OF_2/DIBORANE TECHNOLOGY
VACUUM IGNITION - PHASE II

Report RMD 5536-Q3

Report Period: 15 July 1969 - 14 October 1969

Contract NAS 7-660

Jet Propulsion Laboratory
Pasadena, California

Approved by: T. F. Seamans

T. F. Seamans
Section Chief
Combustion & Physics Research

C. J. Grelecki

C. J. Grelecki
Manager
Research

THIOKOL CHEMICAL CORPORATION
Reaction Motors Division
Denville, New Jersey

FOREWORD

This is the third Phase II quarterly research progress report prepared by Thiokol Chemical Corporation, Reaction Motors Division, Denville, New Jersey, under National Aeronautics and Space Administration Contract NAS 7-660.

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

The technical effort reported herein was conducted during the period from 15 July 1969 through 14 October 1969.

The Project Leader is Mr. Thomas F. Seamans. The Principal Investigator is Mr. George R. Mistler.

TABLE OF CONTENTS

LIST OF TABLES

I. INTRODUCTION

This is the third Phase II Quarterly Research Contract Status Report for continuing investigations being conducted under Contract NAS 7-660*. This report covers the period from 15 July through 14 October 1969.

The purpose of this twelve month technical program is to further define vacuum starting characteristics and potential problem areas in vacuum ignition of space engines using OF_2/diborane and Flox/diborane propellant combinations.

The program consists of three technical tasks as follows:

TASK I - VACUUM IGNITION OF OF_2/DIBORANE

The primary effort of the program and of this task is an experimental investigation of the vacuum ignition of 100-lb thrust rocket engines using the OF_2/diborane propellant combination. The engine and operating parameters to be investigated are: design chamber pressure, dribble volume/injector configuration, propellant valve coupling/type, run tank ullage, propellant lead/lag, oxidizer temperature, fuel temperature and hardware temperature. A correlative effort will be analyses to define the physical and chemical mechanisms which control starting under the test conditions. In addition, phenomena such as ignition spiking, oxidizer manifold pressure perturbations, tank over-pressurization and oxidizer reaction with deposited residue, which were uncovered during the Phase I effort, will be more fully investigated. This will provide information for design concepts and hardware required for reliable vacuum starting of OF_2/diborane space engines.

TASK II - FLOX AS SIMULANT FOR OF_2

This task consists of experimental and analytical studies to determine the effects on engine ignition characteristics when Flox (70% F_2 + 30% O_2) is substituted for the OF_2. Selected Task I tests will be repeated to provide a firm basis for comparison. From the tests and supporting analyses, changes in design concepts and hardware required for

*Phase I of the contract was conducted from 15 February 1968 through 15 October 1968. Results are contained in report RMD 5534-FI, Vacuum Ignition of Flox/Diborane and Oxygen Difluoride/Diborane, published in March 1969.

reliable vacuum starting of space engines when Flox is substituted for OF_2 will be determined.

TASK III - HIGH SPEED MOTION PICTURES

The purpose of this task is to investigate techniques for taking useful high speed motion pictures of the injection transient and ignition processes.

To be useful, the high speed motion pictures must provide sufficient information to allow engineering analysis of the physical/chemical processes involved. The factors to be considered include film and camera speed, resolution, field of view, optical window design, camera placement, lighting and filtering.

II. SUMMARY

Twenty-two runs were conducted during this report period covering, in particular, lead/lag effects and temperature effects.

A potentially important problem was encountered during the testing, namely failure of the oxidizer solenoid valve to open on two successive runs. The problem is attributed to a very small quantity of straw-colored fluid which froze at the cryogenic temperatures immobilizing the poppet. The nature and source of the contamination has not been determined. Following system cleaning, subsequent valve operation has been normal.

It was found that in runs with an OF_2 lead (electrical), ignition pressure spikes were likely. No spikes have been observed in fuel lead runs.

Optical emission in the thrust chamber is detected relatively early in the start-up transients, i.e. often before, even, the start of manifold main pressurization by the lagging propellant. Thus, a weak "pilot" flame can be established while the flow of one propellant is merely the low vapor flow that results from cocking of the valve poppet. This pilot flame allows essentially immediate, full reactions of the bulk flow whenever that occurs. Therefore, "main ignition" (i.e. the start of large-scale reactions that produce substantial chamber pressure) occurs when hard liquid filling of the injector manifolds occurs by the lagging propellant. In the present test system, the time to reach hard liquid filling by the OF_2 exceeds that for B_2H_6 under the specific operating conditions. Thus, minimum delays to main ignition should and do occur with a slight OF_2 lead.

It was found that hardware and propellant temperatures do not affect the time to main ignition although the character of manifold filling is affected. Hard liquid filling of the manifolds may not occur before ignition if the propellant and/or hardware temperatures are sufficiently warm that the vapor pressure of the propellant within the injector exceeds the tank pressure.

Two tests were made using a torque-motor operated bipropellant valve in place of the usual solenoid poppet valves. The first run of the pair proceeded normally and start-up transients were generally similar to those of comparable runs made with the solenoid valves. In the second run, a double malfunction occurred although the two may possibly stem from the same cause. The fuel side of the valve did not properly close during filling of the fuel run tank and the oxidizer side did not close at shut-down due to a piece of metal wedged between the flapper and its seat.

III. TASK I - VACUUM IGNITION OF OF_2/B_2H_6

A. Test Hardware Modifications

The basic hardware and test system for the program have been adequately described in previous reports (Refs. 1-3). Therefore, only those modifications made in the present report period will be discussed here.

1. Propellant Valves

a. Valcor Eng. Corp. Solenoid Valves

The well-used Valcor solenoid propellant valve controlling the oxidizer flow was fitted with a new copper poppet prior to Runs 88 and 94 to minimize leakage. New copper poppets had been installed several times previously for the same purpose (Ref. 3).

In Run 92, the oxidizer propellant valve did not open when energized. The OF_2 was then vented and the area cleared of personnel for about 1 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 with the same results. The valve was 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 sample was too small for analysis. The material evaporated slowly leaving an amber film deposited 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 prior to Run 94, as noted above.

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 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.

Parts to refurbish the well-worn fuel and oxidizer Valcor valves were procured and installed prior to Run 100. The principal parts are the poppet guide housings with stellite seat. Copper poppets were installed to provide good sealing although at the expense of longer life. New springs were also installed.

b. Hydraulics Research Corp. Bipropellant Valve

One part of the experimental program was to evaluate alternate types of propellant valves. The great majority of tests have been conducted with the Valcor solenoid valves. One test was made with explosive valves but blow-by was found to be a problem (Ref. 3). During the present report period tests were conducted with another valve which is also a flight-type valve. The valve is a Hydraulic Research and Manufacturing Co. bipropellant valve 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.

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.

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 Noninal 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)

An adapter for mating the bipropellant valve with the nine-pair doublet injector was designed and fabricated. In the two runs made with this valve (Runs 98 and 99), the valve was conditioned with the injector, however it was also subjected to the propellant vaporization-condensation cycle discussed previously (Ref. 3).

2. Propellants

Prior to Run 94, a new supply cylinder of OF_2 was installed in the test system as a precautionary measure to avoid further occurrences of oxidizer valve freezing. Coupled with the re-cleaning of the oxidizer valve and system as previously described (Sec. III. A. 1, above) operation of the Valcor ox valve has been satisfactory in all succeeding runs.

3. Injector Configuration and Valve/Injector Coupling

The runs made during the present report period used the 100 psia design chamber with both the 9-pair doublet injector and the 1-pair doublet injector. The injectors and chamber are described in detail in Ref. 1.

Two types of valve (Valcor)/injector coupling were used. These are called normal coupling and close coupling. In the former, the propellant valves are conditioned with the respective propellant run tank and isolation tubes separate the valves from the injector which may be conditioned to some other temperature. In the close coupling case, the valves are conditioned with the injector (Ref. 3).

B. Instrumentation Modifications

Two Kistler Model 603A piezoelectric pressure transducers are used to monitor chamber pressure. The sensitivity of one is somewhat greater than the other in order to observe pre-ignition pressure rises. Occasional lack of agreement between the two transducers was traced to the one with the higher sensitivity. A new transducer was installed prior to Run 98; however the problem did not go away entirely. A new Kistler Charge Amplifier (Model 566) was installed prior to Run 104 with satisfactory results.

Another problem frequently encountered is thermal drift of the chamber pressure Kistlers. To improve thermal isolation, longer vulcanization times at atmospheric conditions for the GE RTV Adhesive Sealant became the practice with Run 97.

In preparing for Run 90, one of the sapphire windows in the propellant entry detector device (Ref. 2) was accidentally broken due to excessive torque and so was replaced. The window had been used for forty runs with no evidence of deterioration of any kind.

C. Test Results

Twenty-two test runs were conducted during this report period (Runs 83 through 104). All tests were conducted with the 100 psia chamber. Both the nine-pair injector and single element injector were tested using large ullage and small ullage run tanks as well as "normal" and "close" valve/injector coupling. Valcor solenoid valves were used for all runs except two. In Runs 98 and 99, a Hydraulics Research torque-motor bipropellant valve was used. Conditioning temperatures and propellant lead/lag were operating variables.

The test hardware, test conditions and significant data are summarized in Tables II and III, the former for runs up to No. 99 and the latter for No. 100 and above.

D. Discussion

1. Effect of Propellant Lead/Lag

Runs 83 through 88 were a continuing part of a series starting with Run 77 (but excluding No. 78 which was a test of explosive valves, Ref. 3) to evaluate propellant lead/lag effects in a possible flight type hardware configuration. This series was made with the 100 psia chamber, nine element injector, small ullage run tanks and close valve/injector coupling. The temperature conditioning objective was -200°F for both propellants and hardware.

TABLE I. TEST RUN DATA SUMMARY

NOS. 49 to 99

RUN No	CHAMBER	INJECTOR	CHAMBER INJECTOR TEMP. °F	RUN TANKS (ULLAGE)	VALVE COUPLING	OXIDIZER	FUEL	PROP. LEAD ELECT.	REMARKS
S12CX									
49	100PSIA	9 PAIR	70	LARGE	NORMAL	OF_2	B_2H_6	NONE	
50	"	"	"	"	"	"	"	"	
51	"	"	"	"	"	"	"	11 OX	NO DATA
52	"	1 PAIR	-180	"	"	"	NONE	NA	
53	"	"	-200	"	"	NONE	B_2H_6	NA	
54	"	"	-180	"	"	OF_2	"	NONE	
55	"	"	-205	"	"	"	"	11 OX	
56	"	"	-200	"	"	"	"	11 FUEL	
57	"	"	-215	"	"	"	NONE	NA	
58	"	"	-195	"	"	"	B_2H_6	11 OX	
59	"	9 PAIR	-100	"	"	"	"	NONE	
60	"	"	"	"	"	"	"	"	
61	"	"	"	"	"	"	"	11 OX	
62	"	"	+70	"	"	"	"	11 OX	
63	"	"	-100	"	"	"	"	11 FUEL	TIME BASE [illegible] 5MSEC/C[illegible] WAS 10 M[illegible]
64	"	"	"	"	"	"	"	11 OX	
65	"	"	-200	"	"	"	"	11 "	
66	"	"	-200	"	"	"	"	NONE	
67	"	"	"	"	"	"	"	11 OX	NEW TIMING
68	"	"	+70	"	"	"	"	1 F	
69	"	"	-100	"	"	"	"	1.5 OX	
70	"	"	-200	"	"	"	"	NONE	
71	"	1 PAIR	-100	"	"	NONE	"	NA	
72	"	"	+70	SMALL	INTERUM	OF_2	"	NONE	
73	"	9 PAIR	-100	"	"	"	"	1 OX	
74	"	"	-200	"	CLOSE	"	"	2.5 OX	
75	"	"	"	"	"	"	"	6 OX	
76	"	"	"	"	"	"	"	4 OX	
77	"	"	"	"	"	"	"	4.5 OX	
78	"	"	-100	"	"	"	"	NONE	CONAX VALVE
79	"	"	-200	"	"	"	"	2 F	VALCOR "
80	"	"	"	"	"	"	"	NONE	
81	"	"	"	"	"	"	"	2.5 OX	
82	"	"	"	"	"	"	"	8 OX	
83	"	"	"	"	"	"	"	10 OX	
84	"	"	"	"	"	"	"	8.5 OX	
85	"	"	"	"	"	"	"	1 OX	
86	"	"	"	"	"	"	"	3 F	
87	"	"	"	"	"	"	"	14.5 OX	
88	"	"	-190	"	"	"	"	6.5 OX	
89	"	"	-190	LARGE	"	"	"	6 OX	
90	"	"	-250	"	"	"	"	NONE	
91	"	"	-100	"	"	"	"	"	
92	"	"	"	"	"	"	"	"	
93	"	"	"	"	"	"	"	6 OX	
94	"	"	"	"	"	"	"	4 OX	
95	"	"	-200	"	"	"	"	5.5 OX	
96	"	"	-100	"	"	"	"	6 OX	
97	"	"	-240	"	"	"	"	6 OX	
98	"	"	-260	"	MOD. CLOSE	"	"	None	Hyd. Res. Valve
99	"	"	-210	"	" "		"	"	" "

TABLE II. TEST DATA SUMMARY – NOS 49 to 99

Run No	Ox Tank Set Press.	Ox Temp	Ox Prop. Start	Ox Prop. Open	Ox Man. Start	Ox H_2O Hammer	Remarks
512CX	psia	°F	msec	msec	msec	msec	
49							
50							
51							
52							
53							
54							
55							
56							
57							
58							
59							
60							
61							
62							
63							
64							
65							
66							
67							
68	164	-320	?	18	21	30	
69	"	"	"	18.5	17.5	27.5	
70	"	"	"	19.5	19 24	31	
71	N/A	N/A	N/A	N/A	N/A	N/A	Fuel only
72	146	-320	25	28	13 26		Ox valve slow to open
73	164	"	12.5	15.5	8 26	–	Ox feed improperly soft
74	178	-200	~7 16.5	27	~16.5 22.5	29.5	Ox valve slow to open
75	"	"	13	16	14	–	Ox feed improperly soft
76	"	-205	13.5	18	15 23		
77	"	-220	12.5	17	6.5 20	29	
78	142	-200	– Conax Exp. Valve failed about 1 msec after start				
79	178	-200	8 14	17	9.5 ~20	31	
80	"	"	7 14	17	8.5 28	–	Ox feed improperly soft
81	"	"	6 11	15	7 20.5	27	
82	"	"	6 12.5	16	7.5 ~20	28	
83	"	"	13.5	16.5	8 22.5		
84	"	"	6 12	16	8 21	28	
85	"	"	13	17	8 25.5		
86	"	"	9 17	20	12 22.5	32	
87	"	"	7 14	17	7.5 20	27	
88	"	-210	6 12	15.5	7 19.5	26	
89	"	-215	12.5	15.5	7.5		Ox feed improperly soft
90	"	-320	6 13.5	16.5	8.5 22	29	
91	182	-170	6 12.5	16	8.5	>45	No hammer
92	"	"	Ox Prop. Valve received full voltage but did not open				
93	"	"	" "	"	"	"	" " " "
94	"	"	6.5 11	13	9 16	24	New OF_2 cyl.
95	179	-320	6.5 11.5	14	8.5 14.5	25	Ox manifold disturbances
96	189	-170	6 11	13	8 10	>45	No hammer
97	166	-320	6 9.5	12	15	25	Ox manifold disturbances
98	162	-300	~9	12.3	18	~32	Ox manifold disturbance
99	162	-300	~9.5	11	18.5	27.5	

TABLE II. TEST DATA SUMMARY - NOS. 49 to 99 (pg 3 of 4)

Run No.	Fuel Tank Set Press	Fuel Temp.	Fuel Prop. Start	Fuel Prop Open	Fuel Man. Start	Fuel Hammer	Remarks
SIZC X	psia	°F	msec	msec	msec	msec	
49							
50							
51							
52							
53							
54							
55							
56							
57							
58							
59							
60							
61							
62							
63							
64							
65							
66							
67							
68	178	-240	6 12.5	15.5	15	>45	No hammer
69	"	-250	7.5 14	17	17	23	
70	"	"	7.5 16.5	19	20	26	
71	166	-100	7 14.5	17.5	8 19	21	
72	"	"	7 12	15	8 13		
73	188	"	7 14	18	8.5 22		
74	178	-200	10 19	24.5	~10 18	-	F feed too soft
75	"	"	13 18.5	22	24.5		
76	"	-165	9 11	17	(11) 17	-	F feed improperly soft
77	"	-200	10 17	20.5	11* 19.5	26	
78	144	"	-	-	11		Explosive valve failed
79	178	"	6 12	16	7* ~17	23	
80	"	"	12.5	16	7 22		
81	"	"	8.5 16.5	19.5	10* ~21	26	
82	"	"	13.5 20.5	24.5	14* 23	29	
83	"	"	25	29	(18) 26	-	F feed improperly soft
84	"	"	14 21	25	18.5 24.5	29.5	
85	"	"	15.5	19	19 26	-	F feed improperly soft
86	"	"	5.5 13.5	16.5	8* 17	24	
87	"	"	20.5 28.5	33	31	36	
88	"	"	12 22	26	12 ~25	30	
89	"	"	21.5	25	(14) 26	-	F feed improperly soft
90	"	"	5.5 13.5	18.5	17	22	
91	188	-100	5.5 15	18.5	9 17.5	28	
92	"	"	6 14.5	18	7 16	27	
93	"	"	12 21	24.5	12 21	31	
94	178	"	10 20	24	10.5 24	30.5	
95	"	-200	11 21	25	12.5* 21.5	28	Chamber Pop seen in fuel manifold
96	188	-100	12.5 26	29	12.5 28	35	
97	177	-225	13 22	25.5	13.5* 23.5	30	
98	183	-190	~9	12.3	20.5	~32.5	
99	"	"	~9.5	11	4.5	-	F feed improperly soft

TABLE II TEST RUN DATA SUMMARY - NOS. 49 to 99

RUN NO.	PROPELLANT ENTRY: INITIAL ATTENUATION	PROPELLANT ENTRY: POSITIVE ILLUMINATION	OPTICAL: IGNITION DETECTION	CHAMBER PRESSURE: INITIAL PRESSURE RISE	CHAMBER PRESSURE: MAIN P_c IGNITION	CHAMBER PRESSURE: PEAK PRESSURE	CHAMBER PRESSURE: PEAK PRESSURE	REMARKS
5720X	MSEC	MSEC	MSEC	MSEC	MSEC	MSEC	PSIA	
49								
50								
51								
52	9.5		N/A	22				Singly flowed OF_2
53	15		N/A	16				Singly flowed B_2H_6
54	None	17	21	17	22	28	120	Smooth
55	—	19	(21) 36		36	—	—	Spike
56	None	22	(28) 32	22	32	40	100	Smooth
57	12		N/A	14		~45	~15	Singly flowed OF_2
58	15	19	(19) 29	23	29			Spike
59	None	25	28	26	28	35	25	Fuel as vapor, low P_c
60	18	21	30	27	29	33	85	Smooth
61	None	23	29	27	29	35	35	Fuel as vapor, low P_c
62	"	25	28	27	29	35	140	Moderate ign. overpress, smooth
63	17	31	(31) 41	40	42	45	100	Smooth
64	None	24	27	29	32			Spike
65	25	27	27	27	29			Spike
66	12	22	(18) 30	27	28	35	125	Smooth
67	25(w)	27	28	28	31	34	160	Ign. overpressure
68	19.5	23.5	30	29.5	30	34	100	Smooth
69	None	21.5	29	28	30	30	>250	Spike
70	"	25	?	28	30	32	70	Smooth
71	11		N/A					Singly flowed B_2H_6
72	26	37	37		37	37	200+	Spike at delayed ign, low fuel
73	?	?	(13) 16	22	~25	35	90	Slow smooth ign, ox as vapor
74	20	23	23	23	?	33	100	Smooth but fuel feed too soft
75	21(w)	26	26	26	26	30	20	Ox as vapor, low P_c
76	None	24	25	24	39			Spike, fuel as vapor
77	"	23	25	26	29	31	70	Smooth
78	"	1	1		1			Conax Ox valve blew
79	"	20	20	20	32	?	?	Apparently smooth
80	"	15	?	21	30	36	60	OF_2 as vapor, low P_c
81	17 (w)	21.5	24	19	27			Apparently spike
82	16	23	?	24	~29			Spike
83	?	?	21	26	32	36	65	Fuel as vapor, low P_c
84	?	?	(25) 29	28	30	31	90	Smooth, minor overpressure
85	?	?	(17) 21	26	26	31	80	Smooth slow ign, soft fuel feed
86	None	20	20	~25	32	34	~100	Smooth, minor overpressure
87	"	25	(25) 35	29	35			Apparently spike
88	"	22	22	28	30			Spike
89	"	14	14	27	27	35	80	Smooth slow ign, soft feeds
90	?	?	?	28	30	32	65	Smooth
91	?	?	19	23	29	34	65	Smooth slow ign, soft Ox feed
92	21		N/A					Fuel only as Ox prop hung-up
93	26		N/A					Fuel only as Ox prop hung-up
94	None	14	15	23	27	32	100	Smooth, minor overpressure
95	"	22	(22) 23	28	28	31	120	Smooth, moderate overpressure
96	"	15	(15) 31	~29	~31			Smooth slow ign, soft Ox feed
97	22	23	23	30	30	33	120	Smooth, minor overpressure
98	None	28	31	31	~32	38	95	Hyd. Res. Valve - Smooth ign, 2 steps
99	"	25	31	28	31			" " " - Fuel as vapor

(w) weak attenuation

(X) Transient, low level emission

TABLE III. TEST DATA SUMMARY - NOS. 100 to 104 (pg 1 of 4)

Run No.	Chamber	Injector	Injector Temp	Run Tanks	Valve Coupling	Oxidizer	Fuel	Propellant Lead	Remark
SIZE X			°F	(ullage)					
100	100psia	1 pair	-200	large	normal	OF_2	B_2H_6	4.5 Ox	Rebuilt
101	"	"	-100	"	"	none	"	N/A	Valcor Valv
102	"	"	-15	"	"	"	"	N/A	
103	"	"	-185	"	"	OF_2	"	5 Ox	
104	"	"	-180	"	"	"	"	6 Ox	

TABLE III. TEST DATA SUMMARY - NOS. 100 to 104 (pg 2 of 4)

Run No.	Ox Tank Set Press.	Ox Temp.	Ox Prop. Start	Ox Prop. Open	Ox Man. Start	Ox Hammer	Remarks
512CX	psia	°F	msec	msec	msec	msec	
100	156	-165	6.5	10	8	-	Ox feed improperly set
101	N/A	N/A	N/A	N/A	N/A	N/A	Fuel only
102	N/A	N/A	N/A	N/A	N/A	N/A	Fuel only
103	156	-175	7 11	13	9 ~24	29	
104	156	-175	8 11.5	13.5	8 23	29	

TABLE III. TEST DATA SUMMARY - NOS. 100 to 104 (pg 3 of 4)

Run No.	Fuel Tank Set Press	Fuel Temp	Fuel Prop. Start		Fuel Prop. Open	Fuel Man. Start		Fuel Hammer	Remarks
512CX	psia	°F	msec		msec	msec		msec	
100	156	-200	11.5	16	19	11.5	20	22	
101	167	-100	7	12.5	15	11	19	22	
102	188	-15	6.5	11	13		11	>45	Only fuel vapor at this Te.
103	157	-190	12	16.5	19		17	23	
104	157	-195	13.5	18	20.5		21	23	

TABLE III. TEST DATA SUMMARY - Nos. 100 to 104 (pg 4 of 4)

Run No.	Propellant Entry: Initial Attenuation	Propellant Entry: Positive Illumination	Optical: Ignition Detection	Chamber Pressure: Initial Press. Rise	Chamber Pressure: Main Pc Ignition	Chamber Pressure: Peak Pressure	Chamber Pressure: Peak Pressure	Remarks
S12CX	msec	msec	msec	msec	msec	msec	psia	
100	9.5	13.5	?	19	21			Smooth ign, soft-ox feed
101	13	N/A	N/A					Singly flowed B_2H_6
102	none	N/A	N/A					Singly flowed B_2H_6
103	13	14.5	?	17.5	22.5			Smooth ign.
104	11.5	15	21	20	~22.5			Smooth ign.

Eight meaningful runs were obtained in this series and they covered electrical leads from 3 msec fuel to 14.5 msec oxidizer. (The other three runs suffered from a "soft" fuel or oxidizer feed which indicates less than the full, proper flowrate into the thrust chamber.) The eight meaningful runs are summarized in Table IV which shows that two of the eight runs had electrical fuel leads and that both exhibited smooth start transients. The table also shows that the other six runs had electrical oxidizer leads and that four of the six exhibited ignition spikes in the thrust chamber.

Table IV 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 IV 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 (Ref. 3).

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 IV). 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 V. Although the times 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 IV) however the difference is quite small.

TABLE IV. 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 $T_{inj.} = T_{OF_2} = T_{B_2H_6} = -200^{\circ}F$.

TABLE V. 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 Mainfold 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, $T_{inj.} = T_{OF_2} = T_{B_2H_6} = -200°F$. (Selected runs from 77 to 88)

2. Effect of Temperature

A series of runs (Nos. 90 to 97) was made to extend the investigation of temperature effects on start transients. Table VI summarizes the pertinent warm and cold runs. It is seen from the table that the ignition delays of the three "warm" runs and the three "cold" runs are essentially identical.

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. In the case of the oxidizer manifold, hard liquid filling generally did not occur in the warm runs. As Table VI indicates, the

TABLE VI. 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 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.

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 manifold filling was noted previously in the case of diborane and was discussed in some detail in the Phase I report, Secs. V.B.2 and 6 (Ref. 1).

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

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 three runs of Phase II having otherwise appropriate temperature conditions, i.e. OF_2 at -320°F and the injector at +70°F (Runs 62, 68 and 72). However, two of the runs had large rather than the small ullage run tanks and the third had a modified valve/injector coupling. The significance of these differences 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.

It should be mentioned that post-ignition transients were recorded in Runs 95 and 97, both of which are cold runs (Table VI). In Run 95, a "POP" occurred in the thrust chamber during 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 damped oscillatory disturbance is seen in either the fuel manifold or the chamber.

A very similar, through 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.

3. Bipropellant Valve Tests

Two tests were made with the Hydraulics Research torque-motor bipropellant valve described in Sec. III. A. 1. b. The valve was used in conjunction with the 100 psi chamber, 9-pair injector and large ullage run tanks (Runs 98 and 99, Table II).

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 VII. 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 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 read approx. 0.560 psia instead of the normal 0.000. The OF_2 was conditioned to -200°F.

TABLE VII. 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	~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	~23 (est.)		28	
Ignition Delay for Main Ignition (P_{ch}), msec	30		32.5	
Character of Start Transient	Smooth		Smooth	

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 polaroid display data traces indicate a normal looking oxidizer manifold trace. However all other traces were not normal. The chamber pressure traces deflected downward rather than upward, the fuel manifold trace looked as though there was a "gas flow only" condition and both the propellant entry detector and the ignition detector showed 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 out-let 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 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 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 will be returned to the manufacturer.

4. Single Element Injector, Normal Valve/Injector Coupling

A series of tests was initiated with the single element, doublet injector to evaluate injector design effects on start transients and to provide additional data on chamber pressurization due to propellant vaporization. The series began with the 100 psi chamber, large ullage run tanks and normal valve/injector coupling. The data for the first five runs of the series that were made at the close of the report period are summarized in Table III. A discussion of this data will await completion of the series.

REFERENCES

1. Mistler, G. R. and Seamans, T. F., "Vacuum Ignition Characteristics of Flox/Diborane and Oxygen Difluoride/Diborane," NAS 7-660, Report RMD 5534-F1, Thiokol Chemical Corp., March 1969.

2. Mistler, G. R. and Seamans, T. F., "OF_2/Diborane Technology Vacuum Ignition - Phase II," NAS 7-660, Report RMP 5536-Q1, Thiokol Chemical Corp., April 1969.

3. Mistler, G. R. and Seamans, T. F., "OF_2/Diborane Technology Vacuum Ignition - Phase II," NAS 7-660, Report RMD 5536-Q2, Thiokol Chemical Corp., July 1969.

IV. TASK II - FLOX AS SIMULANT FOR OF_2

No scheduled activity during this report period.

V. TASK III - HIGH SPEED MOTION PICTURES

No further work was performed during this report period (see Ref. 2).

VI. MISCELLANEOUS

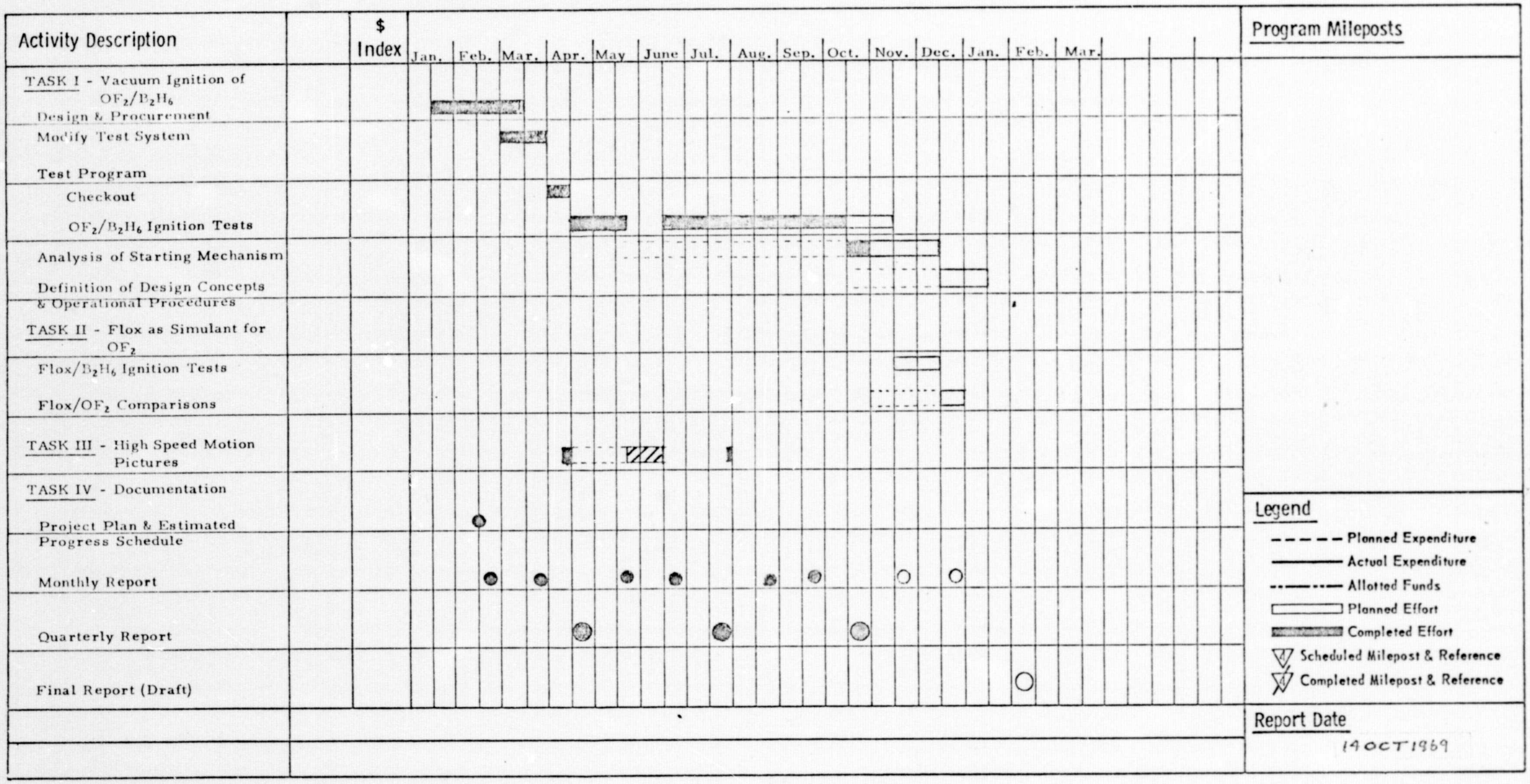
The program schedule and the manpower and rate of expenditure curves are attached.

COMPANY PRIVATE

Thiokol
CHEMICAL CORPORATION
REACTION MOTORS DIVISION
DENVILLE, NEW JERSEY

MILEPOST AND EXPENDITURE CHART

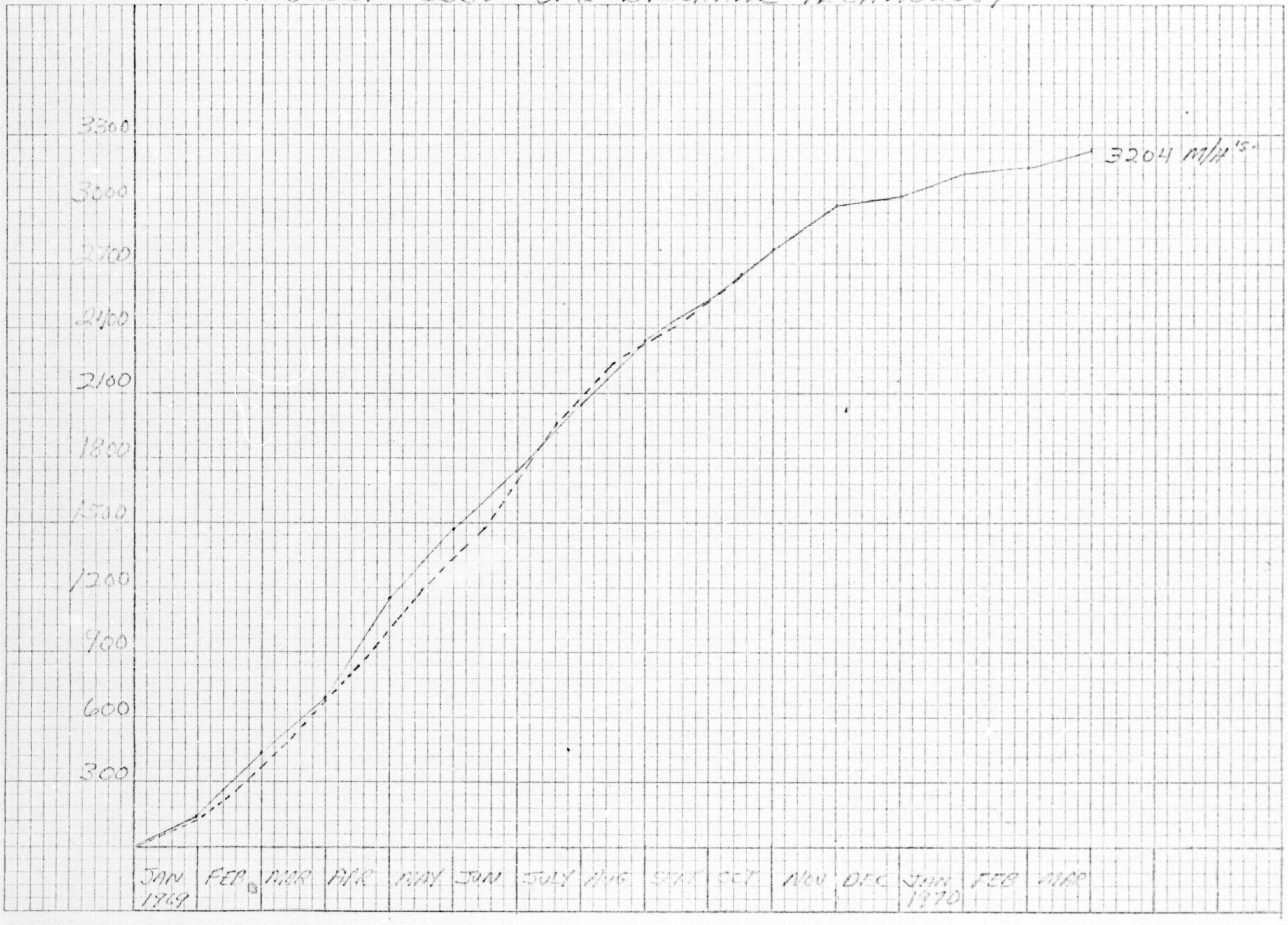
Project Number(s): 5536 Title: OF_2 DIBORANE TECHNOLOGY VACUUM IGNITION



COMPANY PRIVATE

MANPOWER EXPENDITURE CURVE

PROJECT 5536 OF$_2$ DIBORANE TECHNOLOGY



RATE OF EXPENDITURE CURVE

PROJECT 5536 OF_2 DIBORANE TECHNOLOGY