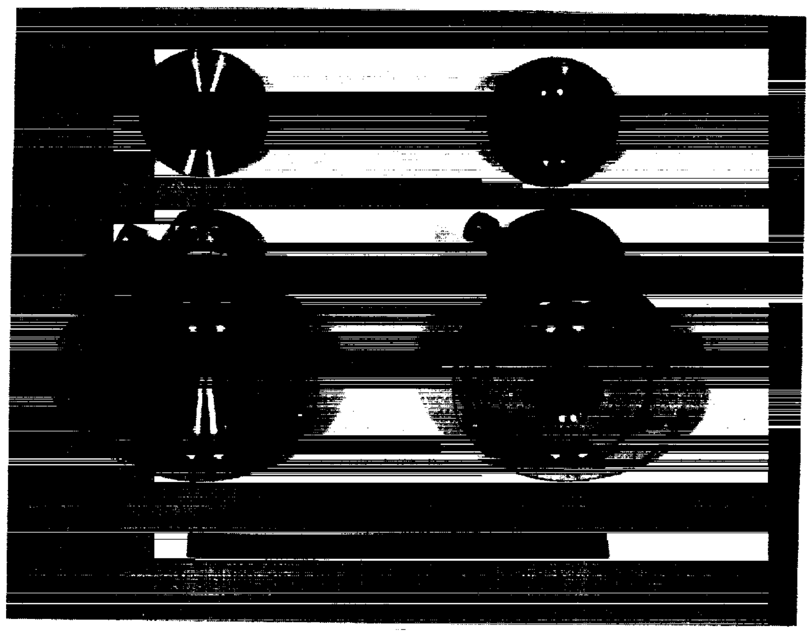
The injectors were designed using Rupe's criteria of unity momentum ratio (Ref. 2). At design flows, injection velocities are 48 ft/sec and 112 ft/sec for Flox and diborane, respectively. Steady state design flow rates are 0.1875 lb/sec for the oxidizer and 0.0625 lb/sec for the fuel. Flow control is managed by propellant tank set pressures and steady state system pressure drops. Therefore, higher than design flowrates occur during the start transient. For a nominal condition of Flox at -320°F, the nine pair injector and the 100 psia chamber, the calculated peak Flox flow is 0.283 lb/sec during the start transient which is 150 percent of the steady state design flow.

The injectors were water flow checked to permit accurate calculations of tank pressure settings to produce design flows at steady state conditions. The water flow calibration curves are given in Figs. 3 and 4. Figures 5 and 6 show the injector assemblies.

The hydraulic "flip" labeled in Figs. 3 and 4 is a phenomenon often encountered during water flow calibration of rocket engine injector orifices (Refs. 3-5). It occurs with orifices which do not have perfectly rounded entrance ports and/or sufficiently long orifice length to diameter ratios and which are flowed without a sufficiently high gas back pressure (Ref. 6). The effect is not noted during normal steady state operation where high back pressures (i.e. chamber pressure) and relatively low injection velocities prevail.

9 Pair Doublet Injector

Single Element Doublet Injector



100 lbf Thrust Chamber, 100 psia

100 lbf Thrust Chamber, 20 psia

FIGURE 1. Thrust Chamber/Injector Assemblies (Exploded View)

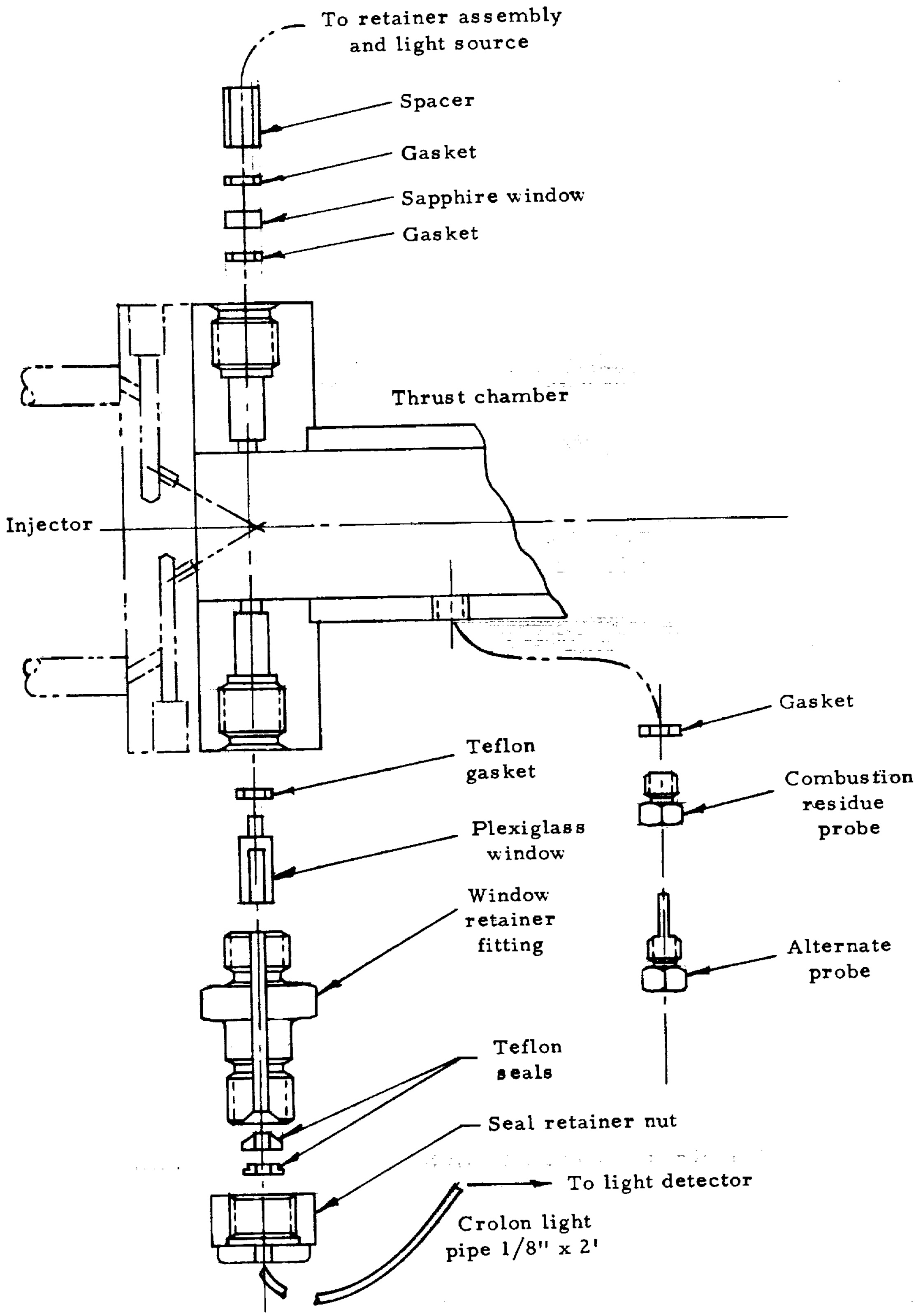
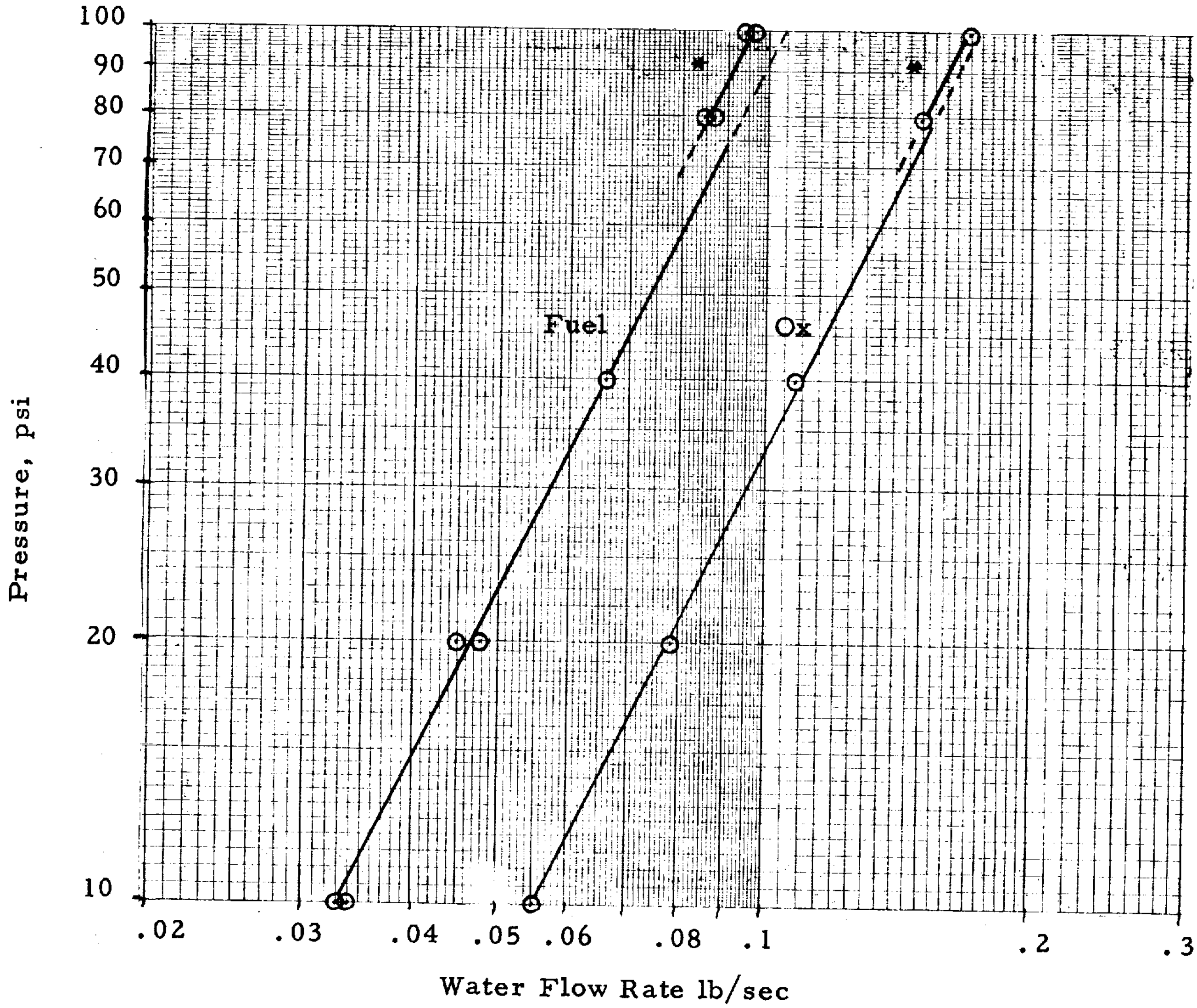
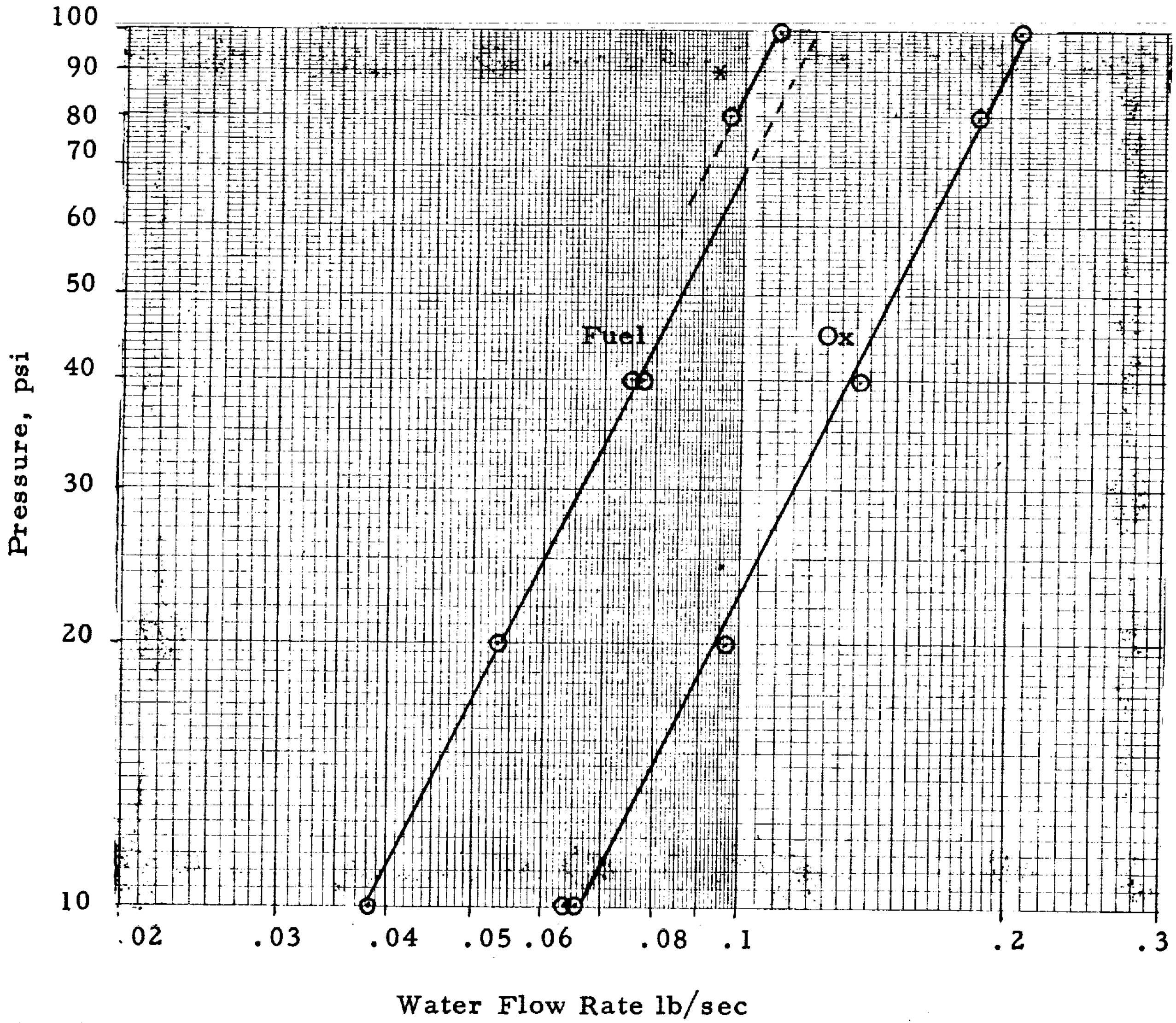


Figure 2. Sketch of Propellant Entry Detector Components and Residue Sampling Probes



*Hydraulic Flip

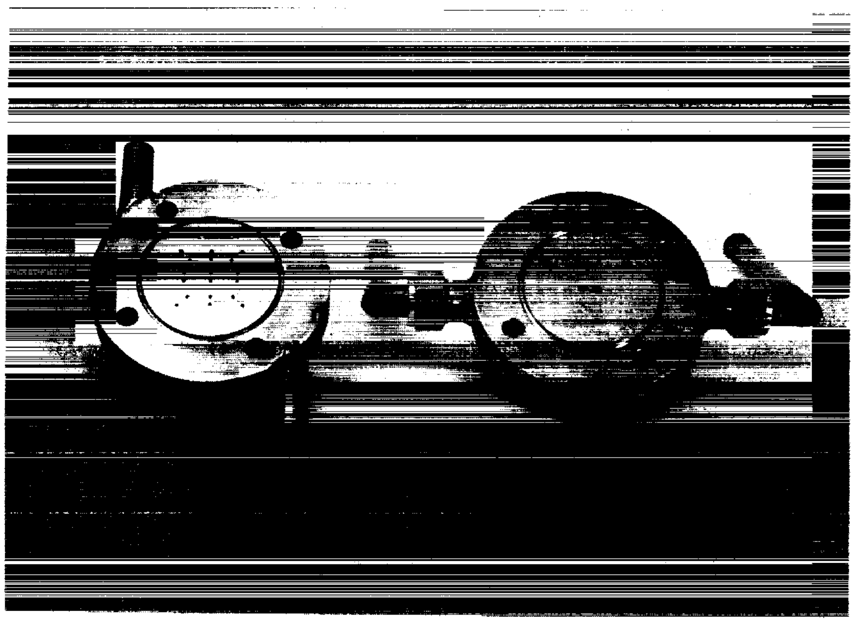
Figure 3. Water Flow Check - Valcor Valve and 9 Pair Doublet Injector (Drilled Inserts Installed)



*Hydraulic Flip

Figure 4. Water Flow Check - Valcor Valve and 1 Pair Doublet Injector (Drilled Inserts Installed)

Nine
Pair
Doublet



Single
Element
Doublet

Figure 5. Face View of Injector Assemblies

Figure 6. Back View of an Injector Assembly

Each injector has provisions for flush-mounting high response Kistler piezoelectric pressure transducers in the fuel and oxidizer injector manifolds (see injector drawings in Appendix A). Some sealing problems were encountered during the program in both the fuel and oxidizer sides. The repeated insertion and removal of the transducers/adapters between the two injectors apparently degraded the 7 mm threads and sealing surfaces to the point where reliable sealing could not be accomplished. This is not uncommon in situations where lubrication is not permitted and "like" or "similar" metal threads are in conjunction. To correct the problem, the 7 mm threaded holes in the injectors were enlarged and rethreaded to accept 7/16 x 20 bolts which had been reworked to contain the Kistler pressure transducers. Dead soft copper gaskets were provided to seal the bolts in the injectors. Because of the construction of the oxidizer manifold, puddled welding formed part of the sealing surface and minute irregularities prevented a proper seal. Sealing was accomplished when a thin lead gasket was substituted for the copper. Sealing was further improved when the transducer holder/injector manifold static seals were changed from lead gaskets to captive teflon sleeves. The teflon seals performed well under temperature cycling from 70°F to -250°F whereas the lead gaskets cold flowed and leaked.

3. Propellant Valves

Three types of propellant valves were used during the course of the program: Valcor solenoid valves, Conax explosive valves and a Hydraulics Research torque-motor bipropellant valve.

a) Valcor Solenoid Valve

The great majority of tests performed under both phases of the program used two identical propellant valves manufactured by Valcor Engineering Corporation and designated P/N V27200-214. These light weight, compact, 1/4-inch valves are straight-through, solenoid operated, poppet type valves incorporating stellite seats and stainless steel seals. The valves have low pressure drops and are designed for very corrosive fluids and for immersion in liquid nitrogen. Figures 7 and 8 give, respectively, the manufacturer's technical data and a sectional drawing of a typical series 272 valve.

Typical valve opening times (poppet transfer times) experienced during the program are 2.5 to 4.5 msec with this period starting some 11-14 msec after application of 24 VDC. Generally, evidence of slight propellant flow was observed by the injector manifold piezoelectric transducers prior to the start of poppet transfer. This low flow resulted from cocking of the valve poppets.

VALCOR

TECHNICAL DATA

VALVE, SOLENOID SERIES 272-C 3/8 C K

VALCOR ENGINEERING CORP. • 365 CARNEGIE AVENUE, KENILWORTH, NEW JERSEY

DESCRIPTION

2-WAY SHUT-OFF SIZE — 1/4" TO 3/8" O.D. LINE
OPERATING PRESSURE — ZERO TO 500 PSI
AVAILABLE: NORMALLY CLOSED

VALVE TYPE

Valve is a direct acting poppet type. Flow is coaxial through the center of the solenoid. Low pressure drop is accomplished by extremely clean flow passage design.

APPLICATION

Series 272-C is applicable to extremely difficult to handle fluids. Its primary usage is in flourine service on advanced rocket engines. It can be readily disassembled for cleaning or flushing on applications where the fluid media must be removed from the system after use. It's welded solenoid construction and metal to metal seating make it particularly suitable for cryogenic applications. The entire valve can be submerged in liquid nitrogen if desired.

FEATURES AND OPERATION

Valve is extremely light weight for its flow and pressure rating as well as current draw. Sealing is accomplished by means of conical hardened ground and lap stellite stem seating on a polished stellite seat. A crushed metal gasket nose piece, permits easy assembly and disassembly of all critical parts. The valve structure is trouble free having a minimum of moving parts. Solenoid plunger and poppet are designed for alignment action. Leakage can be held to a maximum 1 cc/hr. The solenoid construction consists of high temperature magnet wire wound on a welded solenoid plunger housing. The coil is silicone impregnated and baked into a solid homogeneous mass. This is vibration and shock proof, moisture resistant and will withstand temperatures from −450°F to +450°F.

SPECIFICATIONS AND RATINGS

A. TEMPERATURE:
−400°F to +200°F.

B. OPERATING PRESSURE AND FLOW RATINGS:

EQUIV. SHARP EDGED ORIFICE CD = .65	OPER. PRESS. PSI		TEMP. °F	MIN. VOLTS D.C.	C_v
	STAND. COIL	SPECIAL COIL			
.140	500	1500	80	18	.38
.275	275	500	165	18	.56

As the maximum operating pressure requirement is decreased, the actual flow capability of the valve can be increased. This may be accomplished by increasing the plunger stroke.

For higher temperature applications a decrease of maximum operating pressure would be resultant. The degree of this derating would be dependent on your actual operating conditions. Contact Valcor's engineering department for assistance.

C. BURST PRESSURE: 1250 PSI for 500 PSI Valve
700 PSI for 275 PSI Valve

D. LEAKAGE:
External — Zero — Mass spectrometer tight.
Internal — Gases; 2 scc/min.
Liquids; 1 cc/hr.

E. ELECTRICAL DATA:
Voltage — 18-30 V. DC
Duty — Continuous, most applications
Electrical Connection — AN receptacle standard
Response Time — .01 to .040 seconds depending on current input
Current — at 30 V. DC and at 72°F
1.5 amps. max. for standard coil
Dielectric Strength — 1000 volts RMS minimum

F. PORTS:
Standard construction has MS 33656 inlet and outlet. Other sizes and types available.

G. WEIGHT:
1 lb. max.

H. SPECIALS:
Many variations of this valve are available. Simplicity of design allows considerable freedom in this regard. Various combinations, in choice of materials, allows for broad application of this series.

Figure 7. Valcor Technical Data for Solenoid Valve Series 272-C

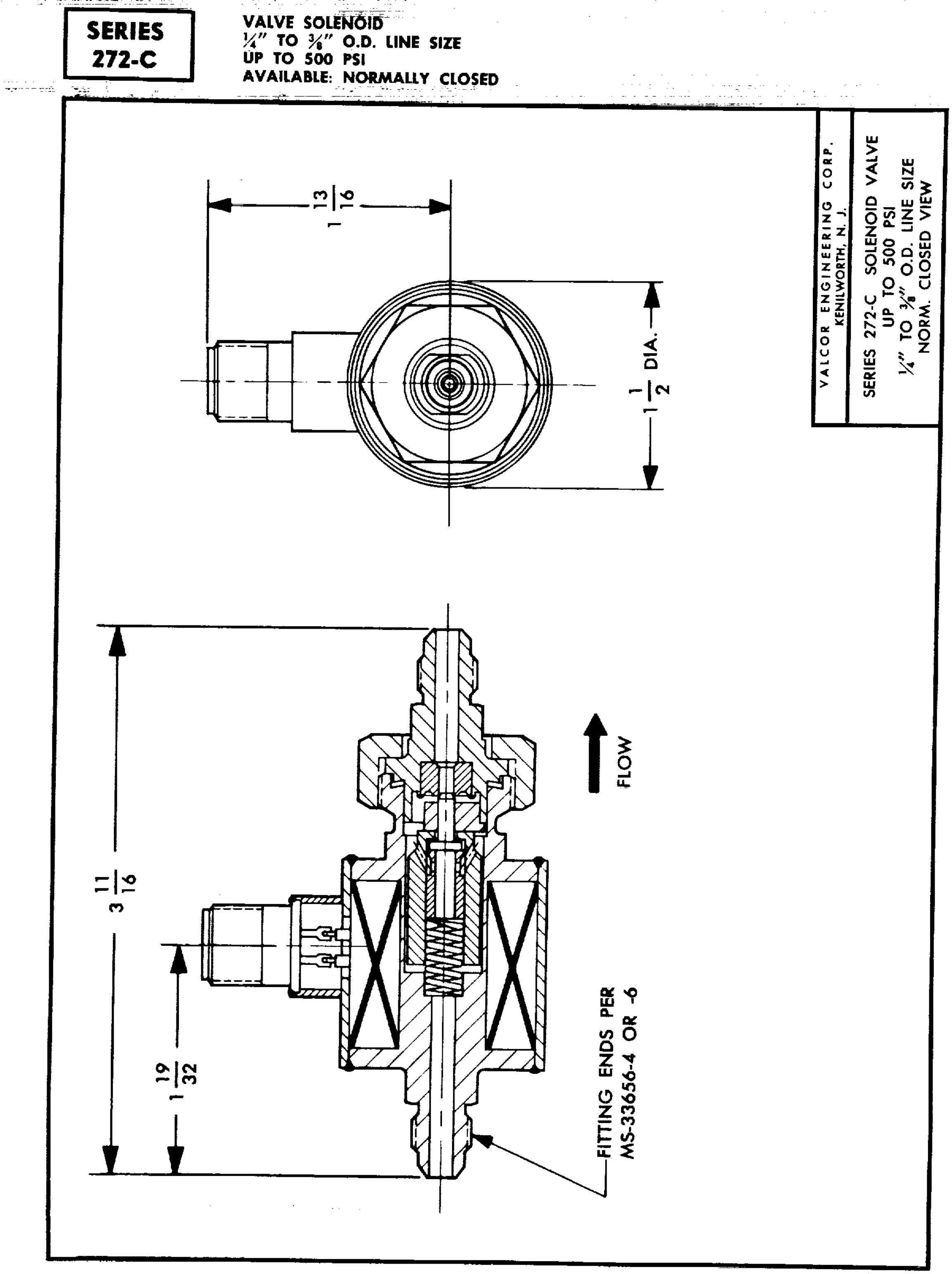


Figure 8. Drawing of Valcor Solenoid Valve Series 272-C

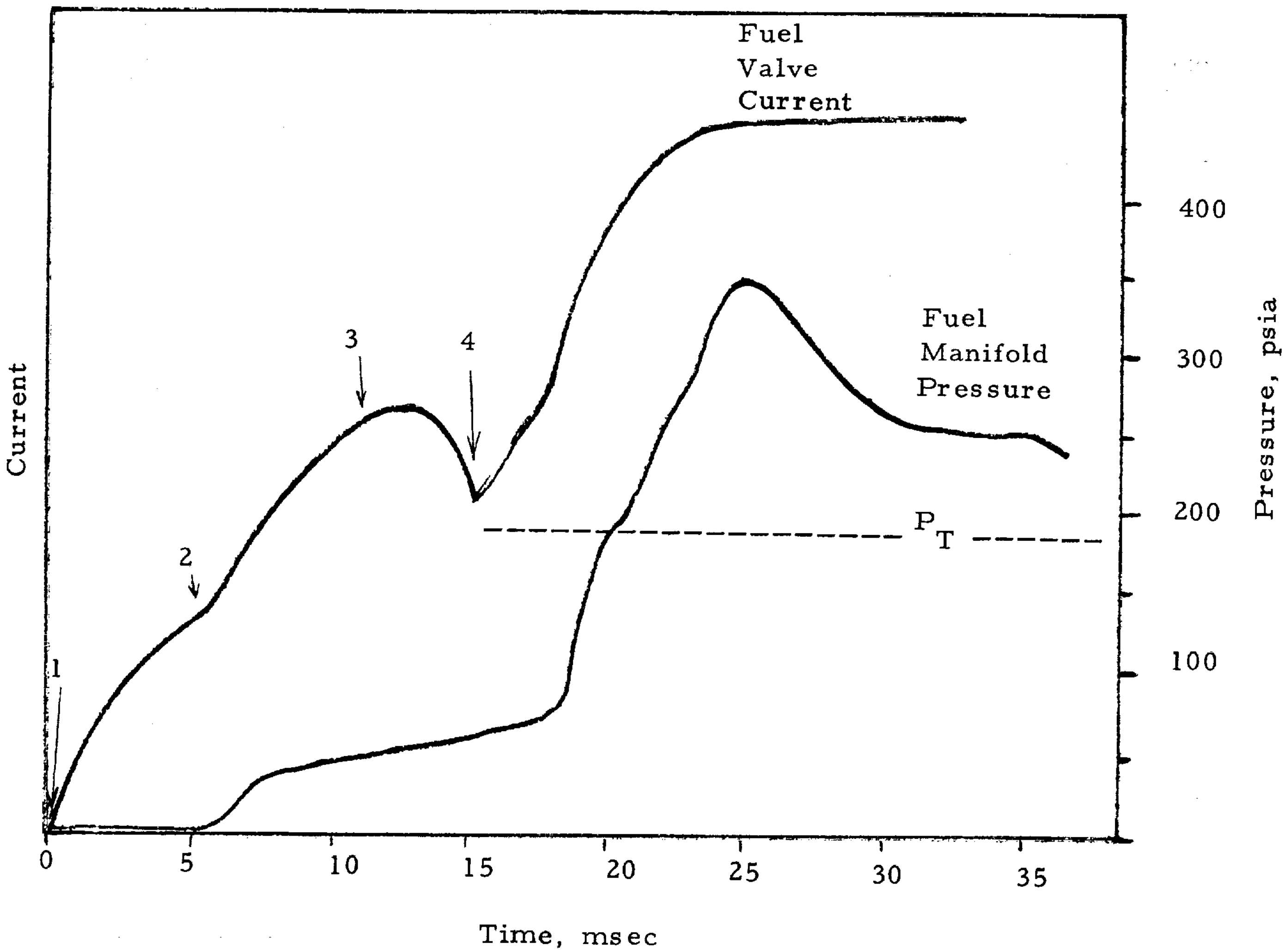
Ideally, with a new lightly coined metal-to-metal poppet and seat and proper axial alignment, the sealing line interface is circular. When the solenoid is energized the coil current starts to build up. At some point when the magnetic flux is still not great enough to overcome the unbalanced pressure and spring load forces, the poppet adjusts radially to the magnetic field causing the sealing surface to become elliptical. This provides two small leakage paths shortly before the flux buildup reaches the point where the poppet starts to transfer axially, lifting off the seat. In the present case, poppet cocking generally occurred 6-7 msec after voltage application. The occurrence of this cocking or radial motion of the poppet prior to valve opening can be determined from valve current traces such as Fig. 9 (Ref. 1) and Fig. 10 (Ref. 7). However, this phenomenon has been little recognized. The effect of the cocking with metal-to-metal poppets and seats is transient leakage, or a slight "pre-flow". The effect with metal-to-plastic or metal-to-elastomer seals may be absorbed by the elasticity of the materials with no resultant leakage.

A major problem of valves that rely on metal-to-metal seals is, of course, leakage which develops or worsens with repeated use. By Run 59, the leakage rate had become unacceptable and so the valves were disassembled and examined. The fuel valve poppet was badly scored. The oxidizer valve poppet was also scored, the seat was etched and the last two turns of the poppet seating spring were broken. The poppets were refaced and the seats were lapped. However, the results were not satisfactory as the fuel valve leaked both gas and liquid. A new poppet was fabricated from copper in an effort to trade-off operational life for better sealing. The copper poppet reduced the leakage rate to an acceptable minimal level. The stainless steel poppet for the oxidizer valve was reworked and performed properly for a few runs but it too had to be replaced with a copper poppet.

As expected, the operational life of the copper poppets was considerably shorter than that of the original stainless steel poppets. New copper poppets were installed in the fuel valve prior to Runs 59, 74, 100 and 109 and in the oxidizer valve prior to Runs 67, 74, 79, 88, 94, 100 and 109. In addition as an overhaul, new stellite seat/poppet guide/housing assemblies and poppet return springs were installed in both valves prior to Run 100.

b) <u>Conax Explosive Valves</u>

Explosively actuated valves (Conax Corporation P/N 1802-130) were used in order to determine the effect of zero propellant leakage (positive sealing) on the starting transient, i.e. in the absence of any pre-flow arising from poppet cocking.



1. Voltage applied to valve
2. Poppet Unseats
3. Poppet starts to transfer
4. Valve full open

Figure 9. Valve Coil Current and Fuel Manifold Pressure vs Time (Ref. 1)

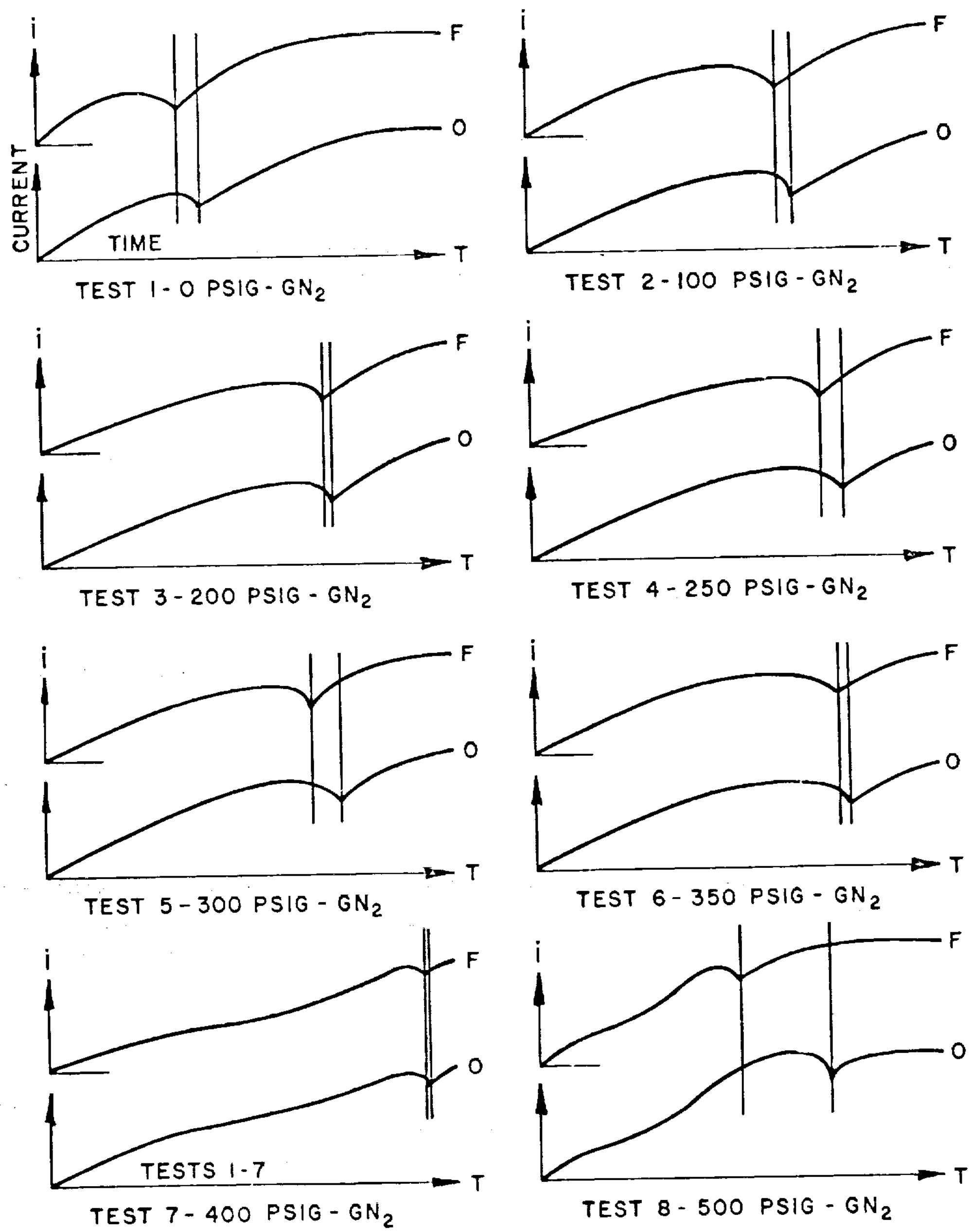


Figure 10. Typical Valve Current Traces (Fig. 19 of Ref. 7)

Figure 11 is a reproduction of page 6 of Conax Explosive Valves Bulletin Number 6200 which describes how standard normally closed and normally open valves operate. To circumvent the possible blow-by problem, a three-way valve was modified (by omitting the normally open port) in order to use not only the interference fit on the ram body to prevent blow-by, but also a tapered shoulder to form a second interference fit at end-of-stroke. In effect this made use of the sealing features of both normally closed and normally open valves. Figure 12 shows a drawing of the valves tested, Conax part number 1802-130.

c) Hydraulics Research Bipropellant Valve

A third valve tested was a flight-type, bipropellant valve manufactured by Hydraulics Research and Engineering Co. and designated P/N 48000880.

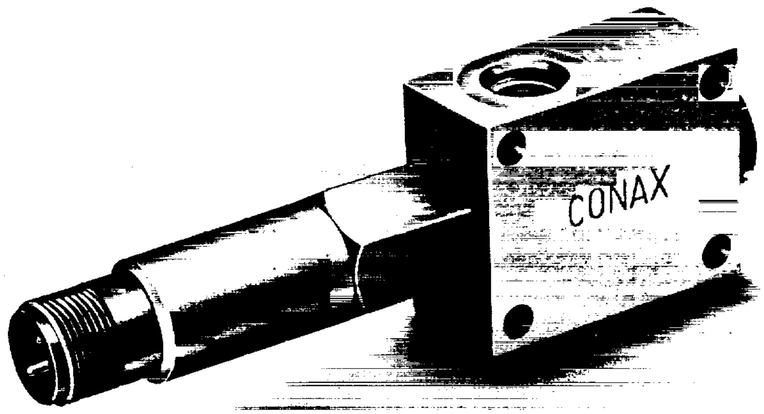
The valve employs a torque motor to open and close the fuel and oxidizer flow control ports simultaneously. This is accomplished by covering or uncovering the ports with a movable flapper. The ports are arranged in separate, fluid sealed chambers that completely isolate the fuel and the oxidizer. The flappers are mounted in separate flexure tubes and are attached to a common armature which mechanically links the flapper assemblies so that two propellants may be controlled simultaneously with one torque motor.

The torque motor is isolated from the fuel and oxidizer chambers by the flexure tubes. This arrangement isolates propellant from the electrical portion of the valve, thereby preventing deterioration of the electrical materials. The valve contains no close fitting, sliding parts and therefore is not susceptible to propellant gumming effects.

When the valve is deenergized, i.e., no electrical signal present, the torque motor is maintained in the shutoff position by magnetic bias and the flappers seal both fuel and oxidizer ports.

When a step input of electrical control is applied, the resulting coil flux produces a torque tending to move the flapper off the ports. The electrical input is designed to saturate the magnetic circuit of the torque motor so that a very high driving force results. This force opens the flappers fully against stops which are preset to give the desired pressure drop across the valve.

Removal of the electrical signal permits the flappers to return to the seal-off position.



detailed operation

FIG. 8 BEFORE FIRING

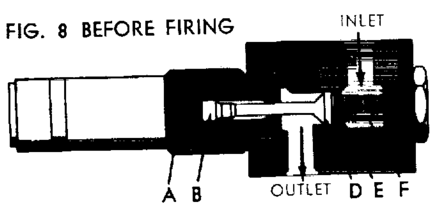
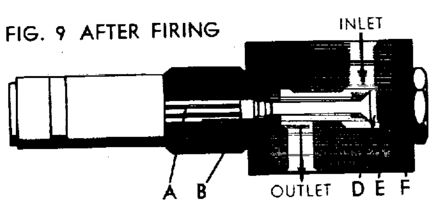


FIG. 9 AFTER FIRING



NORMALLY CLOSED VALVE

FIG. 10 BEFORE FIRING

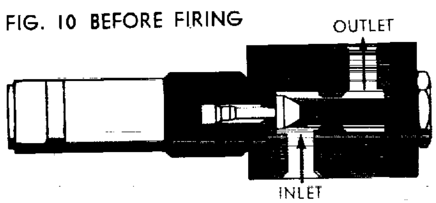
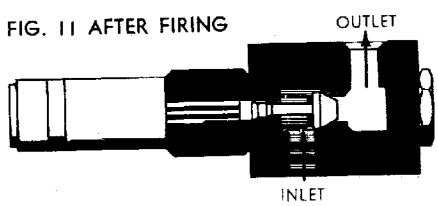


FIG. 11 AFTER FIRING



NORMALLY OPEN VALVE

U.S. Patent No. 2,815,882
Other U.S. and Foreign Patents Pending

—Normally closed valve (Figs. 8 and 9)

In this valve, system pressure is held by a solid metal diaphragm "E" machined as an integral part of the valve body. The piston is interference-fitted into the actuator housing thereby locking it firmly in place and preventing products of combustion from bypassing the piston "B" and entering the fluid stream. This feature also permits complete system proof pressure testing to 7500 psi without bypassing or removing the valve. Upon operating the valve, shearing head "D" on the end of the ram shears the diaphragm as a single piece of metal, holding it captive against the end plug "F". There is no contamination of the working fluid. Throughout the travel of the piston, constant interference-fit metal to metal seal provides leak proof operation. Numerous tests have proven that this seal will hold at least 10,000 pounds per square inch without leakage after firing.

When the valve opens there are four distinct actions:

1. An electrical input causes ignition of detonator "A".
2. The high static friction at point "B" is broken as the ram starts its forward travel.
3. Ram head "D" cuts through diaphragm "E".
4. Diaphragm "E" is carried forward by the ram and pinned against plug "F" leaving a clear flow passage in the form of an annulus.

Detailed Operation—Normally open valve (Figs. 10 and 11).

The operation sequence of the normally open valve, is the same as for the normally closed valve. The ram, however, instead of being concave with a shearing edge on its periphery, is tapered so that when closed, it mechanically deforms the valve seat to create the leak tight seal.

Figure 11. Page 6 of Conax Explosive Valves Bulletin No. 6200

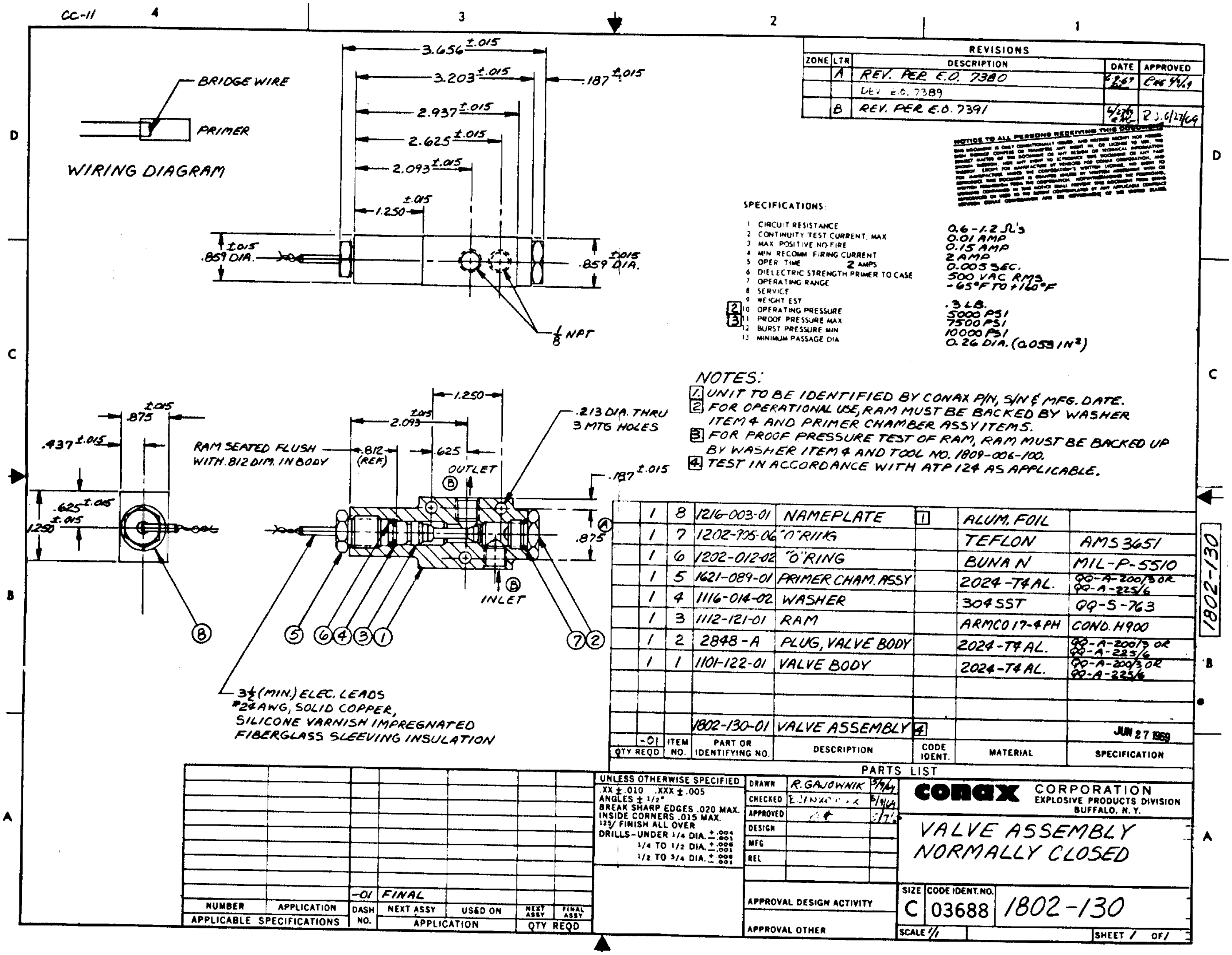


Figure 12. Conax Drawing of Explosive Valves P/N 1802-130.

Propellant inlet filters are provided to protect the torque tube and seat assemblies.

Design parameters for the subject bipropellant valve are listed in Table I. Two views of the valve with the lines adapting it to the test system are shown in Fig. 13.

TABLE I. DESIGN PARAMETERS OF HYDRAULICS RESEARCH BIPROPELLANT VALVE P/N 48000880

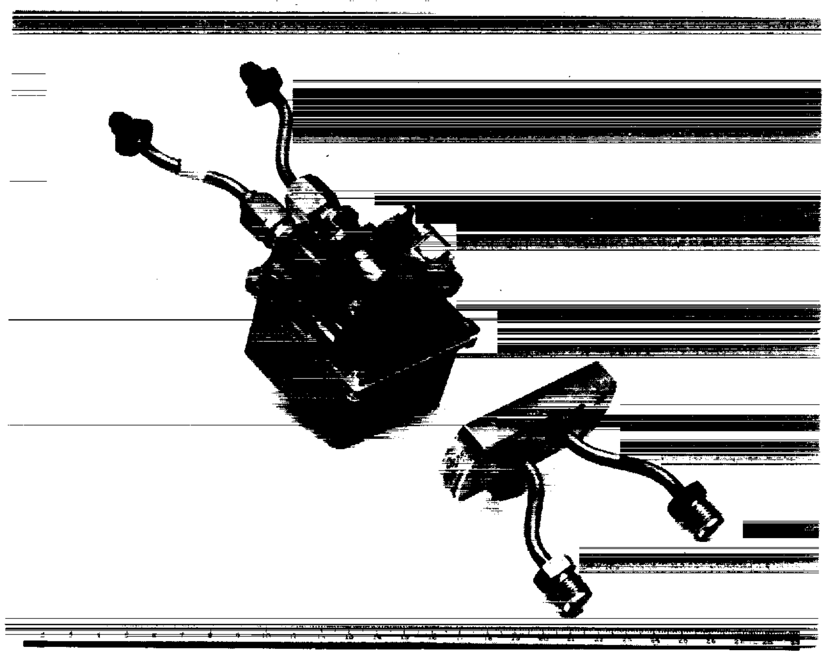
Operating Medium:	Oxidizer: 80% F_2 + 20% O_2
	Fuel: 55% CH_4 + 45% C_2H_6
Operating Pressure:	350 psig
Operating Temperature:	+100°F to -320°F
Flow vs. ΔP (isopropyl alcohol):	Fuel Port: 32 psid @ 0.736 GPM
	Oxidizer Port: 36 psid @ 1.62 GPM
Filter:	Area 2.5 sq. in. minimum
	Nominal 20 micron
Seat Material:	Teflon
Leakage (helium):	External 2 minutes @ 350 psig - none
	Internal 6 minutes @ 350 psig - 0.36 cc max
Response @ 350 psid:	Open 10 msec maximum
Electrical:	24-32 VDC, 1.25 amp @ 28 VDC
Hold-up Volume:	0.01 in.^{3} total (both outlets)

4. Valve/Injector Coupling and Dribble Volumes

With the Valcor solenoid valves, two valve/injector coupling arrangements were tested. These are designated "Normal Coupling" and "Close Coupling".

To assure thermal conditioning of the initially entering propellant to the desired propellant temperature, it was necessary to condition the propellant valves together with the respective propellants. Therefore, short stand-off tubes with drilled inserts to minimize internal volumes were used between the propellant valves and the injectors. The inserts are visible in Fig. 6. Insert diameters are the same as the distribution manifolds in the nine-pair injector. Liquid propellant velocities in the inserts are 20 ft/sec at design flows. This arrangement wherein the propellant valves are conditioned with the propellants is the Normal Coupling configuration. (All tests discussed in Ref. 1 used this valve/injector coupling configuration.)

Of necessity, the Normal Coupling configuration results in somewhat larger dribble volumes due to the presence of the stand-off tubes.



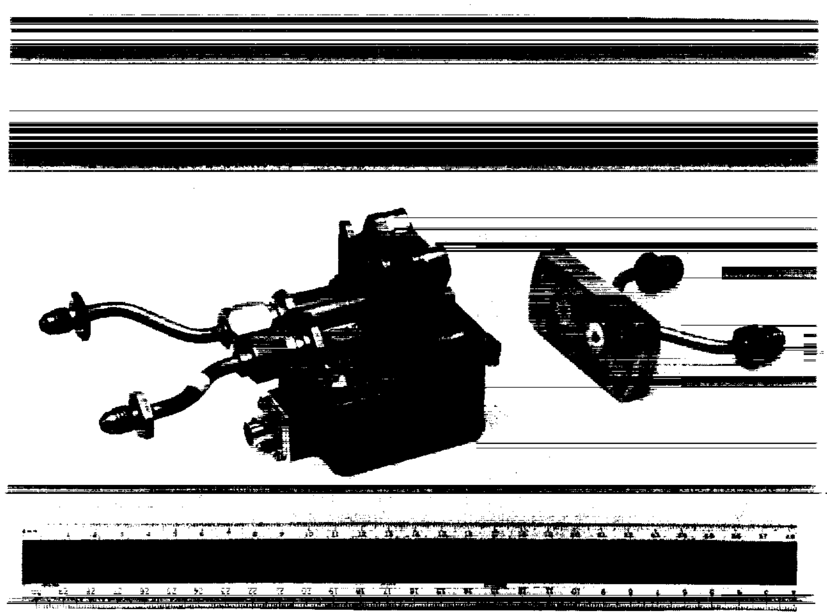


Figure 13. Views of Hydraulics Research Valve P/N 48000880 and Connecting Lines

To examine this effect, the valve and injectors were reworked to minimize the line length, yet maintain the capability for interchanging the injectors and valves. The rework reduced the feed line length by about 49%. This configuration is the Close Coupling arrangement. An important consequence is that the valve is no longer conditioned with the propellant but rather with the injector/chamber.

Sketches of the two valve/injector configurations are given in Fig. 14.

Dribble volume is defined as the propellant volume between the downstream side of the closed propellant valve and the downstream face of the injector. Dribble volumes for the two injectors in each of the two valve/injector coupling configurations are given in Table II.

TABLE II. DRIBBLE VOLUMES OF INJECTOR/VALVE (VALCOR SOLENOID) COMBINATIONS

	NORMAL VALVE/ INJECTOR COUPLING		CLOSE VALVE/ INJECTOR COUPLING	
	1-Pair Injector cu. in.	9-Pair Injector cu. in.	1-Pair Injector cu. in.	9-Pair Injector cu. in.
Ox Prop to Injector	.055	.055	.029	.029
Oxidizer Injector	.026	.083	.026	.083
Oxidizer Dribble Volume	.081	.138	.055	.112
Fuel Prop to Injector	.064	.064	.034	.034
Fuel Injector	.031	.090	.031	.090
Fuel Dribble Volume	.095	.154	.065	.124

5. Valve Timing

With a fixed input voltage, the opening time of a solenoid poppet valve varies directly with inlet pressure and temperature. The inlet pressure adds to the force required to open the valve and the temperature changes the resistivity of the copper coil affecting the energy available to move the solenoid core. The characteristics of the individual Valcor propellant valves were such that under the normal inlet pressures and temperatures (-320°F Ox valve and -100°F fuel valve), the valve opening times were simultaneous with simultaneously applied electrical voltage.

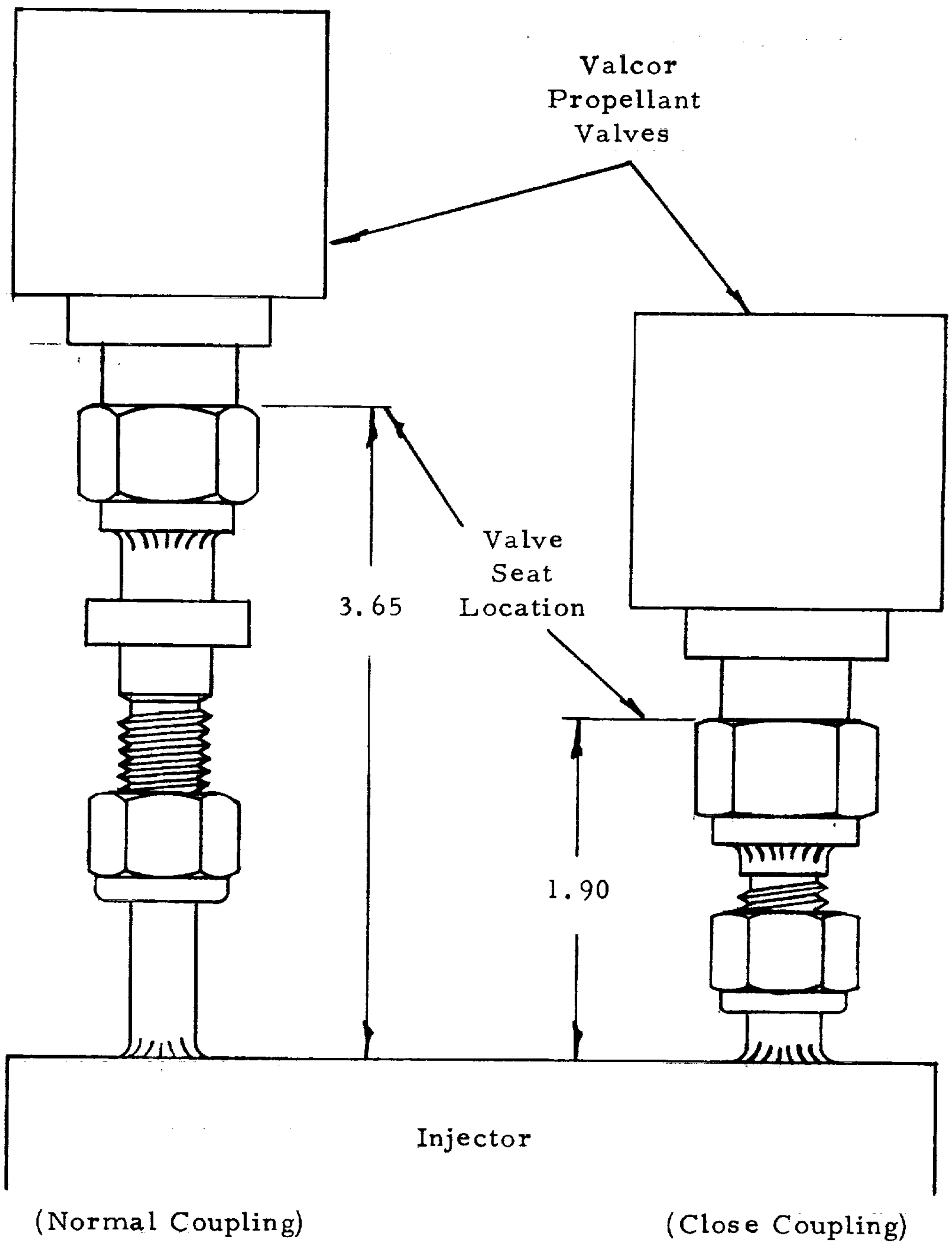


Figure 14. Sketches of Valve/Injector Coupling Configurations

In the Phase I program (Ref. 1) and in the initial runs of the present program, a fixed electrical lead was obtained with an additional time delay (nominally 11 msec) caused by a relay closure in series with the opposite propellant valve. This method had two shortcomings, however. First, propellant leads other than the nominal 11 msec could not be obtained at a given temperature and, second, a constant lead could not be obtained at various temperatures.

The valve timing system was revised prior to Run 67 to provide a continuous range of lead/lags. This was accomplished by introducing a fixed lag in the oxidizer valve circuit and a variable lag in the fuel valve circuit. Figure 15 gives a plot of time delay relay setting in the fuel valve circuit versus electrical lead/lag. Figure 15 was used to set a target electrical lead. The resulting actual electrical lead was determined from valve current traces (Sec. III. C).

6. Run Tank Ullage

In the Phase I program, fuel manifold pressures in excess of tank set pressure were indicated under certain conditions (Ref. 1, pg. 48). As one means for investigation, provisions were made to test a second level of run tank ullage. Specifically, a second pair of run tanks with twice the volume of the first pair were fabricated and fitted to be interchangeable with the original pair.

In addition, a fuel pre-fill tank was added to the fuel system to permit partial loading of the fuel run tank. Previously, the fuel tank had to be completely filled for each run and the propellant was fully expelled each time. (More details of the test system and its operation are given in the following section). Because the run tanks were small, in order to limit the quantity of "exposed" propellants in each run, and even though all line volumes were kept as small as practical, the total ullage volumes in the system were relatively large. Therefore, doubling the run tank volume did not double the ullage volume. Table III summarizes the ullage volumes of the various feed system configurations.

B. TEST SYSTEM

The test system used in the present program is the same one used in the Phase I program (Ref. 1) but with a few additions to improve versatility and/or reliability. For completeness, a full description of the test system follows.

The schematic of the system used in the present program is given in Fig. 16. The system consists of several subsystems: B_2H_6 system; O_2, F_2 and OF_2 systems; helium pressurizing systems; temperature conditioning

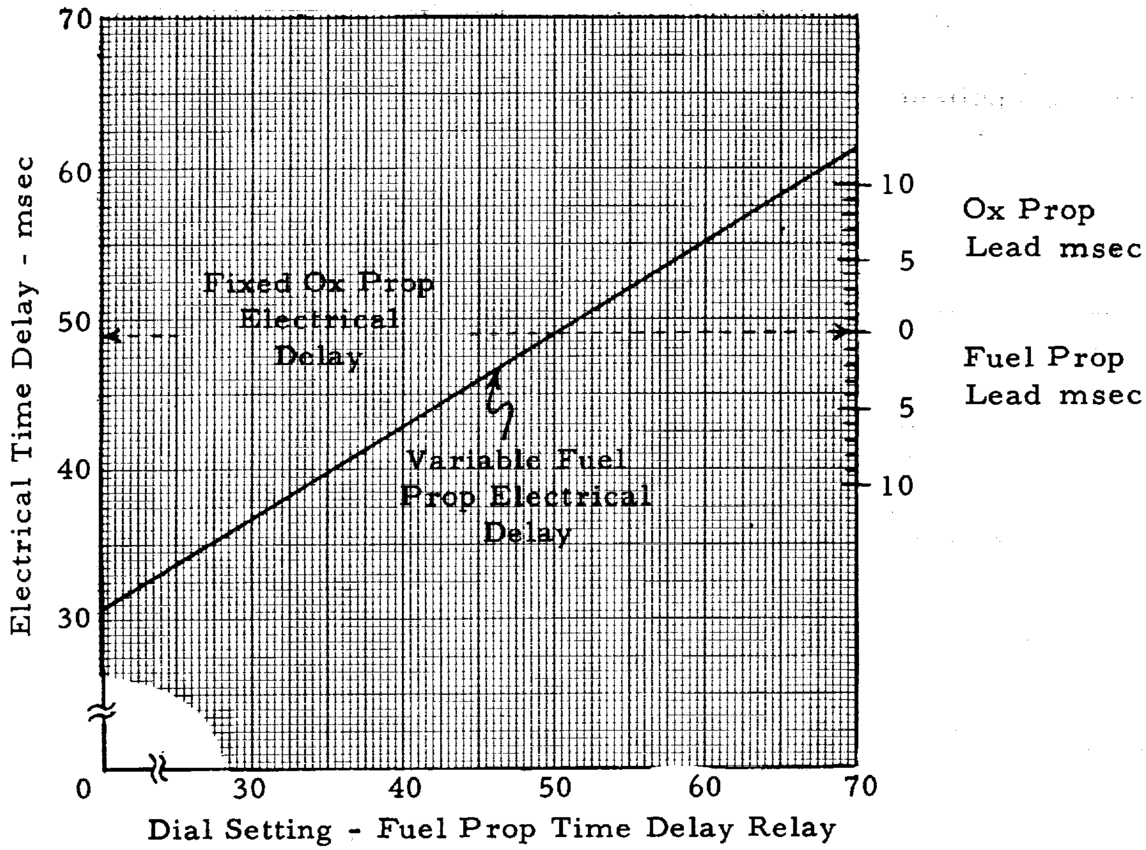


Figure 15. Electrical Lead/Lag Timing of Solenoid Propellant Valves (Run 67 onward)

TABLE III. ULLAGE VOLUMES OF FEED SYSTEM CONFIGURATIONS

	Small Run Tanks			Large Run Tanks		
		Fuel System			Fuel System	
	Oxidizer System	Without Pre-fill Tank[a]	With Pre-fill Tank[b]	Oxidizer System	Without Pre-fill Tank	With Pre-fill Tank[b]
Vol. of pre-fill tank assembly, cu. in.	N/A	N/A	1.29	N/A	N/A	1.29
Vol. of run tank, cu. in.	1.15	1.15	1.15	2.28	2.28	2.28
Vol. of run tank plus liquid vol. to propellant valve seat, cu. in.	1.98	1.69	1.69	3.11	2.82	2.82
Vol. of helium pressurizing lines, cu. in.	1.53	1.38	1.38	1.53	1.38	1.38
Total system volume, cu. in.	3.51	3.07	3.07	4.64	4.20	4.20
Vol. of liquid propellant loaded, cu. in.[c]	0.735	1.69	1.29	0.735	N/A	1.29
% Ullage[d]:						
- based on total system volume	79%	45%	58%	84%	N/A	69%
- neglecting volume of helium pressurizing lines	63%	0%	24%	76%	N/A	54%

(a) Fuel system used in Phase I program (Ref. 1).
(b) Fuel systems used in present program.
(c) Quantity of propellant required for a run: 0.735 cu. in. for OF_2 at -320°F, 1.055 cu. in. for B_2H_6 at -100°F.
(d) % Ullage = Gas Vol. x 100/(Gas Vol. + Liq. Vol.).

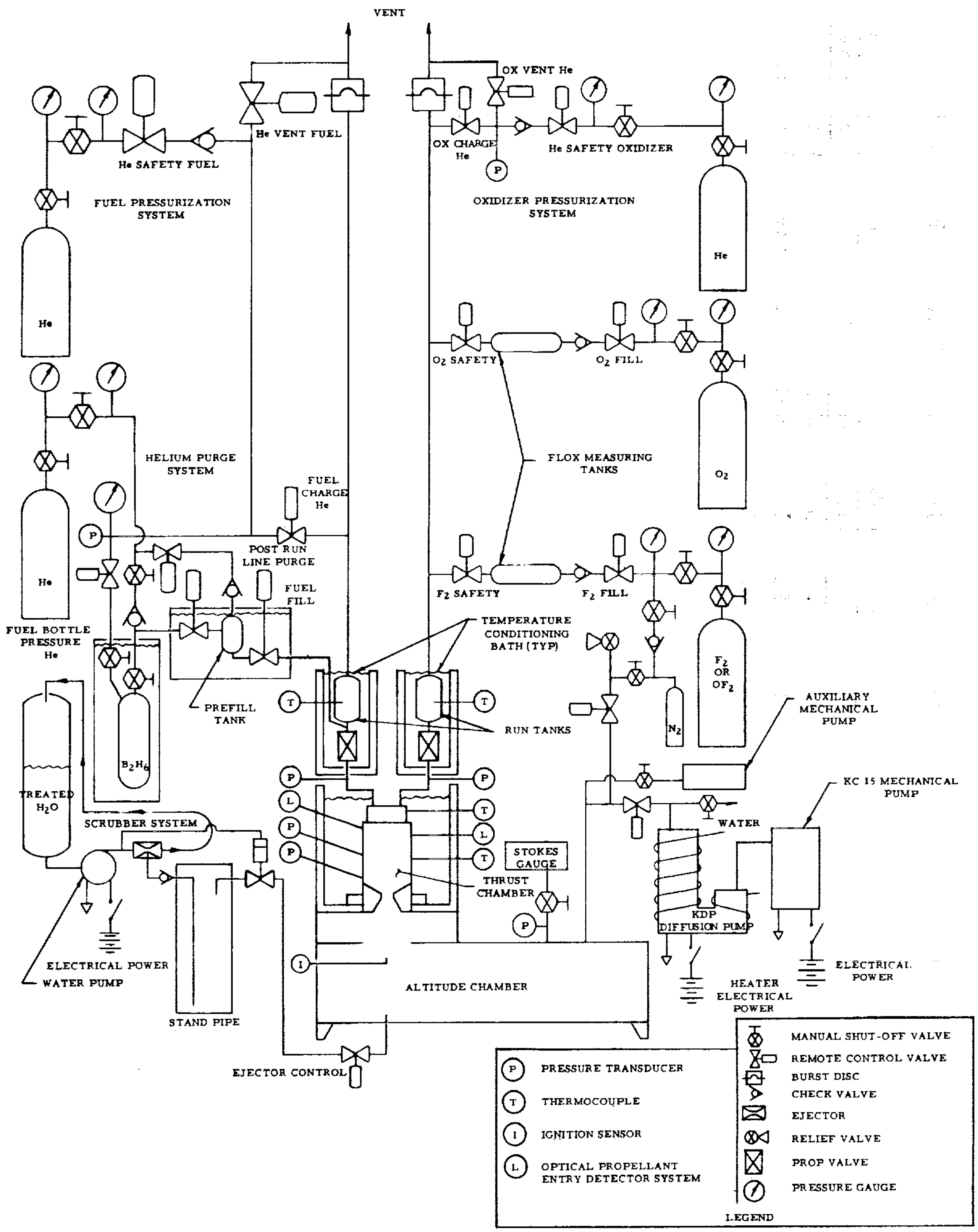


FIGURE 16. SCHEMATIC OF VACUUM IGNITION TEST SYSTEM FOR PHASE II PROGRAM

systems and a vacuum/scrubber system. Each component was meticulously cleaned and degreased prior to assembly. The techniques varied to suit the individual components and included vapor degreasing, acid baths, solvent flushing, hot detergent water flushing, rinsing and vacuum drying. Welded or brazed joints were used wherever possible and Voi-Shan conical flared fitting seals were used with AN flared fitting connectors. Following assembly with cleaned lines and fittings, the system was leak checked with helium and the oxidizer subsystem was passivated with fluorine gas.

The test system is described in greater detail in the following paragraphs.

1. Diborane System

This system provides the proper amount of diborane in the fuel propellant tank for approximately 200 msec of steady state operation. Such short runs are sufficient since the study is concerned with events and processes up to and including ignition but not steady state operation or performance. The reasons for limiting the run tank capacity to one run's worth of propellant were (a) to limit the quantity of "exposed" propellant in the event of a failure or malfunction, and (b) to simplify overall system operation especially when changing the test hardware from one configuration to another. The original diborane system consisted of (1) a diborane storage tank with suitable gas side and liquid side hand valves to permit transfer of the diborane into the test run tank, (2) a remotely operated cryogenic fuel fill valve and (3) a run tank and propellant valve.

The original run tank was sized to hold the needed amount of diborane for a run at 0°F which was the warmest fuel temperature to be tested. At the much lower temperatures, which constituted the bulk of the testing, the tank held an excess of diborane since the loading system did not permit partial loading of the run tank. To provide partial filling, a pre-fill tank was added to the system together with an additional stop valve and a pressurizing valve. The pre-fill tank assembly, with a volume of 1.287 cu. in., allows partial filling of either of the diborane run tanks tested (Table III, Sec. III. A. 6).

Each of the three diborane subsystems is maintained at -100°F with crushed dry ice in separate conditioning baths (Fig. 16). Prior to loading propellant, the system is evacuated from the altitude chamber to the closed liquid transfer hand valve located on the diborane storage tank. The pre-fill tank is then loaded and subsequently transferred to the run tank. This technique provides vacuum fill of the diborane up to the propellant valve seat, thus eliminating trapped gases which could influence start transients. Following each run, the run tank, propellant valve and injector are purged with helium automatically. Subsequently, the fill lines, pre-fill tank and loading valves are also purged with helium.

2. Oxidizer System

The oxidizer system is used to provide the proper amount of either liquid OF_2 or liquid Flox in the oxidizer propellant tank. If Flox is desired, the 70/30 mixture is made from gaseous fluorine and oxygen. If OF_2 is desired, the fluorine cylinder is replaced by a cylinder of OF_2 and the O_2 cylinder is kept closed.

The oxidizer system, then, consists of regulated sources of oxygen and fluorine (or OF_2) gas which are bled into separate measuring tanks (Fig. 16). The volumes of the tanks and the lines between the remotely operated valves are known (F_2 and OF_2 system, 138.22 cu. in.; O_2 system, 62.00 cu. in.). Therefore the desired weights of fluorine and oxygen in the measuring tanks are readily obtained from the measured gas temperatures and the set pressures. The run tank and propellant valve are maintained at -320 °F in an insulated conditioning bath filled with liquid nitrogen. Prior to a run, the prop valve, run tank and oxidizer manifold up to the oxygen and fluorine safety valves are evacuated. Then, the safety valves are opened allowing the gases to condense into the run tank. Since the fluorine and oxygen are condensed into a closed system, the problem of unequal boil-off changing the Flox percentage composition is avoided. It is expected that the turbulence caused by the condensation process, natural convection, the high miscibility of O_2 and F_2 and the short time between preparation of the mixture and firing of the engine (approximately 10 minutes) prevent any significant stratification of the oxidizer mixture in the run tank. The operation is monitored by visually observing the measuring tank pressures on absolute pressure gauges. Because the regulator delivery pressure on the fluorine bottle is limited, the fill operation is repeated. The two charge/condense cycles provide the proper amount of 70/30 Flox for 200 msec of steady state operation. Figure 17 shows the pressure vs temperature settings required to produce the desired Flox weight in the run tank. After each run the manifold, run tank and propellant valve are purged with helium. This system provides the vacuum fill of Flox up to the propellant valve seat thus eliminating the problem of entrapped gases which could influence start transients. The same system and methods apply for OF_2 except that only the fluorine measuring tank is used.

3. Helium Pressurizing Systems

Separate helium systems pressurize the propellant tanks to the levels required for steady state design flow under the various test conditions. Helium is used rather than nitrogen because it is less soluble in diborane (Ref. 8). Separate systems are used for the oxidizer and fuel tanks to provide safety through isolation, and flexibility of control. Referring to Fig. 16, both systems are identical. Each contains a regulated helium supply, safety valve, charge valve, vent valve and check valve to prevent back flow into the supply.

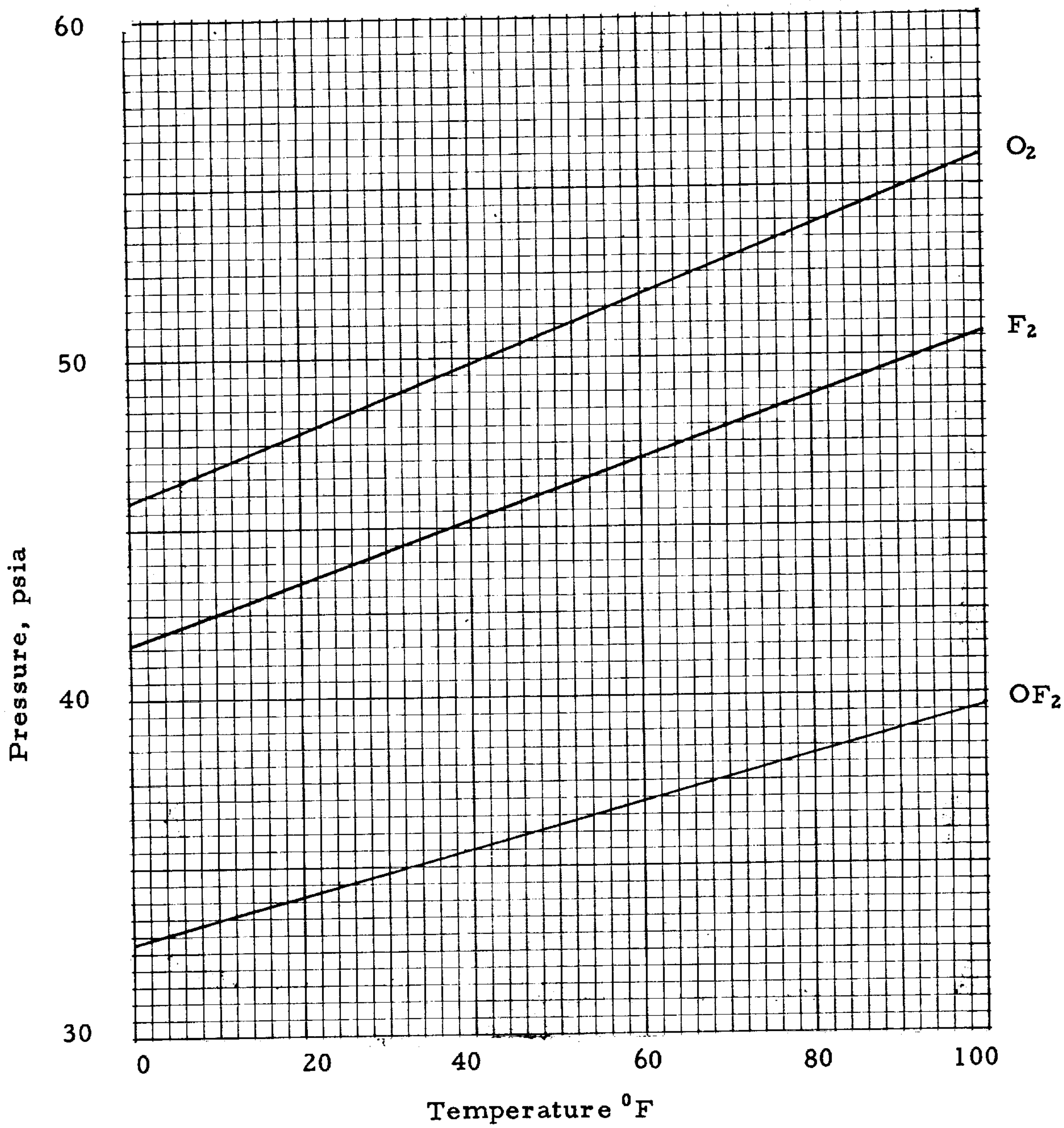


Figure 17. Flox System Pressurization Curves

A similar arrangement provides the helium required for the purge of the diborane loading system.

4. Vacuum Ignition Test Module

Most of the components of the fuel and oxidizer pressurizing systems, Flox mixing system, the run tanks, propellant valves, and conditioning baths for the propellant tanks and valves and the diborane pre-fill tank are mounted on a three foot square by one-half inch thick aluminum plate. This assembly is called the Vacuum Ignition Test Module. Figure 18A shows a top view of the module in the process of being assembled for the Phase I program. Figure 18B shows a front view of the module with the diborane conditioning bath removed to expose the diborane propellant tank and solenoid propellant valve.

5. Temperature Conditioning Systems

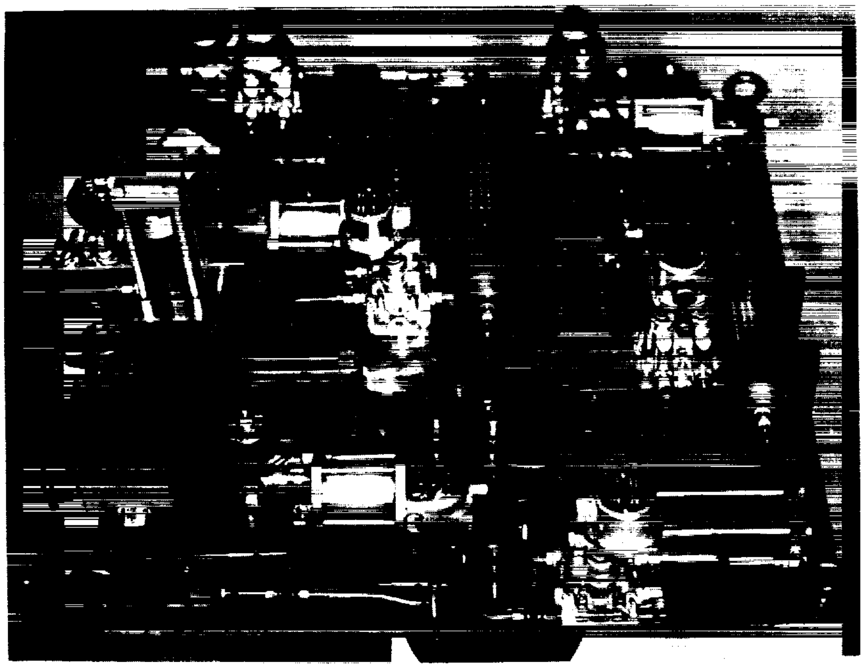
The conditioning of the propellants is described in Secs. III. B. 1 and 2, above, for the fuel and oxidizer, respectively.

The injector/chamber assembly was thermally conditioned to +70°, -100°, -200° and -250°F for the various runs. For the -100°F runs, crushed dry ice was placed in the chamber conditioning bath and the runs were made after the engine temperatures stabilized at the -100°F dry ice temperature. The +70°F runs usually required no conditioning since hardware temperature in the test stand was nominally 68°F. For the -200° and -250°F runs, advantage was taken of the long thermal time constant of the heavyweight assembly. For these runs, the hardware was first chilled to -100° with dry ice. Additional cooling was accomplished with liquid nitrogen chilling the dry ice and hardware to about -220° or -265°F. The engine was fired at -200° or -250°, as desired, as it warmed up to restabilize at -100°.

Figure 19 shows the run tanks and solenoid prop valves (decoupled from the upstream system and without their conditioning baths) connected to the injector/chamber assembly which is mounted in the thrust chamber conditioning bath. The base flange bolts directly to the altitude simulation system.

6. Vacuum/Scrubber System

The vacuum system for the Phase I program was designed to provide an initial pressure altitude in excess of 250,000 ft. It has sufficient volume to contain the products of combustion of the 0.2 second run plus 1.8 seconds of helium purge at a resulting pressure less than 6 psia. Calculations show that flow is choked in the nozzle throughout the ignition



.8A. Top View

18B. Front View

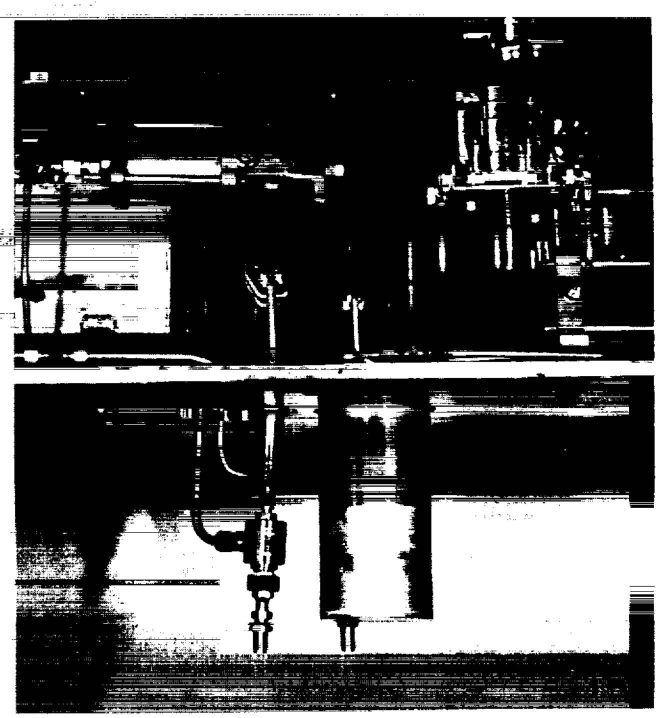


FIGURE 18. Vacuum Ignition Test Module (In Process of Assembly)

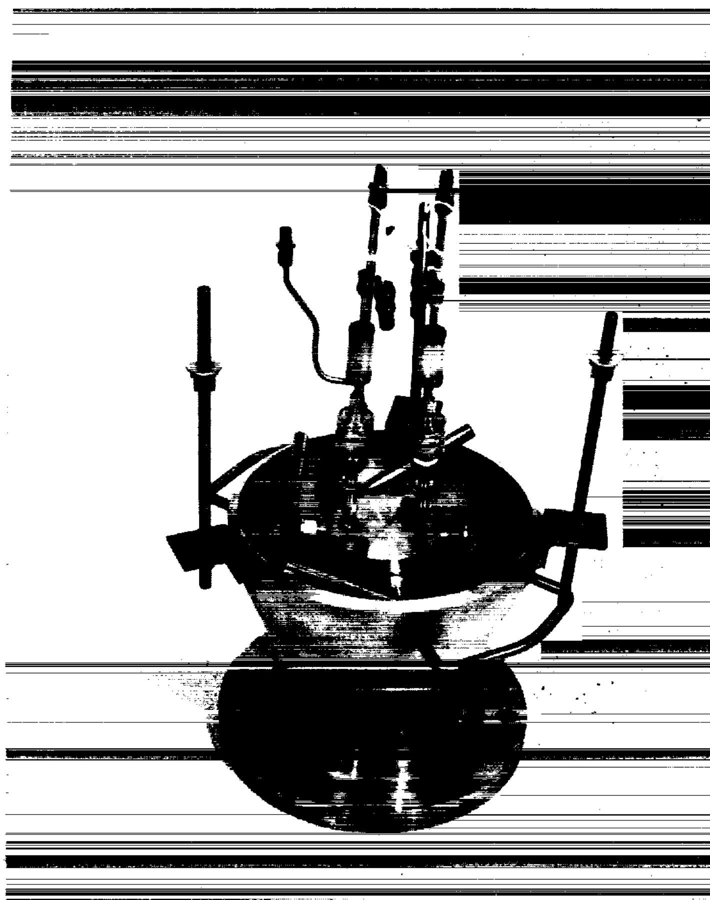


Figure 19. Thrust Chamber Assembly Mounted in Bath

delay period and for the duration of the test run. The thrust chamber bath attaches to a 12 inch length of 8 inch diameter stainless steel pipe which is welded to a 5 foot length of 18 inch diameter carbon steel pipe. A 6 inch Kinney diffusion pump Model KDP-6 is backed by a Kinney mechanical pump KC-15. The pumps are isolated from the vacuum chamber during a run by a 4 inch vacuum valve to minimize ingestion of propellant and combustion products. The ultimate vacuum attained during test conditions was 2 microns which corresponds to a pressure altitude of 282,000 feet. (Figure 20 shows the relation between pressure in microns and geopotential altitude in feet.)

Following each altitude ignition test run, the vacuum chamber was alternately pressurized to 15 psia with nitrogen and pumped to about 7 psia by a water ejector system (Fig. 16). Approximately 97 percent of the gaseous exhaust products were removed from the vacuum chamber in this manner. The gases were entrained in the ejector stream and discharged into a treated water supply. A standpipe and pressure-switch-operated stop valve were added to the scrubber system for the present program to prevent water back-up into the altitude chamber in the event that the discharge pressure of the water pump falls off. Such an incident occurred previously and resulted in some difficulty in de-contaminating the vacuum facility.

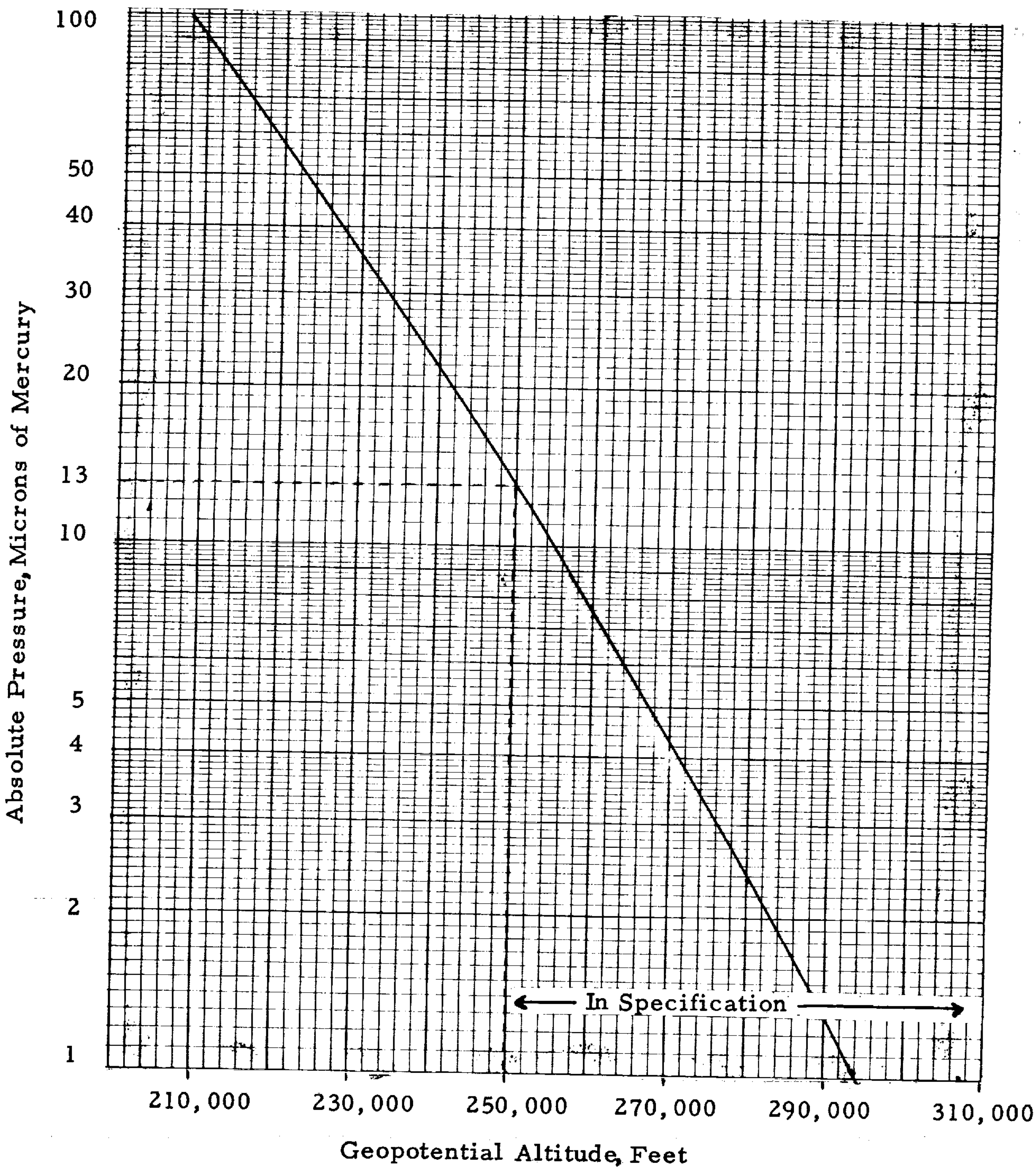
An auxiliary roughing pump was also installed for the present program to evacuate the altitude chamber before opening the 4-inch vacuum valve to the KDP-6 diffusion pump and the KC-15 mechanical pump. This addition was made to reduce contamination of the high vacuum pumping system.

Figure 21 shows a front view of the OF_2/B_2H_6 altitude ignition test system installed in Test Stand S12 Bay C during the Phase I program. The photo shows the vacuum ignition test module suspended from an overhead hoist and supported by four frame posts. The thrust chamber bath assembly is mounted on the altitude chamber and connected to the module. The diffusion pump and mechanical pump are in the foreground and the diborane tank is on the right.

C. INSTRUMENTATION

In addition to conventional instrumentation required for propellant pressurization and system monitoring, special instrumentation was employed to determine ignition delays and monitor pressure transients during the ignition delay period. This instrumentation included an optical system to detect propellant entry into the thrust chamber, a light detector to detect ignition and high response pressure transducers and recording equipment.

Chamber pressure was measured by two Model 603A Kistler piezoelectric pressure transducers and two Model 566 Kistler charge



NOTE: Data converted from NASA U.S. Standard Atmosphere, 1962 Table IV.

Figure 20. Pressure Vs Altitude

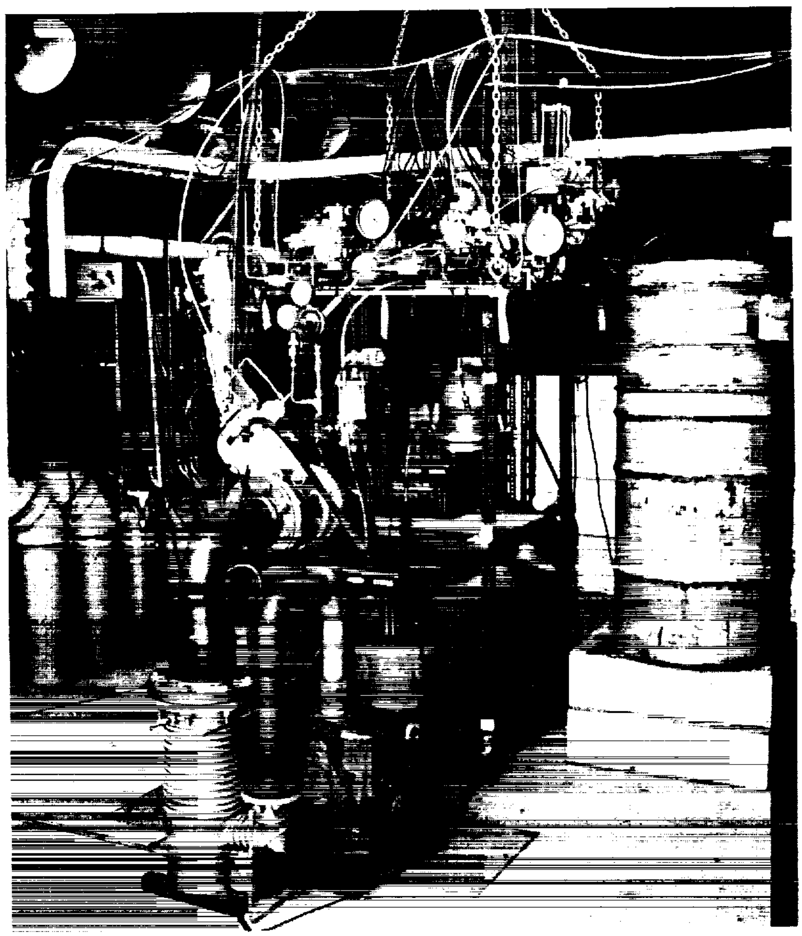


Figure 21. Front View Test Stand S12C Installation

amplifiers. The two transducers were flush-mounted in the chambers in a plane 7/16-inch from the injector face. The gain of one transducer was set high to detect chamber pressure rise due to propellant entry and vaporization prior to ignition. The other transducer was set to detect pressure transients at and after ignition. Both chamber pressure transducers were coated with GE RTV Adhesive Sealant to delay heating (or cooling) of the transducers which would otherwise cause a zero shift. Generally, the coatings had to be replaced every run due to erosion.

Two additional Kistler 603A transducers were located in the oxidizer and fuel injector manifolds, as shown in the drawings of Appendix A. These transducers indicated the start of flow through the injector as well as (a) the occurrence of water hammer pressure peaks upon hard-liquid filling of the injectors and (b) pressure peaks due to chemical reactions inside an injector manifold. The frequency response of the four Kistler pressure measurements is well in excess of 25 kHz.

A propellant entry detector was developed for the Phase II program. The propellant entry detector depends upon attenuation of a light beam by the propellants. A light beam is directed across the injector face over a pair of orifices and to a light pipe located behind an opposing window. The light pipe conducts the incident light to a detector which is conveniently located away from the effects of temperature conditioning. Passage of propellant attenuates the light beam causing a change in the level of the signal which is displayed on an oscilloscope.

Initially, the propellant entry detector consisted of a grain-of-wheat lamp as light source, a GE L14B Light Detector/Planar Silicon Photo Darlington Amplifier and associated electrical circuitry, a 0.125-in. diameter light pipe and oscilloscope read-out. Small sacrificial windows in the chamber wall protect the light source and the light pipe from the hot corrosive gases and are used to effect pressure seals.

Initial tests indicated the need for a higher intensity light source and/or a more sensitive detecting element. Consequently, the grain-of-wheat lamp was replaced by a GE 222 pilot lamp which contains a built-in condensing lens to concentrate the light beam. Also, the GE L14B light detector was replaced by an RCA 1P28 photomultiplier tube. The resulting system yielded more than adequate sensitivity. In fact, low level emission that occurred relatively early in the ignition delay period was generally sensed by this optical system. Components of the system in exploded view are sketched in Fig. 2.

An ignition detector was also added for the Phase II program. The sensor is a GE L14B light detector/amplifier mounted in a probe which extends into the altitude chamber and is positioned directly under the down-firing rocket engine. The light detector element is protected from the direct effects of the ignition and combustion by a four inch length of pyrex glass tubing.

To maintain high response, the signals of the four Kistler transducers and both optical detectors were displayed on oscilloscopes and recorded photographically by Polaroid cameras. Fuel manifold pressure, oxidizer manifold pressure, low sensitivity chamber pressure and propellant entry were displayed on one Tektronix dual-beam oscilloscope by using two type C-A plug-in amplifiers which permit simultaneous display of four parameters. High sensitivity chamber pressure, ignition and propellant entry were displayed on a second Tektronix dual-beam oscilloscope. Joint display of the propellant entry detector signal provided a common reference point for both oscilloscope records and eliminated potential errors due to scope triggering level tolerances. Oscilloscope sweep rates were 10 msec/cm up to Run 62 and 5 msec/cm thereafter. The sweep was triggered by the voltage signal to the leading propellant valve.

Propellant valve voltage and current were monitored on a direct print recording oscillograph. Altitude chamber pressure was measured prior to each run with a Stokes-McLeod gauge and continuously monitored with a strain gauge transducer and digital read-out. Visual gauges mounted on the storage gas bottles gave supply and regulated pressures. Separate absolute pressure visual gauges gave the pressure in each of the two calibrated Flox and OF_2 tanks. System temperatures were measured by copper-constantan thermocouples and monitored with a seven position manual switch and digital read-out.

Table IV provides a listing of parameters measured, type of transducer used and method of read-out. The location of much of the system monitoring instrumentation is indicated in Fig. 16.

TABLE IV. INSTRUMENTATION FOR VACUUM IGNITION TESTS

Parameter	Transducer	Primary Read-out
Instrumentation Used in Phase I:		
Chamber Pressure	Kistler 603A (high gain)	Oscilloscope
Chamber Pressure	Kistler 603A (low gain)	Oscilloscope
Injector Manifold Press. (2)	Kistler 603A	Oscilloscope
Propellant Temp (2) (run tank)	c/c Thermocouple	Indicating
Fuel Bath Temp.	c/c Thermocouple	Indicating
Ox Temp in Measuring Tank (2)	c/c Thermocouple	Indicating
Injector Temperature	c/c Thermocouple	Indicating
Chamber Temperature	c/c Thermocouple	Indicating
Valve Current (2)	----	Oscillograph
Valve Voltage (2)	----	Oscillograph
Altitude Pressure	Stokes-McCleod Gage	Indicating
Altitude Pressure	Teledyne 254SA (0-15 psia)	Indicating
Tank Pressure (2)	Bourdon Tube Gage	Indicating
Ox Measuring Tank Press (2)	Bourdon Tube Gage	Indicating
Additional Instrumentation Used in Phase II:		
Tank Pressure (2)	Dynisco PT-76	Oscillograph
Ignition Sensor	L14B Light Detector	Oscilloscope
Liquid Entry Time	RCA 1P28 Photomultiplier	Oscilloscope

IV. RESULTS

A. IGNITION TEST RESULTS

Seventy-six vacuum ignition test runs were conducted during the Phase II test program (Runs 49-124). Sixty-three of these runs were made with OF_2/B_2H_6, five with Flox/B_2H_6, three with OF_2 alone and five with B_2H_6 alone. All runs were initiated at a pressure altitude in excess of 250,000 feet. Table V is a summary of the test conditions and gives in addition a remark describing the results of each run.

Detailed data summaries of valve opening times, injector manifold pressurization events, and the various chamber data are given for meaningful runs with the solenoid propellant valves in Table VI. Results of tests using two other types of valves are given and discussed in detail in Secs. V.A.7 and 8.

B. COMBUSTION RESIDUE

The fact that a combustion residue is formed and deposited out is readily apparent from the propellant entry detector. The transmission of the windows is decreased 80-90% by the deposit from a single run. For this reason, the chambers were cleaned before all runs except for those marked "Nth Start" in Table V. In four OF_2/B_2H_6 runs and one Flox/B_2H_6 run, samples of the solid material remaining in the thrust chamber were analyzed by various techniques including infrared, X-ray diffraction and flame test. The samples analyzed came from OF_2/B_2H_6 Runs 108, 115, 116 and 124 and Flox/B_2H_6 Run 122. With the exception of Run 124, all samples were taken from a sample plug located in the thrust chamber barrel section two inches from the face of the injector. The plug extended 0.8 in. into the chamber and provided an exposed surface area of 0.74 sq. in. After a run, the sample plug was maintained in a dry nitrogen atmosphere at all times during removal from the engine, transfer to the laboratory area, removal of the sample from the plug and preparation of the sample for the respective analysis. In the case of Run 124, which was the last of the program, the engine was removed from the test system and brought to the laboratory area where the hardware remained exposed to air over a weekend. Subsequently, gray residue was scraped from the face of the 9-pair injector and examined by infrared spectroscopy, X-ray diffraction and flame test. Only this Run 124 sample was subjected to air-exposure.

For the infrared spectra, the samples were mixed with KBr and formed into a pellet. The spectra are given in Figs. 22 through 28.

TABLE V. SUMMARY OF TEST RUN CONDITIONS

Run	Chamber	Injector	Valve/Inj. Coupling	Run Tank Ullage	Propellant Lead (Electrical) msec	Injector Temp. °F	Propellant Temp. Ox °F	Propellant Temp. Fuel °F	Tank Set Pressure Ox psia	Tank Set Pressure Fuel psia	Remarks	
						OF_2/B_2H_6 RUNS						
Valcor Solenoid Valves												
63	100 psi	9-Pair	Normal	Large	13 F	-100	-320	-100	164	188	Smooth ign.	
68					1 F	+70	-320	-240	164	178	Smooth ign.	
49					simul.	+70	-320	-145	164	188	Check-out run.	
50					simul.	+70	-320	-100	164	188	Check-out run.	
59					simul.	-100	-320	-100	164	188	Fuel feed soft.	
60					simul.	-100	-320	-100	164	188	Smooth ign.	
66					simul.	-200	-320	-100	164	188	Fuel feed soft.	
70					simul.	-200	-320	-250	164	178	Smooth ign. but suspect partially frozen fuel.	
69					1.5 Ox	-100	-320	-250	164	178	Strong ignition spike.	
67					10 Ox	-200	-320	-100	164	188	Spike during P_c rise (at 34 msec).	
65					13 Ox	-200	-320	-100	164	188	Strong ignition spike.	
61					11 Ox	-100	-320	-100	164	188	Fuel feed soft.	
64					12 Ox	-100	-320	-100	164	188	Strong spike during P_c rise (at 34 msec).	
62					14 Ox	+70	-320	-100	164	188	Smooth with moderate ignition overpressure.	
116				Small	4 F	-180	-210	-200	178	179	Smooth ign.	Nth start
112					2 F	-100	-170	-100	186	188	Smooth ign.	
124					simul.	-100	-170	-100	186	188	Smooth ign.	
117					simul.	-260	-320	-225	166	171	Smooth ign.	
113					1 Ox	-100	-170	-100	186	188	Smooth ign.	Nth start
114					2.5 Ox	-195	-200	-205	178	179	Smooth ign.	
115					7 Ox	-180	-200	-200	178	179	Smooth ign.	
109					10 Ox	-100	-320	-100	164	188	Smooth ign. with minor overpressure.	
111					10.5 Ox	-100	-320	-100	164	188	Fuel feed soft.	Nth start
110					11 Ox	-100	-320	-100	164	188	Smooth ign. with minor overpressure.	Nth start
91			Close	Large	simul.	-100	-170	-100	182	188	Smooth slow ign., soft Ox feed.	
92					simul.	-100	-170	-100	182	188	No OF_2 flow, Ox valve froze.	
90					simul.	-250	-320	-200	178	178	Smooth ign.	
94					4 Ox	-100	-170	-100	182	178	Smooth ign. with minor overpressure.	
95					5.5 Ox	-200	-320	-200	179	178	Smooth ign. with moderate overpressure (POP at 38 msec).	

93					6 Ox	-100	-170	-100	182	188	No OF_2 flow, Ox valve froze.
96					6 Ox	-100	-170	-100	189	188	Smooth slow ign., soft Ox feed.
89					6 Ox	-190	-215	-200	178	178	Both feeds soft.
97					6 Ox	-240	-320	-225	166	177	Smooth ign. with moderate overpressure (Ox POP at 38 msec).
86				Small	3 F	-200	-200	-200	178	178	Smooth ign. with slight overpressure.
79					2 F	-200	-200	-200	178	178	Smooth ign.
80					simul.	-200	-200	-200	178	178	Ox feed soft.
85					1 Ox	-200	-200	-200	178	178	Fuel feed soft.
74					2.5 Ox	-200	-200	-200	178	178	Fuel feed soft, Ox valve slow to open.
81					2.5 Ox	-200	-200	-200	178	178	Ignition spike.
76					4 Ox	-200	-205	-165	178	178	Fuel feed soft.
77					4.5 Ox	-200	-220	-200	178	178	Smooth ign.
75					6 Ox	-200	-200	-200	178	178	Ox feed soft.
88					6.5 Ox	-190	-210	-200	178	178	Ignition spike.
82					8 Ox	-200	-200	-200	178	178	Ignition spike.
84					8.5 Ox	-200	-200	-200	178	178	Smooth ign. with slight overpressure.
83					10 Ox	-200	-200	-200	178	178	Fuel feed soft.
87					14.5 Ox	-200	-200	-200	178	178	Ignition spike.
Conax Explosive Valves											
78	100 psi	9-Pair	Close	Small	simul.	-100	-200	-200	142	144	Ox valve failure.
Hydraulics Research Bipropellant Valve											
98	100 psi	9-Pair	Mod. Close	Large	simul.	-260	-300	-190	162	183	Smooth ign.
99					simul.	-210	-300	-190	162	183	Valve failure.
Valcor Solenoid Valves											
56	100 psi	1-Pair	Normal	Large	13 F	-200	-200	-200	156	157	Smooth ign.
54					simul.	-180	-270	-170	156	157	Smooth ign.
100					4.5 Ox	-200	-165	-200	156	156	Ox feed soft.
103					5 Ox	-185	-175	-190	156	157	Smooth ign.
104					6 Ox	-180	-175	-195	156	157	Smooth ign.
58					13 Ox	-195	-195	-190	157	156	Ignition spike led to leakage both valves.
55					13 Ox	-205	-200	-210	156	157	Fuel valve opened slowly, ignition spike.
108	20 psi	1-Pair	Normal	Large	5 Ox	-125	-320	-105	66	87	Smooth ign.
107					5 Ox	-205	-200	-195	76	78	Ox feed soft.

FLOX/B_2H_6 RUNS

Valcor Solenoid Valves											
122	100 psi	9-Pair	Normal	Small	7 F	-250	-250	-250	196	174	Smooth ign.
118					simul.	-100	-320	-100	178	188	Smooth ign.
119					simul.	-240	-250	-240	178	188	No data, scope triggered prematurely.
120					simul.	-260	-250	-230	196	174	Smooth ign.
121					3 Ox	-260	-250	-250	196	174	Smooth ign.

SINGLE FLOW RUNS

Valcor Solenoid Valves											
102	100 psi	1-Pair	Normal	Large	B_2H_6	-15	N/A	-15	N/A	188	All gas injection.
71					B_2H_6	-100	N/A	-100	N/A	166	Minimal P_c deflection.
101					B_2H_6	-100	N/A	-100	N/A	167	Minimal P_c deflection.
105					B_2H_6	-100	N/A	-100	N/A	167	Minimal P_c deflection.
53					B_2H_6	-200	N/A	-185	N/A	160	No deflection as expected.
52	100 psi	1-Pair	Normal	Large	OF_2	-180	-205	N/A	166	N/A	Ox feed soft.
57					OF_2	-215	-200	N/A	157	N/A	Reasonable P_c deflection.
106	20 psi	1-Pair	Normal	Large	OF_2	-210	-205	N/A	76	N/A	Ox feed soft.

Run	Propellant Lead (Electrical) msec	Cocking of Valve Poppet Ox	Fuel
63	13 F	~20	6
68	1 F	8	6
60	simul.	-	6.5
69	1.5 Ox	~7	7.5
67	10 Ox	~7	16
64	12 Ox	~6	19
65	13 Ox	~7	20
62	14 Ox	-	23
116	4 F	11	7
124	simul.	6.5	7
117	simul.	7	6
114	2.5 Ox	7.5	9
115	7 Ox	7.5	13
109	10 Ox	7	16.5
110	11 Ox	7.5	19
91	simul.	6	5.5
90	simul.	6	5.5
94	4 Ox	6.5	10
95	5.5 Ox	6.5	11
96	6 Ox	6	12.5
97	6 Ox	6	13
86	3 F	9	5.5
79	2 F	8	6
81	2.5 Ox	6	8.5
77	4.5 Ox	-	10
88	6.5 Ox	6	12
82	8 Ox	6	13.5
84	8.5 Ox	6	14
87	14.5 Ox	7	20.5
56	13 F	19	7
54	simul.	8	7
103	5 Ox	7	12
104	6 Ox	8	13.5
58	13 Ox	7	20
108	5 Ox	6	10.5
122	7 F	14	7
118	simul.	7	6.5
120	simul.	7	7
121	3 Ox	6.5	9.5
102	B_2H_6	N/A	6.5
101	B_2H_6	N/A	7
53	B_2H_6	N/A	6.5
57	OF_2	7	N/A

*Valcor solenoid propellant

(a) Times are to a soft low pea

(w) Weak hammer pressure.

(b) Multiple hammer-like pres

TABLE VI. SUMMARY OF TEST DATA*

Time from Signal-to-Leading-Valve to: (millisecond)

Start of Low Level Manifold Pressurization		Start of Poppet Transfer		Valve Full Open		Start of Manifold Main Pressurization		Hammer in Manifold		Initial Attenuation of Prop. Entry Signal	Low Level Optical Emission	Initial Pressure Rise in Chamber	Ignition Delay for Main Ignition		Remarks
Ox	Fuel	Ox	Fuel	Ox	Fuel	Ox	Fuel	Ox	Fuel				Optical	P_{ch}	
-	6.5	~29	12.5	33	16.5	30.5	16	40	19	16.5	31	37	41	43.5	Smooth
-	-	?	12.5	18	15.5	21	15	30	>45	19.5	23.5	29.5	30	30	Smooth
-	6.5	~14	14.5	19	18.5	19	15	29	19	17	21	20	29	29	Smooth
-	-	?	14	18.5	17	17.5	17	27.5	23	20.5	21.5	23	29	30	Spike
-	17	?	24	17	29	16	27.5	29	31.5	25	27	28	28	31	Spike
-	19	~15	26	19	30	19	31	29	33	none	25	27	27	32.5	Spike
-	19	~16	28	21	32	20	31	29	33	25	27			33.5	Spike
-	19	~18	27.5	21	32	20	29	29	>45	none	25	27	29	29	Smooth
13	-	18	11.5	19.5	14	~18.5	16	(b)	20.5	none	20	25	21	33.5	Smooth
7	7	11.5	13.5	13	16		15	31[w]	20	none	12	19	12.5	~20	Smooth
8	9	11.5	13	13	15.5	18	~16	(b)	21	none	8.5	25	27	26.5	Smooth
9.5	-	13	14	15.5	16.5	14	16	(b)	23.5	22.5	23	26		~30	Smooth
8.5	-	14.5	20	16	22.5	~20	24	(b)	29	none	26	26.5	26.5	~31	Smooth
-	18	11.5	24	13	27	18.5	26	(b)	33	none	25	28	28.5	33.5	Smooth
8.5	19.5	13	26	14	30	18.5	30	(b)	36	none	24.5	28	~29	35	Smooth
8.5	9	12.5	15	16	18.5		17.5	>45	28			23	19	29	Smooth
8.5	-	13.5	13.5	16.5	18.5	22	17	29	22			28		30	Smooth
9	10.5	11	20	13	24	16	24	24	30.5	none	14	23		27	Smooth
8.5	12.5	11.5	21	14	25	14.5	21.5	25	28	none	22	23	23	28	Smooth
8	12.5	11	26	13	29	10	28	>45	35	none	15	28	31	31	Smooth
-	13.5	9.5	22	12	25.5	15	23.5	25	30	22	23	30	23	30	Smooth
12	8	17	13.5	20	16.5	22.5	17	32	24	none	20	20		32	Smooth
9.5	7	14	12	17	16	20	17	31	23	none	20	20		32	Smooth
7	10	11	16.5	15	19.5	20.5	21	27	26	17	21.5	23	24	27	Spike
6.5	11	12.5	17	17	20.5	20	19.5	29	26	none	23	25		29	Smooth
7	12.5	12	22	15.5	26	19.5	25	26	30	none	22	27		30	Spike
7.5	14	12.5	20.5	16	24.5	19.5	23	28	29	16	23	24		29	Spike
8	18.5	12	21	16	25	21	24.5	28	29.5	none		27	29	30	Smooth
7.5	-	14	28.5	17	33	20	31	27	36	none	25	29	35	35	Spike
19	-	26	15	28.5	18	~26	15	32	18	none	21.5	22	32	32	Smooth
-	7	13.5	16	16.5	19.5	13	16	20	20	none	17	17	20	20	Smooth
9	-	11	16.5	13	19		17	24.5[w]	23	13	14.5	17.5		22.5	Smooth
8.5	14.5	11.5	18	13.5	20.5	23	21	25.5[w]	23	11.5	15	20	21	22.5	Smooth
7		14	28	17.5	31	~16		21	29	14	19	23	29	29	Spike
-	12.5	9	16	10	17.5	19	~22		~25	14.5	20.5	20	26		Smooth
15	8	17.5	12.5	19	15	~17.5	15.5	33[a]	19.5	none	15	19	20	35	Smooth
~8	7	12.5	14	14	16.5	17	18	26[a]	21.5	none	15.5	19	25	24	Smooth
7.5	~8.5	12	12.5	13.5	15		14	27[a]	19	none	9	19	19	27	Smooth
8.5	~12	11	15.5	13	18	11.5	~18	29[a]	24.5	none	12	23	24.5	~29	Smooth
N/A	-	N/A	11	N/A	13	N/A	11	N/A	>45	none	N/A	-	N/A	N/A	
N/A	11	N/A	12.5	N/A	15	N/A	19	N/A	22	13	N/A	~24	N/A	N/A	
N/A	-	N/A	13	N/A	17	N/A	16	N/A	19	14.5	N/A	16	N/A	N/A	
7	N/A	13	N/A	15.5	N/A	-	N/A	25	N/A	14	N/A	14	N/A	N/A	

lves were used in all tests listed in this table.

in Runs 120-122 or to the first sharp pressure peak in Run 118 (Ox manifold disturbances). No Flox water hammer was observed.

re peaks at 28-30, 33-35 and ~40 msec, nominally.

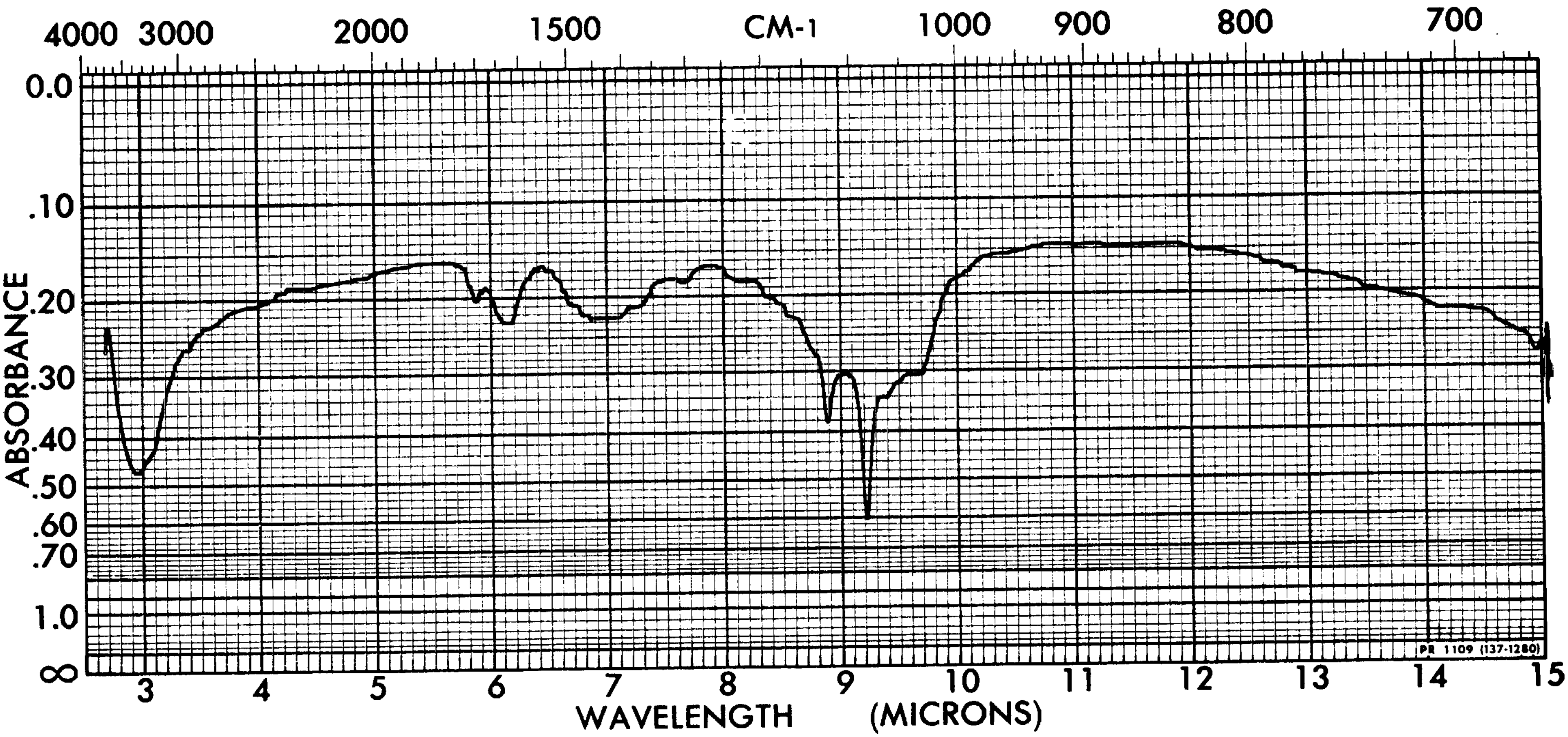


Figure 22. IR Spectrum of Black Powder Residue from OF_2/B_2H_6 Run 108.
(Low Concentration in KBr Pellet)

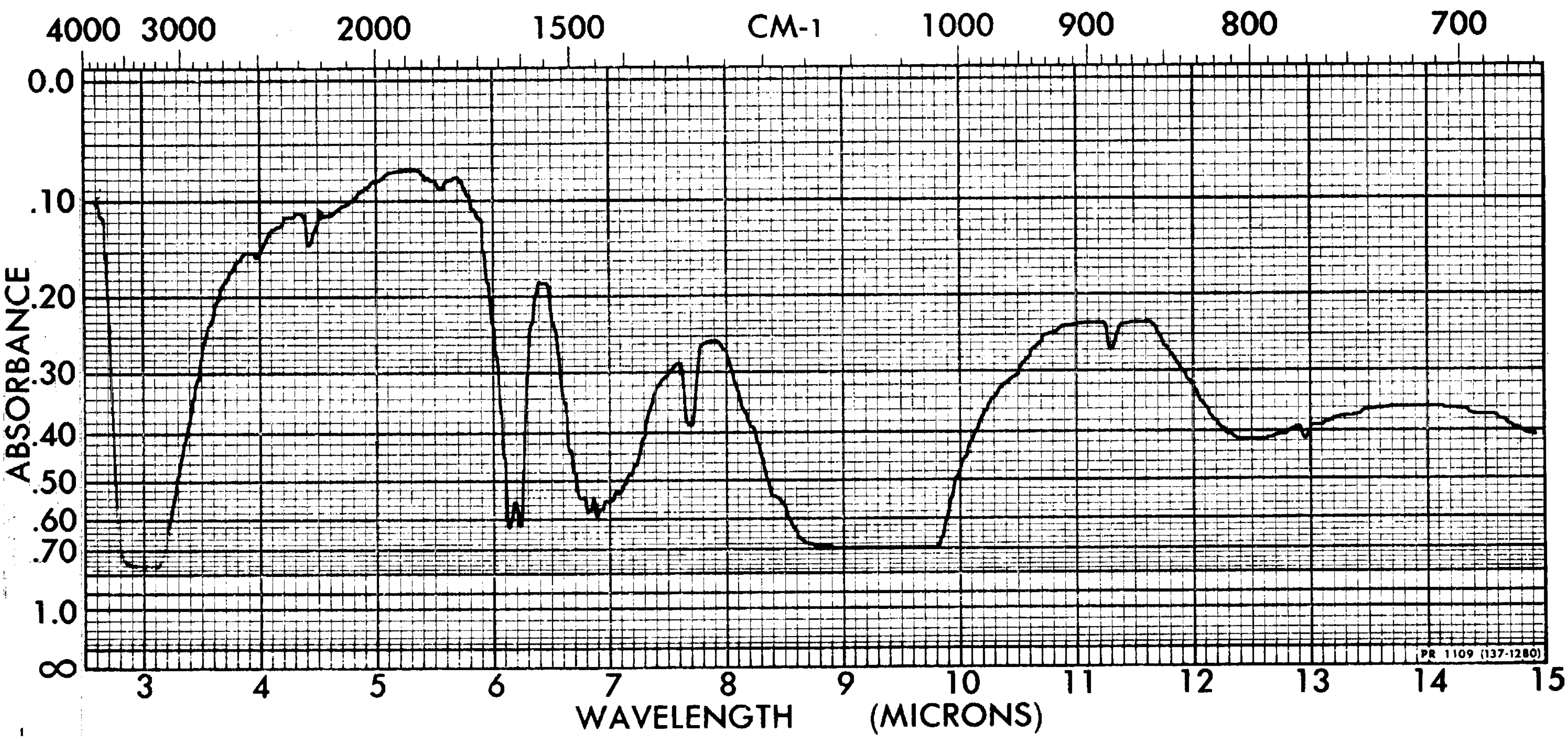


Figure 23. IR Spectrum of Black Powder Residue from OF_2/B_2H_6 Run 108. (High Concentration in KBr Pellet)

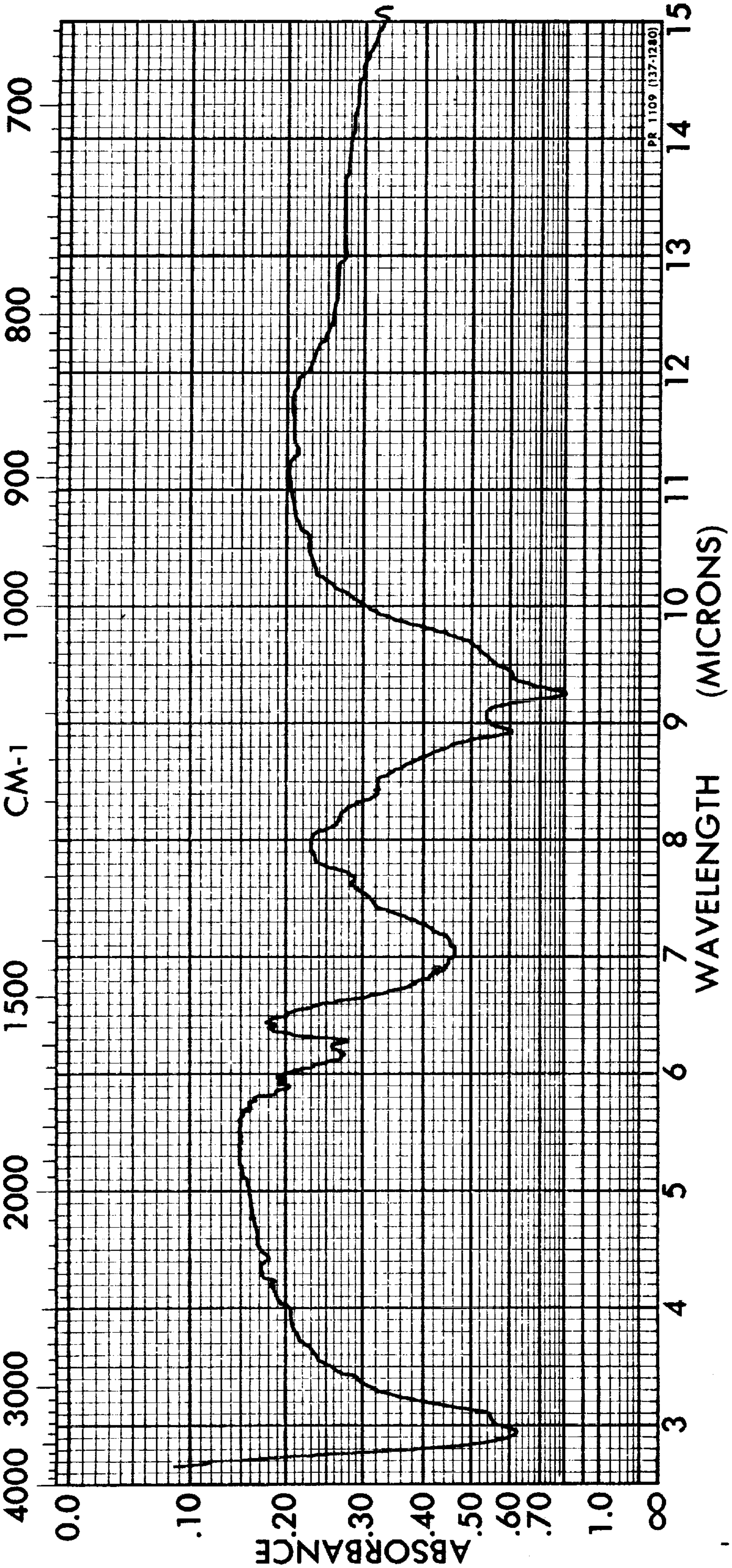


Figure 24. IR Spectrum of Light Gray Powder Residue from OF_2/B_2H_6 Run 108.

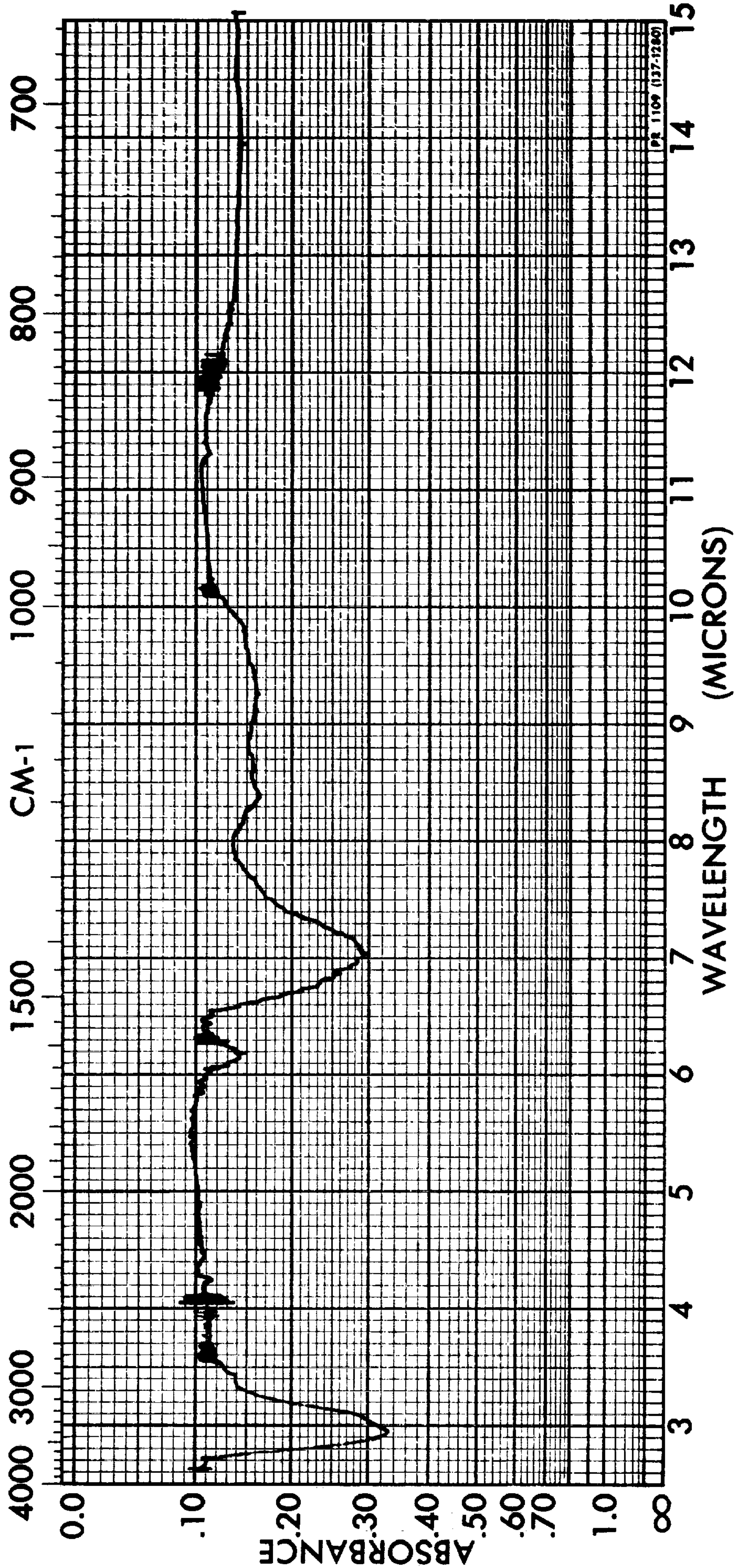


Figure 25. IR Spectrum of Powder Residue from OF_2/B_2H_6 Run 115.

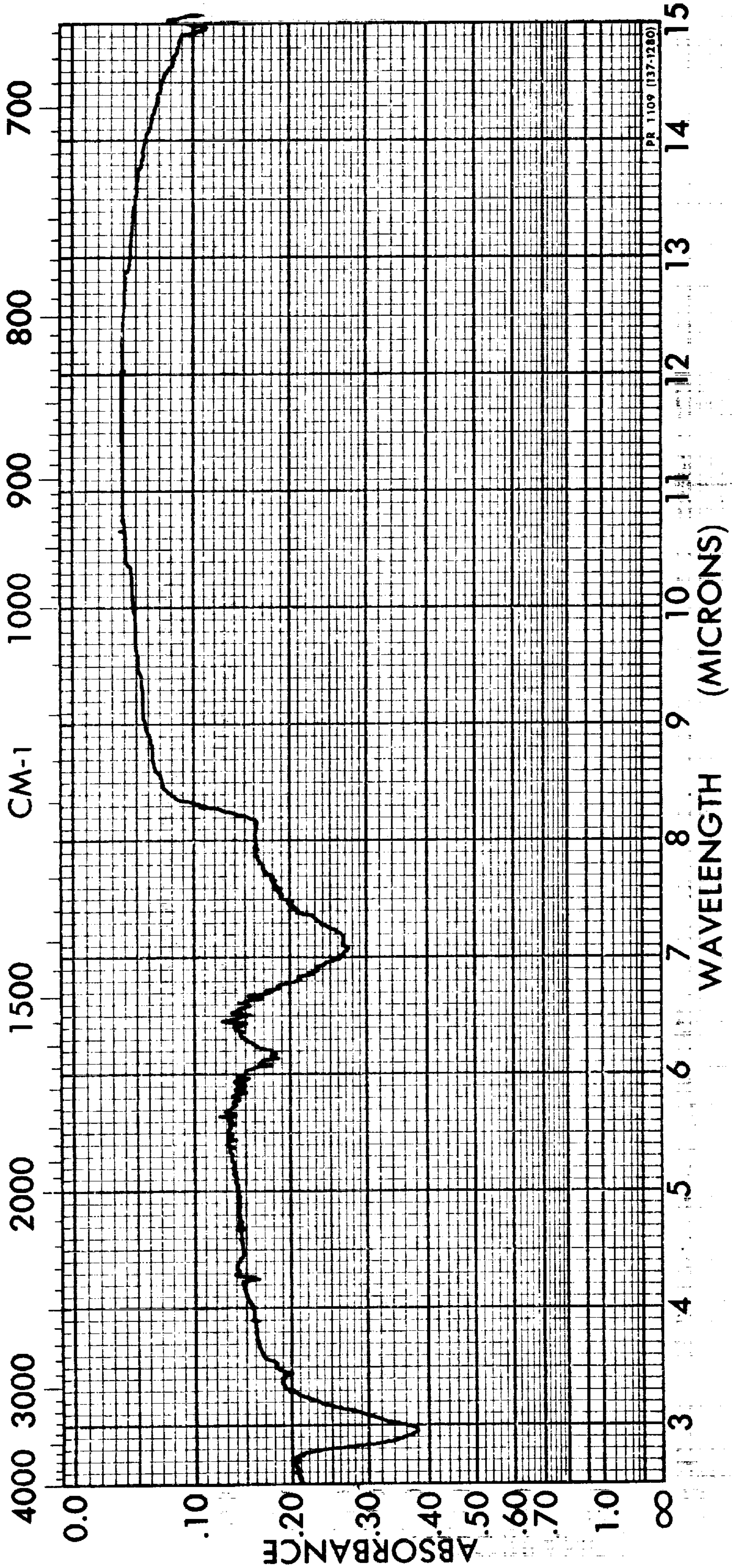


Figure 26. IR Spectrum of Powder Residue from OF_2/B_2H_6 Run 116.

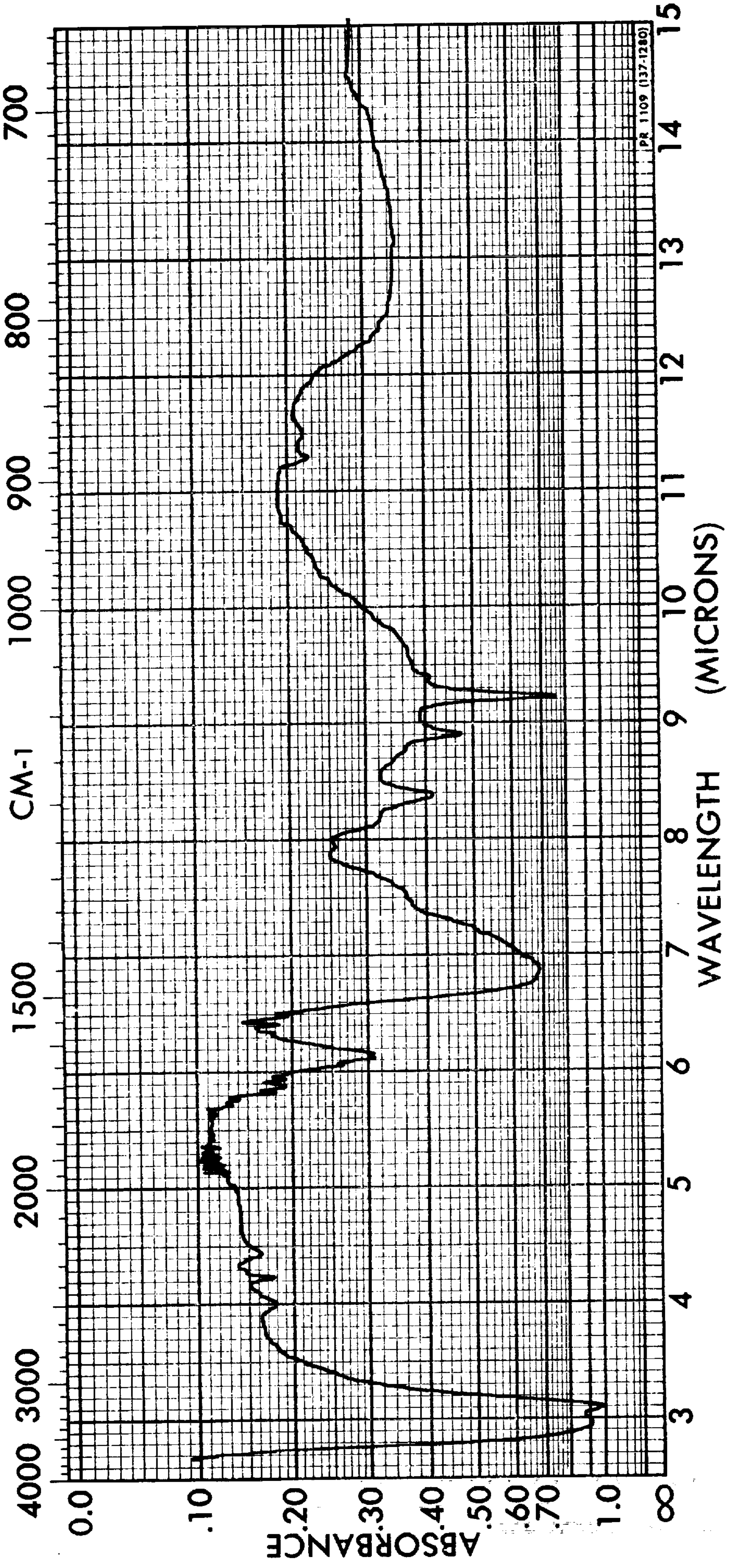


Figure 27. IR Spectrum of Air-Exposed, Gray Residue from OF_2 / B_2H_6 Run 124.

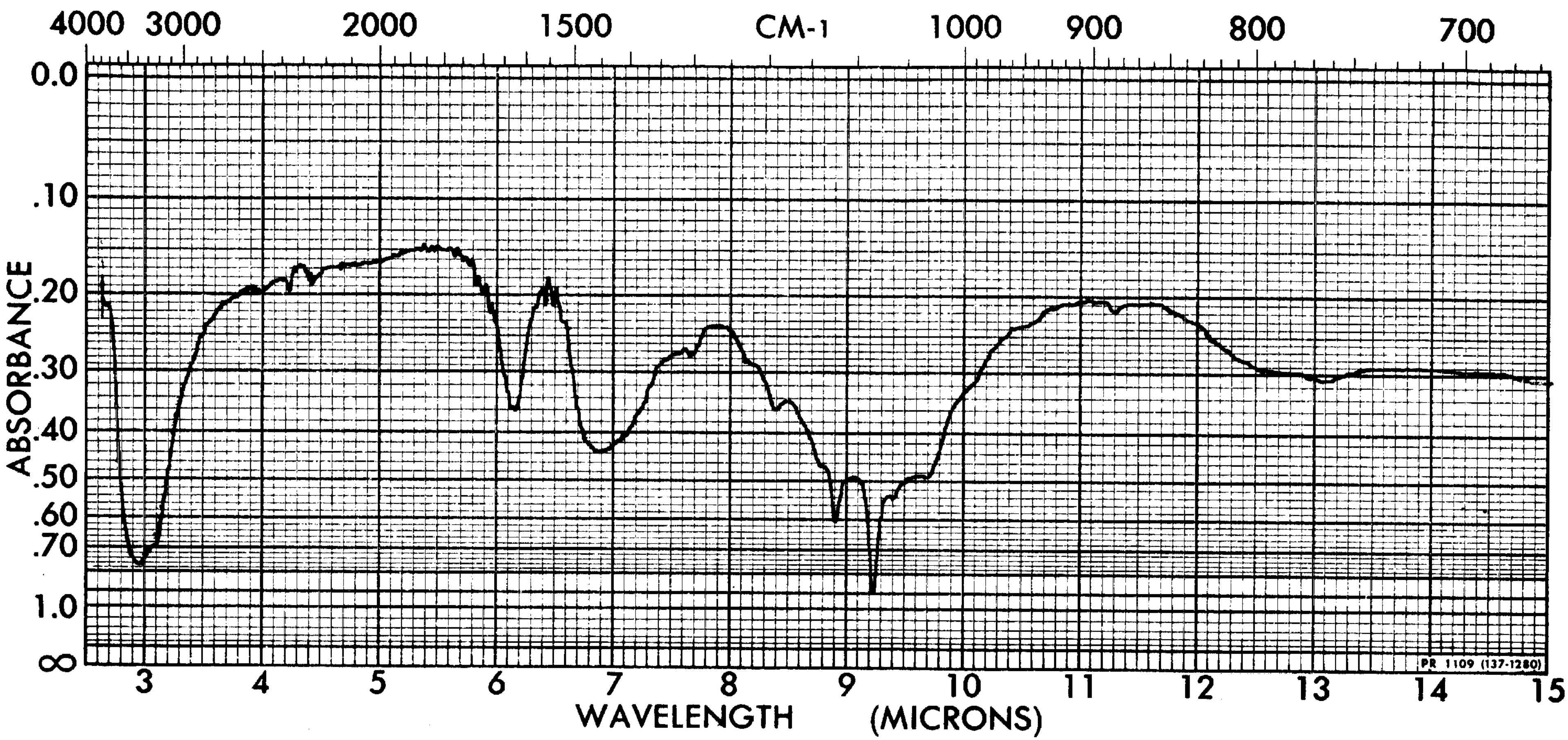


Figure 28. IR Spectrum of Powder Residue from Flox/B_2H_6 Run 122.

Upon removal of the sample plug from the engine following Run 108, the deposit on the plug was roughly 50% gray - 50% black. However, despite the nitrogen environment, the sample changed by the following morning to approximately 5% gray - 95% black. Figures 22 and 23 are IR spectra of the black material at two concentrations in the pellets. Figure 24 is a spectrum of the gray powder. It is seen that all three spectra have significant absorptions at 2.9, 6.2, 7.0, 8.9 and 9.2 microns. The spectra of the gray material differs from the black material in that the 7.0 micron peak is more pronounced relative to the other absorptions.

The IR spectra of samples from Runs 115 and 116 are given in Figs. 25 and 26 respectively. Both spectra indicate that the samples contain mostly the component having the absorption at 7.0 microns. In the Run 116 spectrum, no absorptions above 8.5 microns are present.

The IR spectrum of the air-exposed sample from Run 124 is given in Fig. 27. The spectrum is quite similar to that of the light gray powder residue from Run 108 (Fig. 24). The differences are (a) that several additional absorption bands are readily seen in the spectrum of the air-exposed sample that are only marginally distinguishable in the earlier spectrum and (b) that the band at 7.0 microns repeatedly seen in the earlier spectra is shifted toward shorter wavelengths and is more pronounced in the air-exposed sample. The new bands that are easily seen in Fig. 27 are those at 4.0, 4.2, 4.4. 8.4, 11.3 and 11.5 microns.

The IR spectrum of the residue from Flox/B_2H_6 Run 122 is given in Fig. 28. Similar absorptions are seen in this spectrum as in that of the air-exposed, OF_2/B_2H_6 material. Differences are only that the bands at 7.0 and 8.4 microns are less pronounced in the spectrum of the Flox/B_2H_6 residue.

From the IR spectra, it appears that the samples contain at least three components, one of which is H_2O as indicated by the absorptions at 2.9 and 6.2 microns. The other components are less certain at present. Neither H_3BO_3 (boric acid) nor B_2O_3 is observed in the spectra. However, boron nitride BN may be present. For comparative purposes, the IR spectrum of BN is given in Fig. 29.

A sample of the air-exposed residue from OF_2/B_2H_6 Run 124 was mixed with concentrated sulfuric acid and introduced into a flame. A positive flame test (green color) for borates ($BO_3^{\equiv}$, $B_4O_7^{=}$) was obtained. The IR spectra, however, indicate that neither H_3BO_3 (boric acid) nor B_2O_3 is present in any of the samples.

The gray air-exposed residue of Run 124 was also examined on an X-ray diffractometer. Two strong, sharp peaks were obtained at 6.10 and 3.20 Å. In addition, weak, broad peaks were obtained at 5.47, 2.91 and

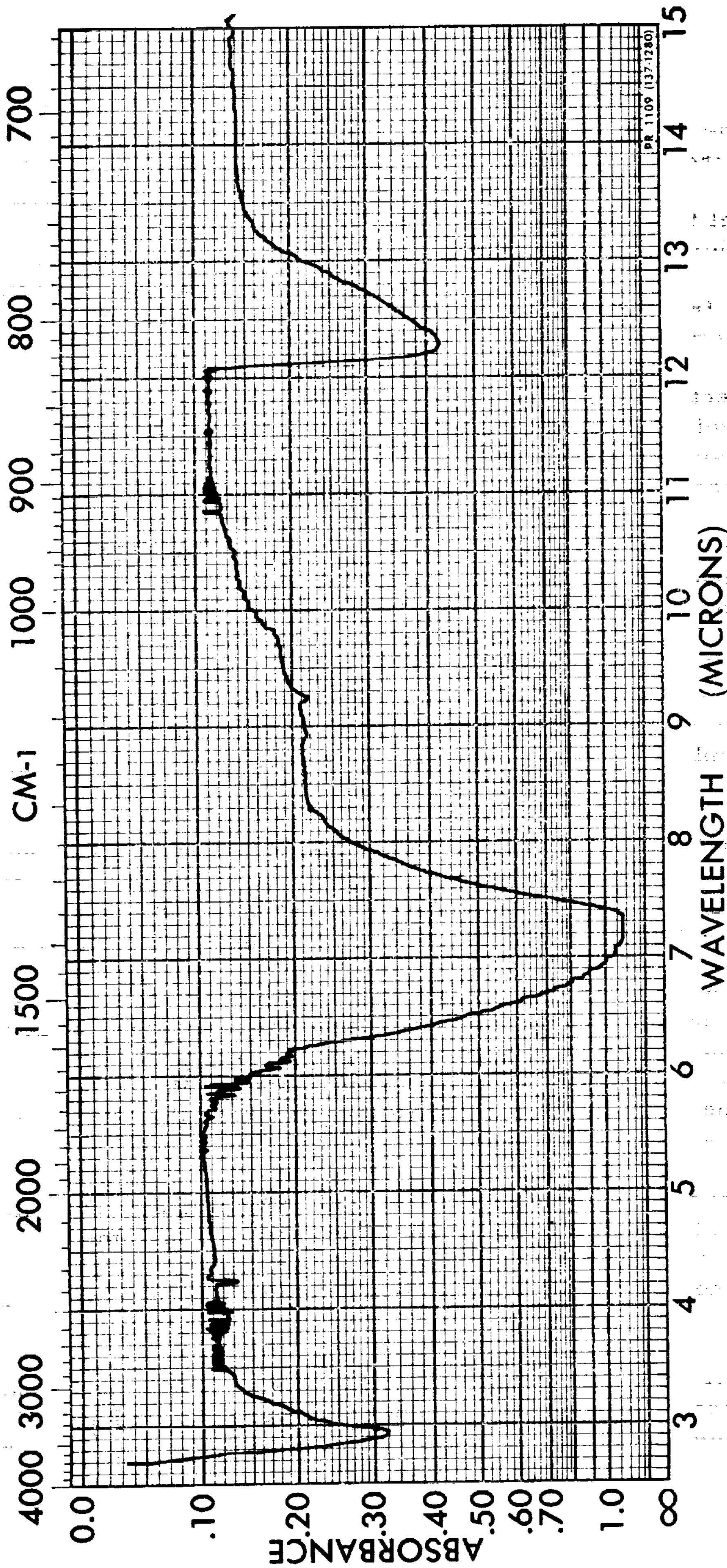


Figure 29. IR Spectrum of Boron Nitride.

2.24 Å. The latter peaks are unidentified but the two strong ones are characteristic of B_2O_3 and H_3BO_3 although other lines from these crystals were not observed. It is possible that compounds involving B, O and F would have similar d-spacings as B_2O_3 and H_3BO_3 both of which have been ruled out by the IR results.

The residues from OF_2/B_2H_6 Runs 108, 115 and 116 were examined by X-ray powder diffraction with a Debye-Scherrer camera. The black powder residue from Run 108 exhibited strong peaks at 6.17 and 3.24 Å which agree reasonably well with the two strong peaks obtained from the Run 124 sample with the X-ray diffractometer. No other lines were detected in the Run 108 sample but a strong amorphous band at 15-25° 2 θ was observed and suggests the presence of elemental, non-crystalline boron. The amorphous band was the only characteristic given by the Run 115 residue, however, the Run 116 residue gave the same powder pattern as the black Run 108 residue. From a geometrical standpoint, then, the Run 115 residue differs from the residues of Runs 108 and 116 and the latter two are the same.

Summarizing the various analytical results gives:

a) Similar species are present in the residues formed by either OF_2 or Flox with B_2H_6.

b) The residues consist of various concentrations of at least amorphous elemental boron, H_2O, and two other components one or both of which are borates ($BO_3^{\equiv}$, $B_4O_7^{=}$).

c) Neither H_3BO_3 nor B_2O_3 is present in the samples but BN may be present.

d) From a geometrical viewpoint, the samples of Runs 108 (black residue), 116 and 124 appear similar and the Run 115 sample is different.

One would expect that the composition of the residues from the various runs would differ since tail-off flows were different. On an idealized basis, the lagging propellant to "run-out" and the duration of flow of that propellant after the other propellant stops is as follows:

OF_2/B_2H_6 Run 108:	B_2H_6 for 83 msec
OF_2/B_2H_6 Run 115:	B_2H_6 for 147 msec
OF_2/B_2H_6 Run 116:	OF_2 for 216 msec
OF_2/B_2H_6 Run 124:	B_2H_6 for 78 msec
Flox/B_2H_6 Run 122:	B_2H_6 for 71 msec

These values were calculated based on step-function mass flowrate profiles with steady design flowrates based on design chamber pressure but allowing for actual tank set pressures and propellant temperatures. It is to be recalled that in the present test system, the total propellant loaded into each run tank is injected into the thrust chamber in each run and is followed automatically by a short helium purge. The large tail-off changes indicated above were obtained by simply loading less than and more than the normal amount of OF_2 in its run tank for the respective runs.

The fact that the Run 115 residue differs geometrically from all others appears due to its very long fuel tail-off which left primarily elemental amorphous boron and the component having the absorption at 7.0 microns. The absence of absorptions above 8.5 microns in the Run 116 residue apparently is linked to the long oxidizer tail-off of this run.

V. DISCUSSION OF RESULTS

In this section, the effects of the programmed variables are discussed first. Then, the mechanisms that control start-up in the test system are described in some detail. Some design concepts and operational procedures necessary to ensure reliable start-ups in space-ambient engines are given and, finally, the problem areas that were encountered during the present program are described.

A. EFFECTS OF THE PROGRAMMED VARIABLES

The parameters investigated are: hardware and propellant temperatures, propellant lead/lag, type of valve/injector coupling, run tank ullage volume, injector configuration, design chamber pressure, type of propellant valve, and oxidizer (OF_2 and Flox). These are discussed in the following paragraphs.

1. Effect of Temperature

In the Phase I program (Ref. 1), it was found that ignition delays of OF_2/B_2H_6 were insensitive to temperature. In those tests, however, either the propellant temperatures were constant and hardware temperature was varied or hardware temperature was constant and the propellant temperatures varied. Because of the unexpected nature of that finding, tests were conducted in the present program in which both hardware temperature and propellant temperatures were varied together. Table VII summarizes the pertinent warm and cold runs. Again, it is found that the ignition delays ("Main Chamber Ignition") are essentially constant.

Although temperature does not affect the overall ignition delay time, the table shows that temperature does affect the rate and type of filling of the injector manifolds. In the cold runs, water hammer pressure peaks in the manifold pressure traces indicate hard liquid filling of both the fuel and oxidizer manifolds. This is to be expected as the vapor pressures of the propellants, even at the injector temperature, are well below the tank set pressures. For example, the vapor pressures of B_2H_6 and OF_2 at -200°F are approximately 1.1 and 46 psia, respectively, while the corresponding tank set pressures for the cold runs were approximately 178 psia for both propellants.

In the three warm runs, hard liquid filling again occurred in the fuel manifold as one would expect (vapor pressure of 38 psia at -100°F versus a tank set pressure of 188 psia). It is noteworthy, however, that the time required to achieve hard liquid filling of the fuel manifold is consistently longer in the warmer runs.

TABLE VII. COMPARISON OF "WARM" AND "COLD" OF_2/B_2H_6 IGNITION TESTS

	"Warm" Runs				"Cold" Runs			
Run	91	94	96	Average	90	95	97	Average
Injector Temp., °F	-100	-100	-100	-100	-260	-200	-250	-237
OF_2 Temp., °F	-170	-170	-170	-170	-320	-320	-320	-320
B_2H_6 Temp., °F	-100	-100	-100	-100	-210	-200	-225	-212
Elec. Lead, msec	0	4 Ox	6 Ox	3.3 Ox	0	5.5 Ox	6 Ox	3.8 Ox
Oxidizer Manifold								
Type of Filling	Soft	Hard Liquid	Soft	Generally Soft	Hard Liquid	Hard Liquid	Hard Liquid	Hard Liquid
Time to H_2O hammer pressure peaks, msec*	>45	24	>45	-	29	25	25	26
Fuel manifold								
Type of Filling	Hard Liquid	Hard Liquid	Hard Liquid	Hard Liquid	Hard Liquid	Hard Liquid	Hard Liquid	Hard Liquid
Time to H_2O hammer pressure peaks, msec*	28	26.5	29	28	22	22.5	24	23
Main Chamber Ignition, msec**	29	27	31	29.0	30	28	30	29.3

Note: All Runs made with Valcor solenoid propellant valves, 100 psia design P_c chamber, 9-pair doublet injector, large ullage run tanks and close valve/injector coupling.

*Time measured from signal to respective valve.

**Time from signal-to-leading-valve to "main ignition" based on low-gain Kistler chamber pressure transducer, i.e. neglecting any preceding low level vapor reactions.

In the case of the oxidizer manifold, hard liquid filling generally did not occur in the warm runs. As Table VII indicates, the injector (and chamber) was conditioned to -100°F while the OF_2 run tank was conditioned to -170°F. The vapor pressure of OF_2 is 490 psia at the former, warmer temperature but approximately 115 psia at -170°F. Since the OF_2 tank set pressure in these "warm" runs was approximately 180 psia, water hammer pressure peaks could occur only for effective propellant and injector temperatures of -150°F or below. This temperature was not reached in two of the warm runs but evidently was in the third (Run 94).

Other evidence that Run 94 was in fact colder than the other two comes from the oxidizer valve current traces. The decreased resistance of the solenoid valve coil with decreasing temperature results in a valve current deflection that varies with coil temperature. The valve current deflection in Run 94 is noticeably greater than in Runs 91 and 96, indicating therefore that the valve is colder in Run 94.

The effect of temperature on diborane manifold filling was observed previously and is discussed in some detail in the Phase I report (Secs. V.B.2 and 6 of Ref. 1).

For completeness, other previously observed temperature effects on OF_2/B_2H_6 start transients are summarized below.

Temperature-caused high frequency oscillations in the OF_2 manifold were observed in Phase I and are discussed in Sec. V.A.2.b of the Phase I report (Ref. 1). This "cool-down" phenomenon was not observed in two runs of Phase II having otherwise appropriate temperature conditions, i.e. OF_2 at -320°F and the injector at +70°F (Runs 62 and 68). However, these runs had the large rather than the small ullage run tanks. The significance of this difference is not apparent at present.

It was found also that in runs with warm B_2H_6 (i.e. -10°F) strong reactions occurred in the OF_2 manifold prior to ignition (Sec. V.B.6 of Ref. 1). These reactions sometimes caused a momentary interruption of the oxidizer flow due to the pressures generated in the manifold and resulted in delayed ignition in the thrust chamber.

2. Effects of Propellant Lead/Lag

In the Phase I program (Ref. 1) only one ignition spike was observed. It occurred in one of the OF_2/B_2H_6 runs and, furthermore, it occurred in the only run made with an OF_2 lead (Run 37). To determine whether the OF_2 lead was significant, tests with varying leads were conducted in the present program. One series was OF_2/B_2H_6 Runs 74 through 88 (but excluding No. 78 which was a test of explosively actuated valves, Sec. V.A.8 below). This series was made with the 100 psia chamber, nine element injector, small ullage run tanks and close valve/injector coupling (Table V). The temperature conditioning objective was -200°F for the propellants and the hardware.

Eight meaningful runs were obtained in this series and they covered electrical leads from 3 msec fuel to 14.5 msec oxidizer. (The other runs suffered from a "soft" fuel or oxidizer feed which indicates less than the full, proper flowrate into the thrust chamber, see Sec. V.A.3, below). The eight meaningful runs are given for convenience in Table VIII which shows that two of the eight runs had electrical fuel leads while the other six runs had electrical oxidizer leads.

Both fuel lead runs exhibited smooth start transients but, significantly, four of the six oxidizer lead runs exhibited ignition spikes in the thrust chamber.

Table VIII also shows that the minimum ignition delay occurred with a slight oxidizer lead (electrical) and that the ignition delays with all other reasonable leads (i.e. 3 msec F to 8.5 msec Ox) were nearly constant.

The ignition delays referred to above are the delays that precede a rise of chamber pressure to a substantial level. Evidence of chemical reactions prior to a substantial rise in chamber pressure is frequently observed by the optical instrumentation. The first occurrence of optical emission is given in Table VIII in the column labeled "Low Level Optical Emission". In every case, this initial emission occurs prior to hard liquid filling of the injector by either the fuel or oxidizer and sometimes occurs prior to the start of manifold main pressurization by one of the propellants. In other words, reactions with emission can occur in the thrust chamber when the flow of one propellant is two-phase through the injector orifices while the other is only low level vapor flow that arises from poppet cocking (Sec. III.A.3.a).

The reactions that produce the low level emission apparently act as a pilot flame which allows essentially immediate, full reactions upon hard liquid filling of injector manifolds by both propellants (compare "Ignition Delay" times to "Hammer in Manifold" times in Table VIII). In this case, then, "Main Ignition" occurs when the full mass flow of both propellants into the chamber occurs.

Since main ignition depends upon attainment of full mass flow of both propellants, it is of interest to consider the valve and fluid mechanical events that occur during start-up. A comparison of these events for the OF_2 and B_2H_6 in the subject eight runs is given in Table IX. Although the times

TABLE VIII. SUMMARY OF DATA SHOWING LEAD/LAG EFFECTS*

Electrical Lead msec		Time from Signal-to-Leading-Valve to: (millisecond) Cocking of Valve Poppet		Start of Low Level Manifold Pressurization		Start of Poppet Transfer		Valve Full Open		Start of Manifold Main Pressurization		Hammer in Manifold		Initial Attenuation of Prop. Entry Sig.	Low Level Optical Emission	Ignition Delay for Main Ignition		Character of Start Transient	Run No.
		Ox	Fuel	Ox	Fuel	Ox	Fuel	Ox	Fuel	Ox	Fuel	Ox	Fuel			Optical	P_{ch}		
3	F	9	5.5	12	8	17	13.5	20	16.5	22.5	17	32	24	-	20		32	Smooth	86
2	F	8	6	9.5	7	14	12	17	16	20	17	31	23	-	20		32	Smooth	79
2.5	Ox	6	8.5	7	10	11	16.5	15	19.5	20.5	21	27	26	17	21.5	24	27	Spike	81
4.5	Ox	-	10	6.5	11	12.5	17	17	20.5	20	19.5	29	26	-	23		29	Smooth	77
6.5	Ox	6	12	7	12.5	12	22	15.5	26	19.5	25	26	30	-	22		30	Spike	88
8	Ox	6	13.5	7.5	14	12.5	20.5	16	24.5	19.5	23	28	29	16	23		29	Spike	82
8.5	Ox	6	14	8	18.5	12	21	16	25	21	24.5	28	29.5	-	?	29	30	Smooth	84
14.5	Ox	7	20.5	7.5	-	14	28.5	17	33	20	31	27	36	-	25	35	35	Spike	87

*Engine configuration and temperatures: 100 psia chamber, 9-pair injector, small ullage run tanks, close valve/injector coupling, and $T_{inj.} = T_{OF_2} = T_{B_2H_6} = -200°F$.

of the events are not perfectly reproducible, it is clear that a longer time is required to achieve full mass flow of the OF_2 than of the B_2H_6 in the subject hardware configuration under the specific operating conditions. It follows from the preceding, then, that the minimum delay to main ignition will occur with a short oxidizer lead. This is found to be the case (Run 81, Table VIII) however the difference is quite small.

TABLE IX. COMPARISON OF OXIDIZER AND FUEL START-UP EVENTS*

	Time from Signal to: Ox Valve msec	Fuel Valve msec
Cocking of Valve Poppet	6-7	5.5-6
Start of Low Level Manifold Pressurization	7-8	6.5-8
Start of Poppet Transfer	11-14	12-14
Valve Full Open	15-17	15-17
Start of Manifold Main Pressurization	18-21	15-17
Hammer in Manifold	~27-29	~22-24

*Engine Configuration and Temperatures: 100 psia chamber, 9-pair injector, small ullage run tanks, close valve/injector coupling,
$T_{inj} = T_{OF_2} = T_{B_2H_6} = -200\,^\circ F$.
(Selected runs from 77 to 88)

Referring again to the effect of propellant lead/lag on the character of the start transients, further evidence that an OF_2 lead can produce undesirable pressure transients is seen in the first block of tests in Table VI. In this series, which differed from the series discussed above in temperatures, valve/injector coupling and run tank ullage (Table V), four of the five runs with oxidizer leads resulted in ignition spikes. Two fuel lead runs and one no-lead run exhibited smooth start transients.

In the one non-spiking oxidizer-lead run (Run 62), the injector was conditioned to +70 °F which resulted in massive flashing of the incoming propellants (Ref. 1, p. 48) and consequently a lower rate of massflow increase into the thrust chamber. Although no spiking occurred, there was a moderate (140 psia) initial overpressure in this run.

In all other series of runs, ignition spiking generally did not occur regardless of the propellant lead condition. In total, of the 23 OF_2/B_2H_6 runs having an electrical oxidizer lead in Table VI, nine or 39% exhibited ignition spikes. As in the Phase I program, no ignition spikes were observed in the $Flox/B_2H_6$ runs.

3. Effect of Valve/Injector Coupling

In the "normal" valve/injector coupling configuration (Sec. III. A. 4), short stand-off tubes are used to isolate the injector which is thermally conditioned in one bath from the propellant valves which are thermally conditioned in two additional baths. This method assures that the initially flowing propellant is at the desired propellant temperature. The stand-off tubes, however, unavoidably cause somewhat larger dribble volumes.

To reduce dribble volumes, the stand-off tubes were minimized, resulting in the configuration designated "close" valve/injector coupling. In this configuration, the valves are no longer conditioned with the propellant but rather with the injector. Since the injector was generally conditioned to a warmer temperature than the propellants, difficulties in obtaining hard-liquid filling up to the valve seats increased. Under these conditions of warm valve/injector and cold propellants, the propellants that condensed in the run tanks during the initial loading phase would run down the feed lines from the tanks and vaporize in the warm propellant valves. If the vapors then rise into the run tanks and re-condense, a heat pipe action is set up which gradually cools the valves to a degree that allows hard-liquid filling up to the valve seat. This process is time-consuming, however. Another practical consideration is that valve static leakage apparently was greater with OF_2 vapor than with OF_2 liquid. A long hold time to accommodate the vaporization-condensation cooling process could cause propellant loss and vacuum degradation when using the solenoid metal-seated propellant valves. A consequence of this valve conditioning problem is that a number of runs exhibited improperly soft fuel or oxidizer feeds as determined from injector manifold pressure traces. The evidence is a lack of water hammer pressure peaks under conditions where hard-liquid filling should have occurred. Although ignition nevertheless occurred, initial propellant massflow rates differed and therefore these runs are not included in the data summaries of Table VI.

Considering only runs exhibiting hard-liquid filling, several runs with normal and close valve/injector coupling are compared in Blocks I and II of Table X. In the table runs with similar lead/lags are paired where possible. All runs were made with the 100 psi chamber and nine-element doublet injector. The temperatures of injector, OF_2 and B_2H_6 were all nominally -200°F for the Block I tests. In the Block II tests, the OF_2 run tank was conditioned to -320°F. The B_2H_6 tank and injector were conditioned to various temperatures from -100 to -250°F (Table V).

From the viewpoint of dribble volume alone, ignition delays to main ignition should be shorter with the close valve/injector coupling due to its smaller dribble volume. The Block I tests follow this trend, however,

TABLE X. DATA SUMMARY OF OF_2/B_2H_6 RUNS SHOWING VALVE/INJECTOR COUPLING EFFECTS AND RUN TANK ULLAGE EFFECTS

Valve/Injector Coupling	Run Tank Ullage	Propellant Lead (Electrical) msec	Cocking of Valve Poppet		Start of Low Level Manifold Pressurization		Start of Poppet Transfer		Valve Full Open		Start of Manifold Main Pressurization		Hammer in Manifold		Initial Attenuation of Prop. Entry Sig.	Low Level Optical Emission	Initial Pressure Rise in Chamber	Ignition Delay for Main Ignition		Character of Start Transient	Run
			Time from Signal-to-Leading-Valve to: (millisecond)																		
			Ox	Fuel	Ox	Fuel	Ox	Fuel	Ox	Fuel	Ox	Fuel	Ox	Fuel				Optical	P_{ch}		
BLOCK I TESTS[a]																					
Normal	Small	4 F	11	7	13	-	18	11.5	19.5	14	~18.5	16	(b)	20.5	none	20	25	21	33.5	Smooth	116
Close	Small	3 F	9	5.5	12	8	17	13.5	20	16.5	22.5	17	32	24	none	20	20		32	Smooth	86
Normal	Small	2.5 Ox	7.5	9	9.5	-	13	14	15.5	16.5	14	16	(b)	23.5	22.5	23	26		~30	Smooth	114
Close	Small	2.5 Ox	6	8.5	7	10	11	16.5	15	19.5	20.5	21	27	26	17	21.5	23	24	27	Spike	81
Normal	Small	7 Ox	7.5	13	8.5	-	14.5	20	16	22.5	~20	24	(b)	29	none	26	26.5	26.5	~31	Smooth	115
Colse	Small	6.5 Ox	6	12	7	12.5	12	22	15.5	26	19.5	25	26	30	none	22	27		30	Spike	88
BLOCK II TESTS[c]																					
Normal	Large	simul.	-	6.5	-	6.5	~14	14.5	19	18.5	19	15	29	19	17	21	20	29	29	Smooth	60
Close	Large	simul.	6	5.5	8.5	-	13.5	13.5	16.5	18.5	22	17	29	22			28		30	Smooth	90
Normal	Large	1.5 Ox	~7	7.5	-	-	?	14	18.5	17	17.5	17	27.5	23	20.5	21.5	23	29	30	Spike	69
Close	Large	5.5 Ox	6.5	11	8.5	12.5	11.5	21	14	25	14.5	21.5	25	28	none	22	23	23	28	Smooth	95
Normal	Large	10 Ox	~7	16	-	17	?	24	17	29	16	27.5	29	31.5	25	27	28	28	31	Spike	67
Close	Large	6 Ox	6	13	-	13.5	9.5	22	12	25.5	15	23.5	25	30	22	23	30	23	30	Smooth	97
BLOCK III TESTS[d]																					
Normal	Large	13 F	~20	6	-	6.5	~29	12.5	33	16.5	30.5	16	40	19	16.5	31	37	41	43.5	Smooth	63
Normal	Small	11 F	18	5	-	6	~25	12	29	15.5	27	~16		22	N/A	N/A	~37	N/A	40	Smooth	35
Normal	Large	simul.	-	6.5	-	6.5	~14	14.5	19	18.5	19	15	29	19	17	21	20	29	29	Smooth	60
Normal	Small	simul.	~6	6	-	6	?	12	~16.5	16	16	16		21	N/A	N/A	26	N/A	28	Smooth	33
Normal	Small	10 Ox	7	16.5	-	18	11.5	24	13	27	18.5	26	(b)	33	none	25	28	28.5	33.5	Smooth	109
Normal	Small	11 Ox	7.5	19	8.5	19.5	13	26	14	30	18.5	30	(b)	36	none	24.5	28	~29	35	Smooth	110
Normal	Large	12 Ox	~16	19	-	19	~15	26	19	30	19	31	29	33	none	25	27	27	32.5	Spike	64
Close	Small	4.5 Ox	-	10	6.5	11	12.5	17	17	20.5	20	19.5	29	26	none	23	25		29	Smooth	77
Close	Large	5.5 Ox	6.5	11	8.5	12.5	11.5	21	14	25	14.5	21.5	25	28	none	22	23	23	28	Smooth	95
Close	Small	6.5 Ox	6	12	7	12.5	12	22	15.5	26	19.5	25	26	30	none	22	27		30	Spike	88

(a) 100 psi chamber, 9-pair injector, $T_{inj.} = T_{OF_2} = T_{B_2H_6} \approx -200°F$.

(b) Multiple hammer-like pressure peaks at 28-30, 33-35 and ~40 msec, nominally.

(c) 100 psi chamber, 9-pair injector, $T_{OF_2} = -320°F$, $T_{inj.}$ and $T_{B_2H_6}$ from -100°F to -250°F (Table V).

(d) 100 psi chamber, 9-pair injector.
Runs 63, 35, 60, 33, 109, 110 and 64: $T_{OF_2} = -320°F$, $T_{inj.} = T_{B_2H_6} \approx 100°F$.
Runs 77, 95 and 88: $T_{OF_2} = T_{B_2H_6} = T_{inj.} \approx -200°F$ except $T_{OF_2} = -320°F$ in Run 95.
There was no optical instrumentation in the Phase I program; therefore, Runs 33 and 35 lack this data.

the Block II tests do not. In both cases the differences are small and, in fact, are generally within reproducibility.

Regarding spiking tendencies, spikes occurred with close coupling in the Block I tests and with the normal coupling in the Block II tests. In short, the coupling configurations tested had little effect on start-ups provided the tests were initiated with hard liquid filling of the feed systems up to the valve seats.

4. Effects of Run Tank Ullage

The very small run tanks used in the Phase I program were replaced for some tests in the present program by run tanks of twice the volume. However, because line volumes were large by comparison, as discussed in Sec. III. A. 6, the resulting change in ullage volume was relatively small.

Several tests with the two ullage volumes are summarized in Table X under Block III. As in the case of the valve/injector coupling configurations, there is little difference in the ignition delays to main ignition with the large and small ullage systems. Furthermore, no consistent significant effect on manifold filling characteristics by either propellant was observed.

5. Effect of Injector Configuration

Only very limited tests were conducted in the Phase II program with the single-element doublet injector in the 100 lbf thrust engines since it is considered to be a poorer performing injector than the nine-element one and its effect with Flox as oxidizer was determined previously (Ref. 1).

Runs 65 (9-pair) and 58 (1-pair) were made with the same hardware configurations, except for injectors, and with the same propellant lead, 13 msec OF_2 (Table V). Injector temperatures in both cases were approximately -200°F which, from vapor pressure vs. tank pressure considerations, leads to hard liquid filling of both the OF_2 and B_2H_6 injector manifolds.

The test data for Runs 65 and 58 in Table VI show as expected that hard liquid filling occurs faster in the case of the 1-pair injector which has the smaller dribble volume. Filling times based on water-hammer pressure peaks (comparatively weak with the 1-pair injector) for OF_2 and B_2H_6 were 21 vs. 29 msec and 29 vs. 33 msec, respectively, for the 1-pair and 9-pair injectors. Low level optical emission was observed earlier with the 1-pair injector (19 msec vs. 27) and ignition delay for main ignition was shorter (29 msec vs. 33.5). This result agrees with the previous finding which was based on Flox as the oxidizer.

Other runs which are comparable (except for temperatures) are Runs 54 and 60 (zero propellant lead) and Runs 56 and 63 (13 msec electrical fuel lead). As expected, the response of the 1-pair injector is faster.

6. Effects of Design Chamber Pressure

The earlier finding that ignition delays increase with decreasing design chamber pressure (Ref. 1) was corroborated in the present program. Previously, the nine-element injector was used whereas, in the present case, the single-element injector was used with the 20 and 100 psi design P_{ch} chambers (Runs 108 vs. 103 and 104). Based on the optical ignition detector, ignition delay for main ignition increased from 21 to 26 msec.

7. Bipropellant Valve Tests

Two tests were made with the Hydraulics Research torque-motor bipropellant valve described in Sec. III. A. 3. c. The valve was used in conjunction with the 100 psi chamber, 9-pair injector and large ullage run tanks (Runs 98 and 99, Table V). The valve was thermally conditioned with the injector, however it was also subjected to the propellant vaporization-condensation cycle discussed above in Sec. V. A. 3.

The first run of the pair proceeded normally. It may be compared to Run 90 which used the solenoid valves but which otherwise was made under the same conditions including an electrical lead/lag of zero. Pertinent data are compared in Table XI. The table shows that full liquid filling of the injector manifolds, as indicated by water hammer pressure oscillations, takes slightly longer in the case of the bipropellant valve despite the fact that this valve reaches full open first. Since attainment of injector hard liquid filling takes longer, the delay to main ignition is also longer in the case of the bipropellant valve. The difference, however, is small. The start-up transients in both cases were smooth.

Run 99 was intended as a duplicate of Run 98 to gain further experience with the bipropellant valve. In the second run, however, apparently a double malfunction occurred although the two may stem from the same cause. A description of the test follows.

The test hardware and both propellants were being conditioned at -200°F in preparation for Run 99. The fuel, which had been loaded into the prefill tank, was in process of being transferred into the fuel run tank when a loud metallic click was heard over the intercom system. The click occurred at approximately 110 seconds into the 120 second transfer sequence. At the completion of the fuel loading, the transducers were read-out on the digital voltmeter to determine if all conditions were normal. However, the digital voltmeter readings were intermittent and erratic. The meter would not

TABLE XI. COMPARISON OF RUNS DIFFERING IN PROPELLANT VALVES

Propellant Valve Type	Solenoid		Torque-Motor	
Run	90		98	
	Ox	Fuel	Ox	Fuel
Elec. Lead, msec	0		0	
Injector Temp., °F	-260		-260	
Propellant Temp., °F	-320	-210	-300	-190
Poppet Cocking, msec	6	5.5	-	
Start of Low Level Manifold Pressurization, msec	8.5	?	-	-
Start of Poppet/Flapper Transfer, msec	13.5	13.5	$\sim$9	
Valve Full Open, msec	16.5	18.5	12.3	
Start of Manifold Main Pressurization, msec	22	17	18	20.5
Hammer in Manifold, msec	29	22	32	32.5
Low Level Optical Emission, msec	$\sim$23 (est.)		28	
Ignition Delay for Main Ignition (P_{ch}), msec	30		32.5	
Character of Start Transient	Smooth		Smooth	

provide the proper display from the internal calibration signal and the results of the read-out were questionable. The decision was made to continue since the B_2H_6 was already loaded.

The oxidizer was loaded into the run tank by remotely observing the visual gauge on the OF_2 measuring tank. At the completion of the loading process the digital voltmeter seemed to be working again. All readings were approximately correct except that the altitude chamber pressure reading was 0.560 psia instead of the normal 0.000. The OF_2 was conditioned to -200°F.

The run was conducted following the usual sequence. At the completion of the test run, the altitude pressure reading was 21.95 psia. A normal run produces pressures of 2-3 psia.

The photographed oscilloscope data traces indicate a normal looking oxidizer manifold trace. However all other traces are not normal. The chamber pressure traces deflect downward rather than upward, the fuel manifold trace looks as though there was a "gas flow only" condition and both the propellant entry detector and the ignition detector show erratic combustion.

The pressure of the helium cylinder which is used to pressurize the liquid OF_2 showed a loss of approximately 200 psi.

The conditioning bath material was removed from the chamber/valve assembly and the hardware was examined for signs of failure. There was none externally visible. The system was scrubbed and maintained at vacuum condition overnight.

The following day it was determined that both sides (fuel and oxidizer) of the valve leaked. This was done by applying an upstream pressure and observing the altitude chamber pressure. The valve was then removed from the system and examined. It was confirmed that both the oxidizer and fuel ports leaked through. Visual examination of the outlet ports showed a circular metallic obstruction between the flapper and the seat in the oxidizer port. The size and shape of the obstruction seemed such that it was too big to have entered the valve from the outside. The valve was actuated causing the obstructing piece to fall away from the seat inside of the valve. The oxidizer side then sealed properly. The fuel side of the valve still leaked through. Following the finding, the technician reported that the valve had exhibited an erratic sealing condition on the fuel side when it was checked out on arrival but that the condition cleared up after one or two cycles and the valve then performed properly.

Based upon the above information it is believed that the fuel port remained open during the major portion of the fuel loading operation for

Run 99 and that the fuel was charged directly into the altitude chamber. The loud metallic click heard over the speaker system was the fuel port suddenly sealing. The valve opened normally at the fire signal but failed to shut down properly because of the obstruction in the oxidizer flapper/seat area. This allowed oxidizer pressurizing gas (helium) to continue to charge the altitude chamber until the safety valves were shut off in the shut down sequence. It is not known at present whether the erratic closing of the fuel side of the valve is related to the foreign metal piece which prevented proper closing of the oxidizer side of the valve.

The valve was returned to the manufacturer for their evaluation of the cause of failure. Their findings as reported via telecon are summarized as follows (Ref. 9):

i) The oxidizer seat and flapper were in "like-new" condition.

ii) No foreign material (such as described above) was noticed in the oxidizer side of the valve. However, the valve had been reworked several times to put in new torque tubes prior to the present testing with OF_2/B_2H_6. It is possible that a piece of foreign material may have been overlooked in the subsequent disassembly.

iii) The fuel seat and flapper were partially eroded making sealing impossible.

iv) The fuel seat and flapper were covered with a reddish crystalline material similar in appearance to iron rust.

It is not known what reaction could have taken place between B_2H_6 and the seat and flapper material to form the resultant red deposit. The seat/flapper material is made from a mixture of 96% tungsten carbide and 4% cobalt, the latter being used as a binder. Since the deposit was not analyzed, positive identification is not possible.

The manufacturer indicated that North American Aviation Co. had a similar experience with an identical make valve using N_2O_4 and MMH. Analysis of the contaminant proved it to be iron rust.

In the present case, however, iron rust seems unlikely as the causitive agent of failure since the valve employs 20 micron filters in the inlet ports and the fuel seat material was actually corroded. Furthermore, the corrosion cannot be attributed to the OF_2 since the oxidizer seat and flapper remained in like-new condition.

8. Explosively Actuated Valve Test

To determine the effect of zero propellant leakage on the starting transient, i.e. in the absence of any pre-flow arising from poppet cocking, a run was conducted using two explosively actuated Conax valves. The valves are described in some detail in Sec. III.A.3.b.

In the subject run (Run 78), the propellants (OF_2 and B_2H_6) were conditioned at -200°F in small ullage run tanks contained in separate conditioning baths. The Conax valves (close coupled), nine-pair injector and 100 psia chamber were conditioned at -100°F (Table V).

The explosive valves were initiated simultaneously with 24V DC fused for 5 amperes. There was a loud report closely followed by the sound of falling shrapnel. Examination of the hardware showed that the oxidizer valve body plug had blown out. The resultant reaction drove the valve body back pivoting on the tubing from the oxidizer run tank. This resulted in the fitting connecting the valve to the injector to pull free from the valve body. The injector feed line was bent at the injector face and the weld was broken. In addition, the coaxial cables were pulled loose from the connectors to the oxidizer injector manifold transducer and from the low sensitivity chamber pressure transducer. The protective burst disc in the oxidizer feed line (set for 1000 psi) had ruptured. There was no other damage. Figure 30 shows the hardware, with the chamber conditioning bath removed, on the day following the test.

The test data showed that the oxidizer manifold and the low sensitivity chamber pressure traces vanished one millisecond after actuation of the fire signal. Propellant entry was indicated at 1 msec, ignition detection and start of chamber pressure rise (from the high sensitivity chamber pressure trace) occurred at 1.5 msec. The ignition detector trace also showed that the combustion flame started to extinguish at 32 msec and was completely out by 44 msec.

The damage was very local. Figure 31 shows two views of the injector and the explosive valves used for the test. Figure 32 shows a comparison between a new valve and the damaged valve. The cause of the failure is attributed to fuel rich squib combustion products blowing by the shear ram into the downstream cavity of the valve. Shearing of the integral valve body diaphragm caused the OF_2 and the squib combustion by-products to mix in the valve body and resulted in a detonation which blew out the valve body plug as described above.

It must be pointed out that the Conax valves were designed for a minimum operating temperature of -65°F whereas they were conditioned to -100°F for the run. Furthermore, vaporization-condensation cooling during the OF_2 loading operation reduced the temperature to about -150°F.

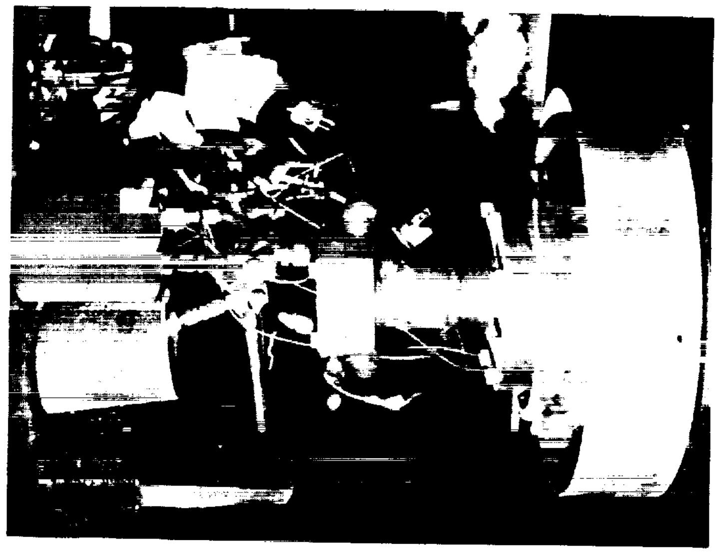


Figure 30. Test Hardware Following Explosive Valve Failure

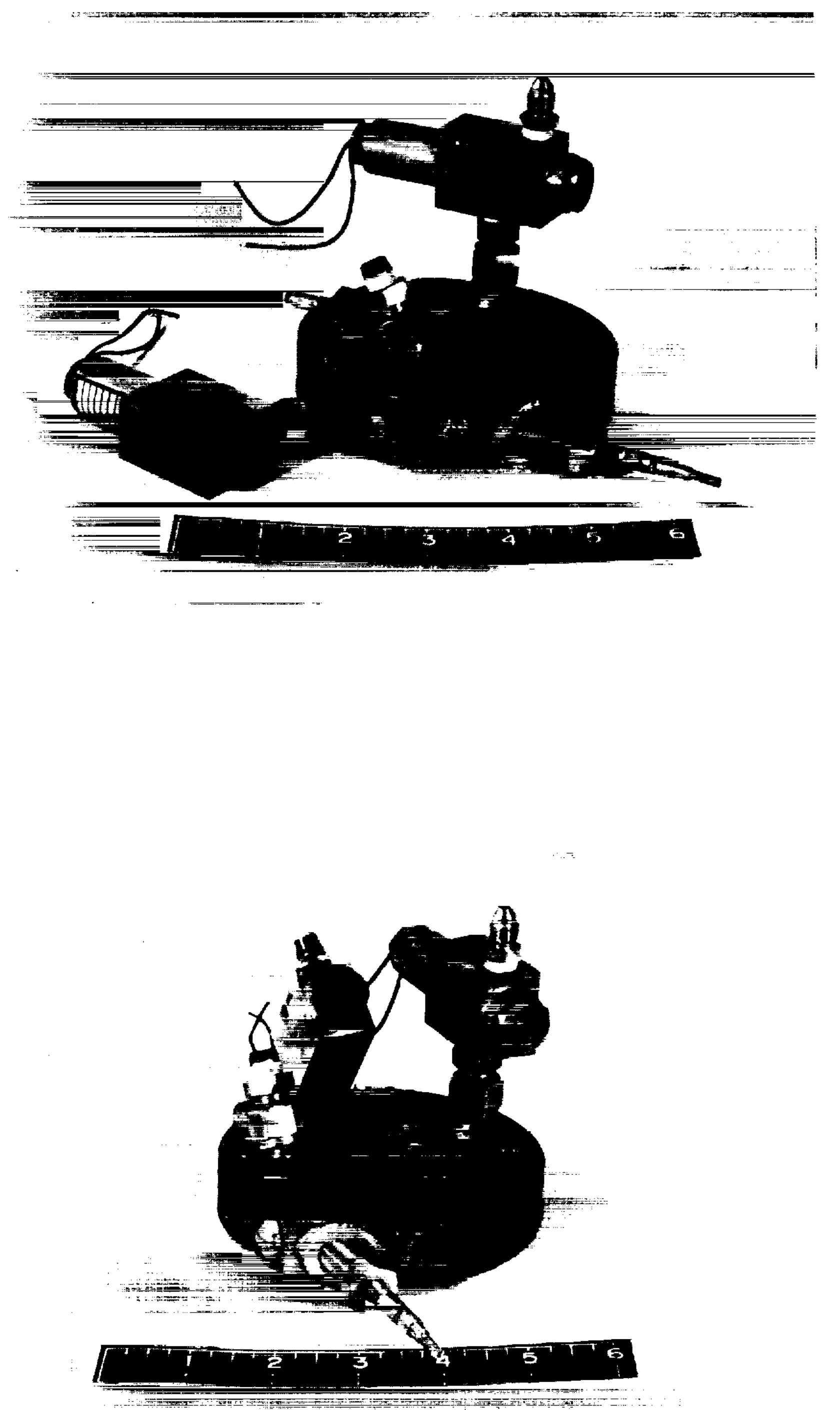


Figure 31. Injector and Explosive Valves after Run 78

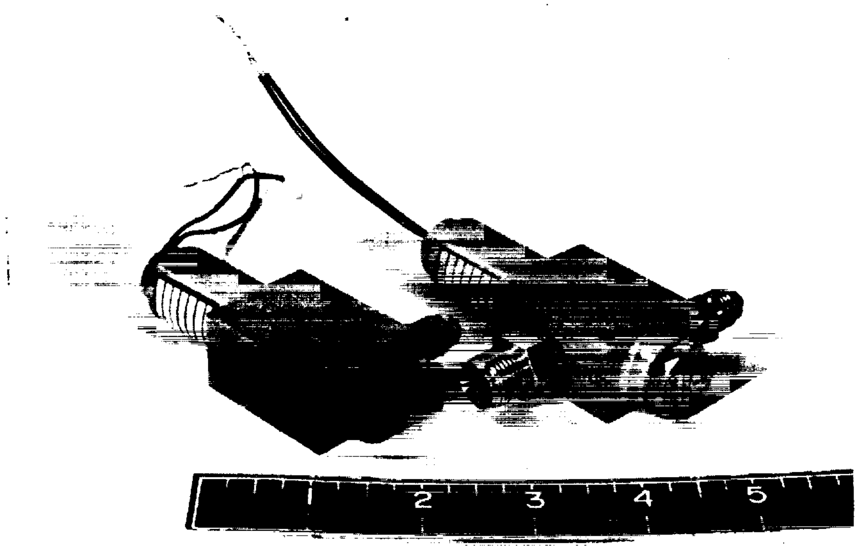


Figure 32. Explosive Valve Used in Run 78 and New Valve

Two candidate solutions to the problem are offered: (a) redesign the charge composition to produce oxidizer rich combustion blow-by products which are less reactive with OF_2 and retain the present hardware configuration, or (b) redesign the valve to prevent blow-by by utilizing a design such as the Rolldex-Rolling Metal Diaphragm Explosively Actuated Valve being developed by the Elkton Division of Thiokol Chemical Corporation for the Jet Propulsion Laboratory (Ref. 10).

No further testing of explosive valves was conducted.

9. OF_2-Flox Comparison

Five runs were made in the present program with Flox as the oxidizer in place of the OF_2 (Runs 118 to 122). These runs are discussed first and then these and other Flox runs from the Phase I program are compared with similar OF_2 runs.

The first run, Run 118, was made under the same conditions as Run 10 from the Phase I program (Ref. 1) to check reproducibility. The results of these two runs are given in Table XII. The Run 10 data includes additional valve opening data which is reported for the first time.

Table XII shows that the duplicate runs repeated quite well despite a lapsed time of 15 months between them. It is true that the "Ignition Delay" for Run 10 is listed as 24 msec in Table XII but as 22 msec in Reference 1. The small change is due to a slightly different definition of ignition delay in the two places.

The effects of propellant lead/lag at near isothermal conditions (approximately -250°F) were examined in Runs 120 to 122 (Table V). As stated in Table VI, the start transients were smooth in all cases including the Flox-lead case. This was expected based on the results of the Phase I program in which no ignition spikes occurred in any of the Flox runs.

The most striking difference between Flox and OF_2 as oxidizer is the lack of ignition spikes with the former but the occurrence of ignition spikes with the latter, especially with an oxidizer lead.

Manifold filling characteristics also differ between the two oxidizers due to their physical properties. Hard liquid filling of the injector occurs quickly under the test conditions with OF_2 and the injector at -200°F or below. On the other hand, in Flox Runs 120-122 the hardware and propellant temperatures (approximately -250°F), the Flox tank set pressure and the vapor pressures of O_2 and F_2 are such that the O_2 component would be liquid--following an initial, brief flashing phase--but the F_2 component would be at or somewhat above boiling point conditions. Therefore, water

TABLE XII. REPRODUCIBILITY OF FLOX/B_2H_6 TESTS

	Time from Signal-to-Leading Valve to: (millisecond)			
	Run 10		Run 118	
	Ox	Fuel	Ox	Fuel
Valve Signal	0	0	0	0
Cocking of Valve Poppet	7	5	7	6.5
Start of Low Level Manifold Pressurization	7.5	6	~8	7
Start of Poppet Transfer	12	12.5	12.5	14
Valve Full Open	16	16	14	16.5
Start of Manifold Main Pressurization	18	17	17	18
First Main Pressure Peak in Manifold	26[(a)]	23.5[(b)]	26[(a)]	21.5[(b)]
Ignition Delay for Main Ignition	24		24	
Character of Start Transient	Smooth		Smooth	

Notes: Engine configuration: 100 psia chamber, 9-pair injector, small ullage tanks, normal valve/injector coupling, solenoid propellant valves.

Temperatures: $T_{inj} = -100°F$, $T_{Flox} = -320°F$ and $T_{B_2H_6} = -100°F$.

(a) Times are to first sharp pressure peaks (Ox manifold disturbances). No Flox water hammer was observed.

(b) Times are to start of fuel water hammer in injector manifold.

hammer pressure peaks would not be expected. Only soft low peaks were observed (Table VI).

B. START-UP PROCESSES

A descriptive accounting of the physical and chemical processes that occur during start-up under the test conditions is given below. First, the fluid mechanical aspects are discussed and then the chemical aspects.

Upon application of voltage, a magnetic field begins to form in each solenoid propellant valve. At some point when the magnetic flux is still not great enough to overcome the unbalanced pressure and spring load forces, the poppet adjusts radially to the magnetic field. With the metal-to-metal seats, this cocking of the poppets opens small leakage paths through which propellants pass into the injector manifolds. Since the pressure is low (<13 microns), the propellants flash vaporize and slightly pressurize the manifolds. This very low "pre-flow" starts 6-7 msec following application of voltage and lasts until 11-14 msec at which time axial transfer of the poppets starts. The solenoid valves are full open at 15-17 msec.

With start of poppet transfer, liquid propellant begins to flow into the injector manifolds where it undergoes vaporization to a degree that depends on the propellant temperature and the valve/injector temperature(s). As the manifold filling proceeds and the manifold walls cool due to the vaporization, propellant passes through the injector orifices first as a vapor, then as a vapor/liquid two-phase mixture, and finally, provided the temperatures and tank pressure are appropriate, as all liquid flow. The emerging liquid enters the low-pressure environment of the thrust chamber and undergoes further atomization due to internal boiling in the liquid (Ref. 11) and droplet vaporization (Ref. 12).

For hard-liquid filling of the injector manifolds, the vapor pressure of the propellant at its effective temperature in the manifold must be less than the static pressure in the manifold, or approximately the tank pressure (minus system pressure drops to the injector). This condition is easily met in the case of the nine-element injector with both B_2H_6 and OF_2 at effective temperatures of -100° and -170°F or below, respectively. In the case of Flox, effective temperatures of less than -260 to -270°F would be required for the more volatile component F_2.

Under the appropriate conditions, hard liquid filling occurred in the following range of times (nine-element injector, 100 psia chamber, and solenoid propellant valves):

Propellant	Times to hard-liquid filling: From Signal to Respective Valve msec	From Start of Poppet Transfer msec
OF_2	24-31	~11-19
B_2H_6	19-29	5-13

The longest times occurred with the "warm" temperature conditions, i.e. $T_{OF_2} = -170^\circ F$, $T_{B_2H_6} = -100^\circ F$ and $T_{inj.} = -100^\circ F$.

The optical instrumentation added for the present program revealed an important characteristic of the subject propellant systems that was not detected previously. In the Phase I program (Ref. 1), ignition was taken as that time at which chamber pressure began to develop to significant levels, indicating the start of significant thrust generation. The added instrumentation in the Phase II program shows repeatedly the occurrence of optical emission well ahead of any significant pressure rise.

Of the two optical detectors added (Sec. III. C), the RCA 1P28 photomultiplier tube in the propellant entry detector system was markedly more sensitive to optical emission than the ignition sensor detector. Nevertheless, the field of view of the 1P28 was limited by the small field of the light pipe/window assembly. Despite this, generally the 1P28 indicated the start of visible emission (the tube is insensitive to infrared) well ahead of any signal from the ignition sensor (Table VI). In fact, usually though not always the ignition sensor indicated ignition at the same time as the chamber pressure transducer (Table VI).

The 1P28 data says that, generally, visible emission starts very nearly with the start of manifold main pressurization by the second propellant. However, in a number of cases, the 1P28 data shows that visible emission starts prior to the start of manifold main pressurization by the second propellant (Table VI). In other words, "first ignition" occurs during the period of pre-flow of one propellant, i.e. during the very low flow that occurs due to poppet cocking just prior to the start of normal poppet transfer in the lagging valve. Furthermore, in a few cases, visible emission was detected during the pre-flow period of both propellants. In these cases, two of which were OF_2/B_2H_6 runs (Nos. 94 and 117, Table VI) and one was Flox/B_2H_6 (118), first ignition occurred under conditions of very low gas densities as well as low temperatures.

Due to the frequency with which visible emission was detected during the pre-flow of at least one propellant and since these cases encompassed both oxidizers, all hardware configurations, all temperature levels, the full range of propellant lead/lags, and both spiking and non-spiking runs, and in view of the limited field of view of the 1P28 detector, it is concluded that "first ignition" occurs essentially spontaneously upon contact of the low pressure, low temperature gaseous fuel and oxidizer and that this first ignition results in a weak pilot flame. The flame then increases in intensity as the mass input into the thrust chamber increases provided a reasonable balance between fuel and oxidizer is maintained. When the mass input of one propellant lags markedly, the pilot flame remains weak and "main ignition" is delayed.

Main ignition is defined as the time at which pressure starts to rise to significant levels and corresponds closely to the definition used in Phase I. Examination of Table VI reveals that main ignition occurs very closely with hard liquid filling of the injector manifold by the second propellant. The first indication of pressure rise in the thrust chamber frequently corresponds to hard liquid filling by the first propellant, however, this result clearly depends upon the sensitivity of the pressure transducer.

In summary, the striking feature of the vacuum ignition of OF_2/B_2H_6 and Flox/B_2H_6 is the very rapid ignition of the first low pressure, low temperature propellant vapors and the attendant formation of a pilot flame to "ignite" the bulk flow which follows. The cocking of the solenoid valve poppets may well be a desirable feature which, by permitting the establishment of a weak, short-duration pilot flame, promotes smooth starts.

C. PROBLEM AREAS ENCOUNTERED

In this section, problems that were encountered during the program are listed and briefly discussed. Some were significant, e.g. freeze-up of the oxidizer solenoid valve. Others were not harmful but might be in flight-weight hardware, e.g. manifold POPS.

1. Oxidizer Valve Freeze-Up

In two instances (Runs 92 and 93), the oxidizer solenoid valve failed to open upon voltage application. The instances are described in the following paragraphs.

Preparations for OF_2/B_2H_6 Run 92 were made in the usual way. This run was to be the fourth run following a hardware change from small to large ullage run tanks. The first three runs proceeded without incident. In Run 92, when voltage was applied to the oxidizer solenoid valve, it did not open although the fuel valve functioned normally. The OF_2 was then vented and the area cleared of personnel for about an hour. Upon return, the valve functioned and sealed properly. A few helium gas runs were made and the valve seemed to operate in a normal manner. The following day a repeat run (#93) was attempted but with the same result. The valve was then removed from the system and disassembled. The poppet and seat were found to be wet with a straw-yellow fluid which appeared oily. The valve parts had an OF_2 odor. The fluid material, which was insufficient for analysis, evaporated slowly leaving an amber film on the surfaces. The poppet was etched and scored and had a small nick on the sealing surface. The valve was cleaned and reassembled with a new poppet (Sec. III. A. 3. a) prior to Run 94.

It is believed that the straw-colored liquid froze in the valve during temperature conditioning and/or propellant loading causing the valve to hang up. The system was checked for evidence of contaminating fluid elsewhere although none was found. The nature and source of the contaminant is unknown. As a precautionary measure, however, the OF_2 supply tank, which was nearly empty, was replaced and the system was thoroughly flushed and cleaned. No further action to identify the contaminant was taken due to other pressures of the program. No other incidents of this nature occurred thereafter.

2. Contamination

In the first run of the Phase II program (Run 49, Table V), some metal degradation occurred. Examination of the hardware after the run showed that the lead gasket seal and the Kistler pressure transducer adapter bolt end in the oxidizer manifold had been slightly burned. Also the pressure transducer had failed. The injector itself was essentially unharmed except that the transducer adapter bolt sealing surface was somewhat degraded.

It is now believed that the parts had become contaminated during the assembly process. The cleaning technique used for the first run of the Phase II program was changed in one detail from the procedure used during the Phase I program. The last cleaning step prior to assembly was to flush the parts with Vythene and dry them with N_2. The Vythene was contained in a small beaker. The test pieces were placed in the beaker and agitated. It is suspected that the Vythene or the beaker may have contained some dissolved organic material.

The test pieces for a duplicate run included a new lead gasket and a blank adapter bolt (one not drilled out for a transducer). The pieces were flushed with jets of container-fresh Vythene (as had been the procedure for the Phase I tests) dried with N_2 and assembled. The second run (Run 50) was conducted successfully. The Phase I cleaning procedure was reinstituted to prevent a reoccurrence of component contamination.

3. Propellant Valves

The present program did not include as an objective an exhaustive evaluation of various candidate propellant valves. Nevertheless, as discussed in detail in preceding sections, three types of propellant valves were tested and each had its shortcomings. The solenoid valves which were used for 121 runs during the two consecutive programs suffered primarily from degradation of the metal-to-metal seals. The problem was circumvented to a large extent by using soft copper poppets but these had to be replaced at relatively frequent intervals (Sec. III. A. 3. a). An additional characteristic of the solenoid valves is the short "pre-flow" that occurs due to cocking of the valve poppets just prior to axial transfer (Sec. III. A. 3. a). However, this characteristic may be advantageous, rather than detrimental, to start transients since ignition of the weak flows provides a pilot flame for the bulk flows that quickly follow.

The bipropellant valve tested operated normally in one run but suffered a malfunction in the second run. The particular unit had been reworked several times by the manufacturer prior to the present testing so that the malfunction was presumably an unfortunate, isolated instance.

The explosively actuated valves tested performed satisfactorily in the fuel side even at sub-design point temperatures. In the oxidizer side, however, the fuel-rich squib products came in contact with the oxidizer due to blow-by and resulted in valve failure. The blow-by problem must be resolved in order for explosively actuated valves to be satisfactory for OF_2 service.

Since each of the three types of valves exhibited significant shortcomings, the need for improved, highly reliable, flight weight valves for space storable applications is obvious.

4. Post-Ignition Chamber and Manifold POPS

In two runs, "POPS" occurred shortly after ignition during otherwise steady combustion. Both runs were made under cold conditions (Runs 95 and 97, Table V).

In Run 95, a "POP" occurred in the thrust chamber during otherwise steady combustion approximately 10.5 msec after ignition. Evidence of the disturbance is seen also in both injector manifold pressure traces. The disturbance in the OF_2 manifold occurred simultaneously with the chamber disturbance but the fuel manifold disturbance was slightly delayed. A second, separate disturbance occurred in the OF_2 manifold approximately 2 msec after the first disturbance. No evidence of this second damped oscillatory disturbance is seen in either the fuel manifold or the chamber.

A very similar, though slightly stronger, damped oscillatory disturbance also occurred in Run 97. This disturbance occurred only in the oxidizer manifold during otherwise steady conditions approximately 8.5 msec after ignition. The cause of these oscillations is unknown but the potential of causing damage in flight-weight hardware remains.

VI. CONCLUSIONS

The following conclusions are drawn based on the results of the investigation.

Cocking of the solenoid valve poppets as the magnetic flux builds up opens small leakage paths through the metal-to-metal seals prior to the start of normal poppet transfer. The poppet cocking results in a "pre-flow" which, in the present case, has a duration of 4-8 msec prior to the start of poppet transfer.

Initial ignition is very fast. It occurs in the vapor phase when one or both of the propellants is in the pre-flow period. Propellant concentrations are very low and temperature is also very low.

The initial ignition produces a weak flame that acts as a pilot flame for the oncoming bulk flows. Main ignition, or the time when significant chamber pressure--and therefore thrust--begins to develop, occurs when the full mass flow of the lagging propellant occurs.

It is necessary that the propellant valves be thermally conditioned with the propellants in order (a) to obtain and maintain hard liquid filling up to the valve seats in a sun-soaked, zero "g" environment, or (b) to avoid propellant freezing, B_2H_6 in particular, if the valves are in shade.

With the OF_2/B_2H_6 propellant system, oxidizer leads (electrical) can result in ignition spikes. On the other hand, no spikes were observed with fuel leads or with simultaneous valve signals. With 70/30 Flox as the oxidizer, no ignition spikes were observed under any conditions.

Shorter delays to main ignition are favored by high design chamber pressures due to the higher initial propellant flows which result from the higher tank pressures.

Short delays to main ignition were also favored by the single element injector due to the shorter manifold filling times which result from the smaller dribble volume than in the nine element injector.

Based on infrared spectra and X-ray diffraction, similar species are present in the combustion residues formed by B_2H_6 with either OF_2 or 70/30 Flox. These species are amorphous elemental boron, H_2O and at least two other components one or both of which are borates ($BO_3^{\equiv}$, $B_4O_7^{=}$). The composition of the residues depends to some extent on the lagging tail-off propellant.

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VII. RECOMMENDATIONS

Several factors pertinent to vacuum ignition of OF_2/B_2H_6 in space-ambient engines that were uncovered during the course of this investigation and that require further study are enumerated below:

1. An instance of oxidizer valve freeze-up occurred and was traced to a yellow liquid that coated the valve parts. The origin of the material is unexplained at present and its composition is unknown. As the valve became completely inoperative without any warning, the basic cause should be determined so as to prevent any re-occurrence during a mission.

2. With the solenoid propellant valves, "first ignition" and formation of a pilot flame occurred during the "pre-flow" of at least one of the propellants. The pilot flame then permitted rapid reaction of the oncoming bulk propellants. The weak pilot flame may play an important role in providing smooth starts. This aspect should be evaluated as the need for a brief pre-flow might be a requirement for satisfactory start characteristics.

3. Each of the three flight-type valves tested exhibited shortcomings of various degrees as discussed in Sec. V.C.3. Improved valves with high reliability are required for the space-storable propellants considered in this investigation.

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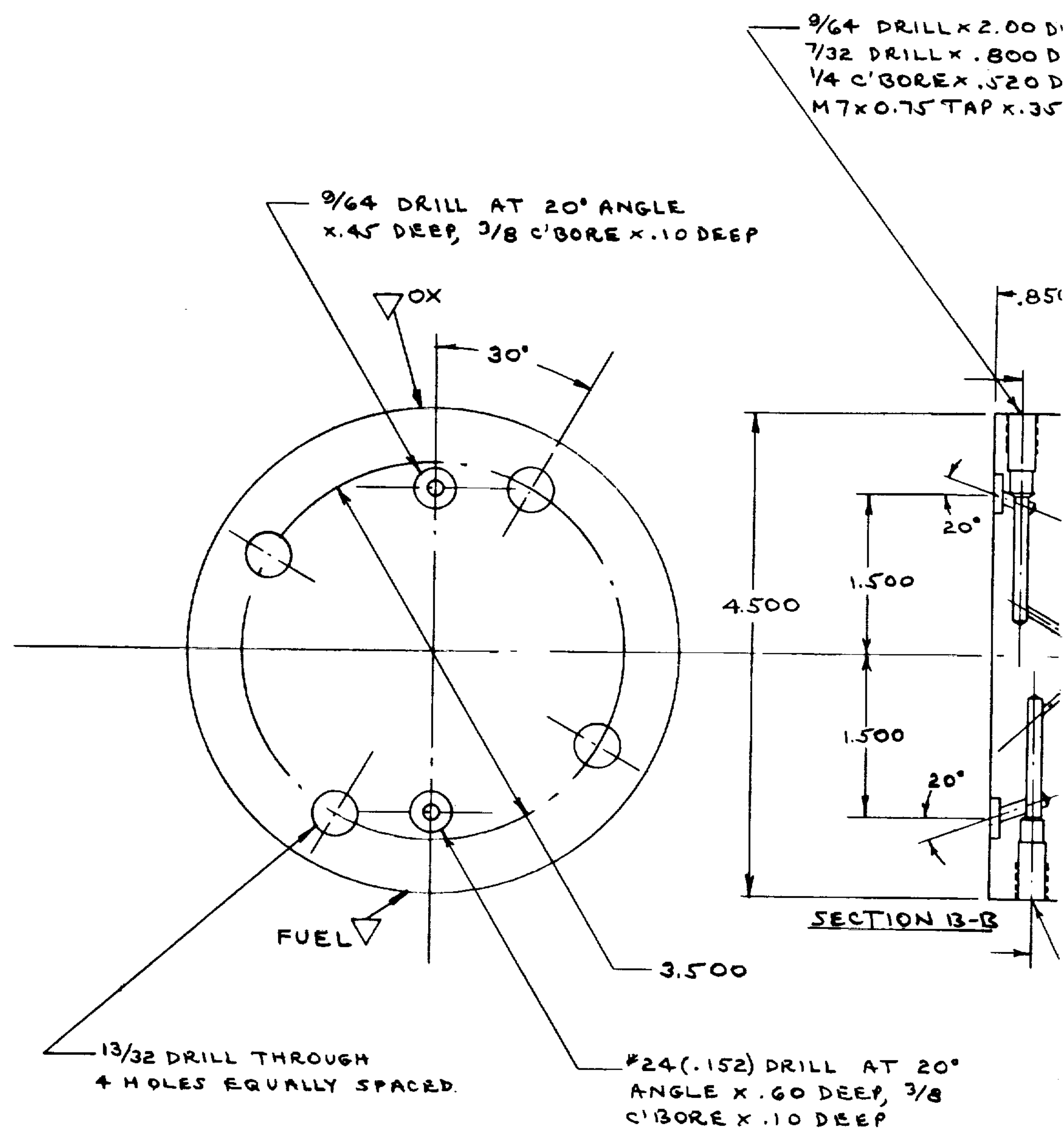
APPENDIX A

INJECTOR DRAWINGS



RMD SPECIFICATIONS	
IDENTIFICATION OF PARTS & ASSY'S	7145
SURFACE ROUGHNESS, WAVINESS & LAY	7401
WELDING & ALLIED PROCESSES	7044
MFG & INSPECTION STANDARDS	7400

UNLESS OTHERWISE SPECIFIED

ALL DIMENSIONS IN INCHES

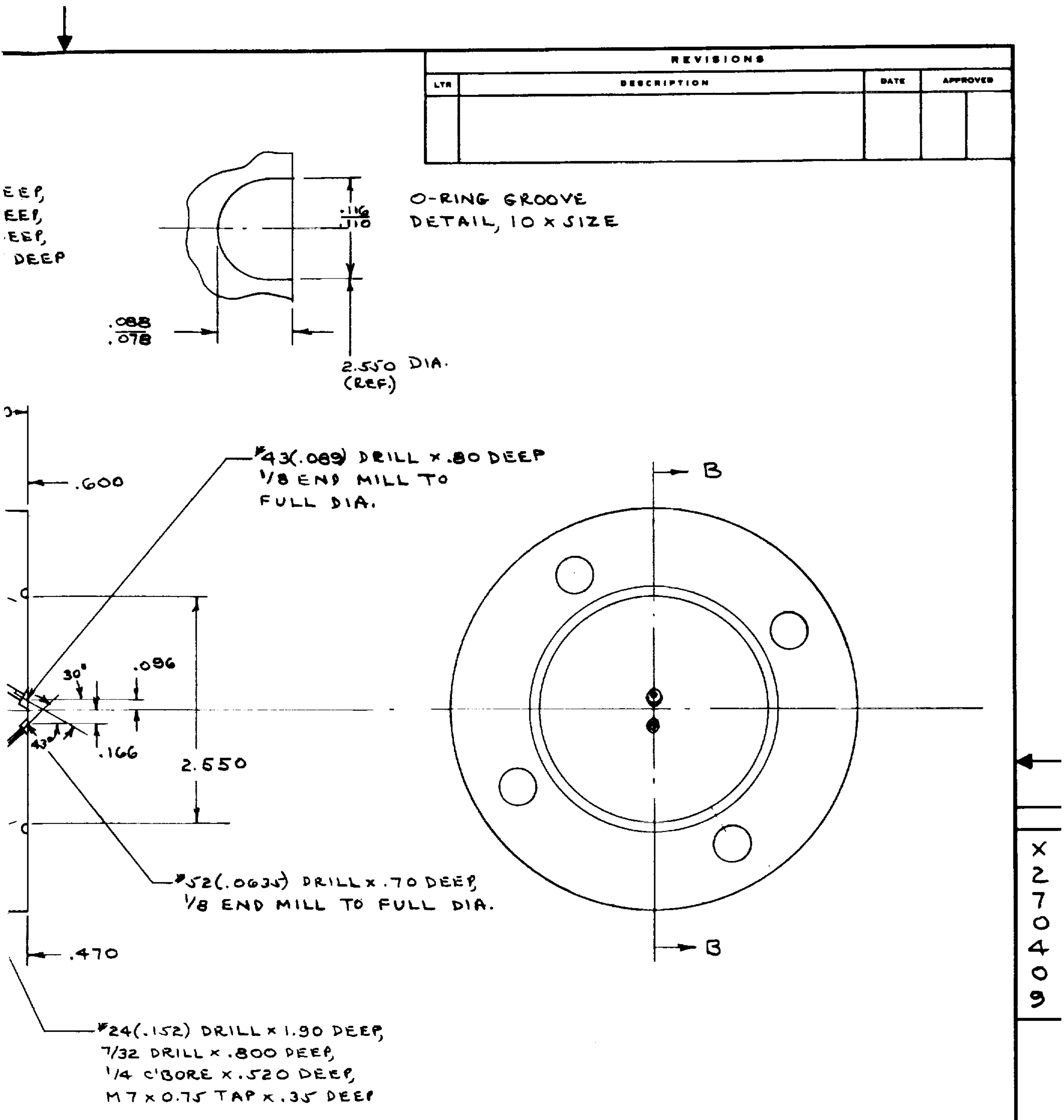
TWO PLACE DEC. ± .03 THREE PLACE DEC. ± .01

ANGLES ± 2° 125 ALL FINISH SURFACE

BREAK SHARP EDGES .003–.015

ALL SMALL FINISH FILLETS .020–.040 R

A SURFACES SHALL BE CONCENTRIC, PARALLEL, FLAT, SQUARE & TRUE (AS APPLICABLE) TO EACH OTHER WITHIN__________F.I.R.



ITEM NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	QTY REQD

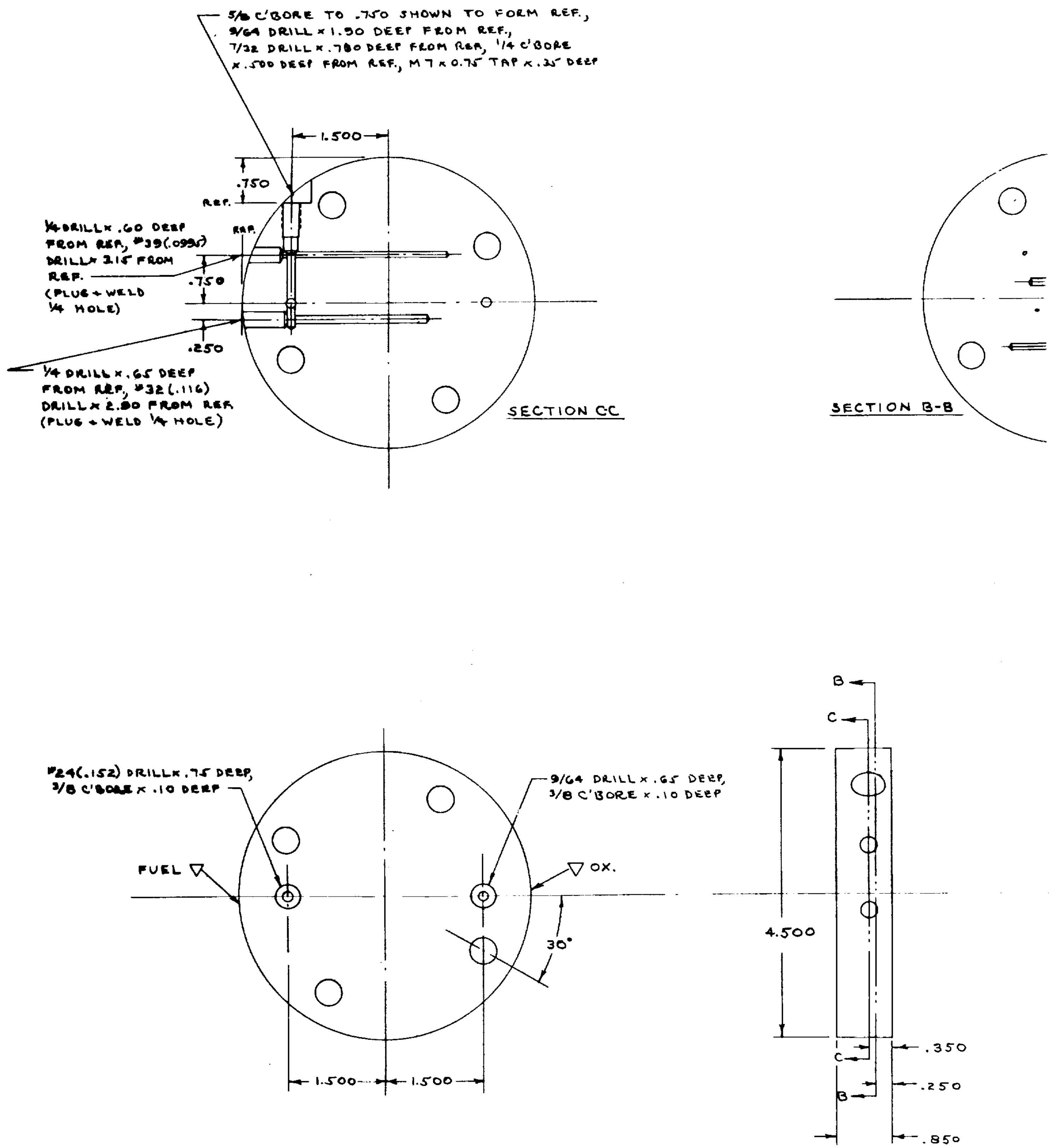
LIST OF MATERIALS

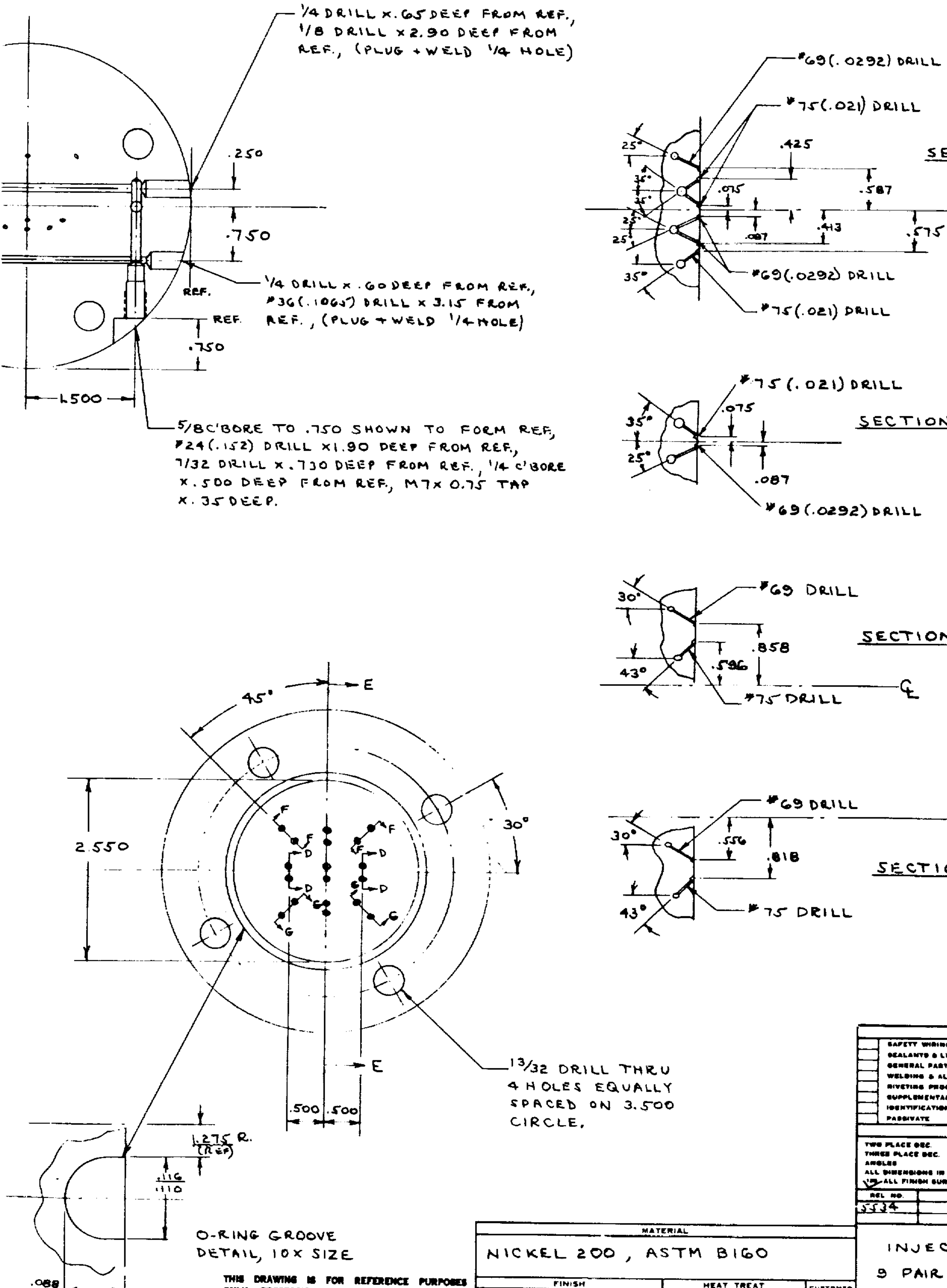
MATERIAL	DRAWN	CHECKER	MAT.	STAFF ENG.
NICKEL 200 ASTM B160	DAWSON 2/23/68			
	FAB.	DES. ENG.	ENGR.	STRESS
FINISH	REL. NO. 5534	NEXT ASSY. (REF.)		
HEAT TREAT			RMD CLASS IV	

Thiokol CHEMICAL CORPORATION
REACTION MOTORS DIVISION
DENVILLE, NEW JERSEY

INJECTOR – SINGLE DOUBLET

SIZE	CODE IDENT	
C	83323	X270409
SCALE FULL	WEIGHT	SHEET


5/8 C'BORE TO .750 SHOWN TO FORM REF.,
9/64 DRILL × 1.50 DEEP FROM REF.,
7/32 DRILL × .780 DEEP FROM REF., 1/4 C'BORE
× .500 DEEP FROM REF., M 7 × 0.75 TAP × .25 DEEP
1.500
.750
REF.
REF.
1/4 DRILL × .60 DEEP
FROM REF, #39(.0995)
DRILL × 2.15 FROM
REF.
(PLUG + WELD
1/4 HOLE)
.750
.250
1/4 DRILL × .65 DEEP
FROM REF, #32 (.116)
DRILL × 2.80 FROM REF
(PLUG + WELD 1/4 HOLE)
SECTION CC
SECTION B-B
#24(.152) DRILL × .75 DEEP,
3/8 C'BORE × .10 DEEP
9/64 DRILL × .65 DEEP,
3/8 C'BORE × .10 DEEP
FUEL
OX.
30°
1.500
1.500
B
C
4.500
C
B
.350
.250
.850



X270410

NOTE: 1/16 END MILL 9 #69 AND 9 #75 HOLES AT INDICATED ANGLE TO FULL END MILL DIA.

LET.	REL. NO.	DATE	CHANGE	CKR.	APP.

RMD SPECIFICATIONS

- SAFETY WIRING
- SEALANTS & LUBRICANTS
- GENERAL PART & ASSEMBLY CLEANING PROCEDURE
- WELDING & ALLIED PROCESSES
- RIVETING PROCESSES
- SUPPLEMENTARY MFG. & INSPECTION STANDARDS
- IDENTIFICATION OF PARTS AND ASSEMBLIES
- PASSIVATE

UNLESS OTHERWISE SPECIFIED

TWO PLACE DEC. ± .03
THREE PLACE DEC. ± .010
ANGLES ± 1°
ALL DIMENSIONS IN INCHES
125 ALL FINISH SURFACES

BREAK SHARP EDGES .005 - .015
ALL SMALL FINISH FILLETS .005 - .040 R
SURFACES SHALL BE CONCENTRIC, PARALLEL, FLAT, SQUARE & TRUE (AS APPLICABLE) TO EACH OTHER WITHIN ______ F.I.R.

REL. NO. 5534 — NEXT ASSEMBLY (REFERENCE ONLY)

MATERIAL: NICKEL 200, ASTM B160

FINISH	HEAT TREAT	CUSTOMER

DRAFTSMN	CHECKER	MAT	STAFF ENGR	FAB	DES ENGR	ENGR	STRESS
DAWSON 2/[illegible]/69							

INJECTOR, 9 PAIR DOUBLET

CLASS	SCALE	WEIGHT
IV	FULL	

Thiokol CHEMICAL CORPORATION
REACTION MOTORS DIVISION
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X270410

APPENDIX B

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