PROGRESS REPORT

PR 91570-510-5

For the Period of November 1, 1963, through November 30, 1963

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DEVELOPMENT OF A HYDROGEN-OXYGEN SPACE POWER SUPPLY SYSTEM

NASA Contract NAS 3-2787

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INTRODUCTION

This report is issued to comply with the requirements of NASA Contract, NAS 3-2787, and to report the work accomplished during the period November 1 through November 30, 1963. The objectives of this program are to conduct engineering studies, design, fabrication, and test work culminating in the design of an auxiliary power generation unit.

This Contract, NAS 3-2787, is a continuation of NASA Contract NAS 3-2550.

PROGRAM SCHEDULE

The program schedule is shown in Fig. 1.

FLIGHT TYPE POWER SYSTEM DESIGN

No work was accomplished during this reporting period on the flight type power system design. Flight system design work has been postponed as a result of technical direction from the NASA Technical Program Manager.

RELIABILITY AND QUALITY ASSURANCE

The Reliability and Quality Assurance Program Plan Milestone Chart, Fig. 2, shows the status of work performed against the work scheduled.

During November, three meetings were held between the NASA Western Operations Office reliability and quality assurance monitor and Vickers Incorporated reliability personnel. The provision

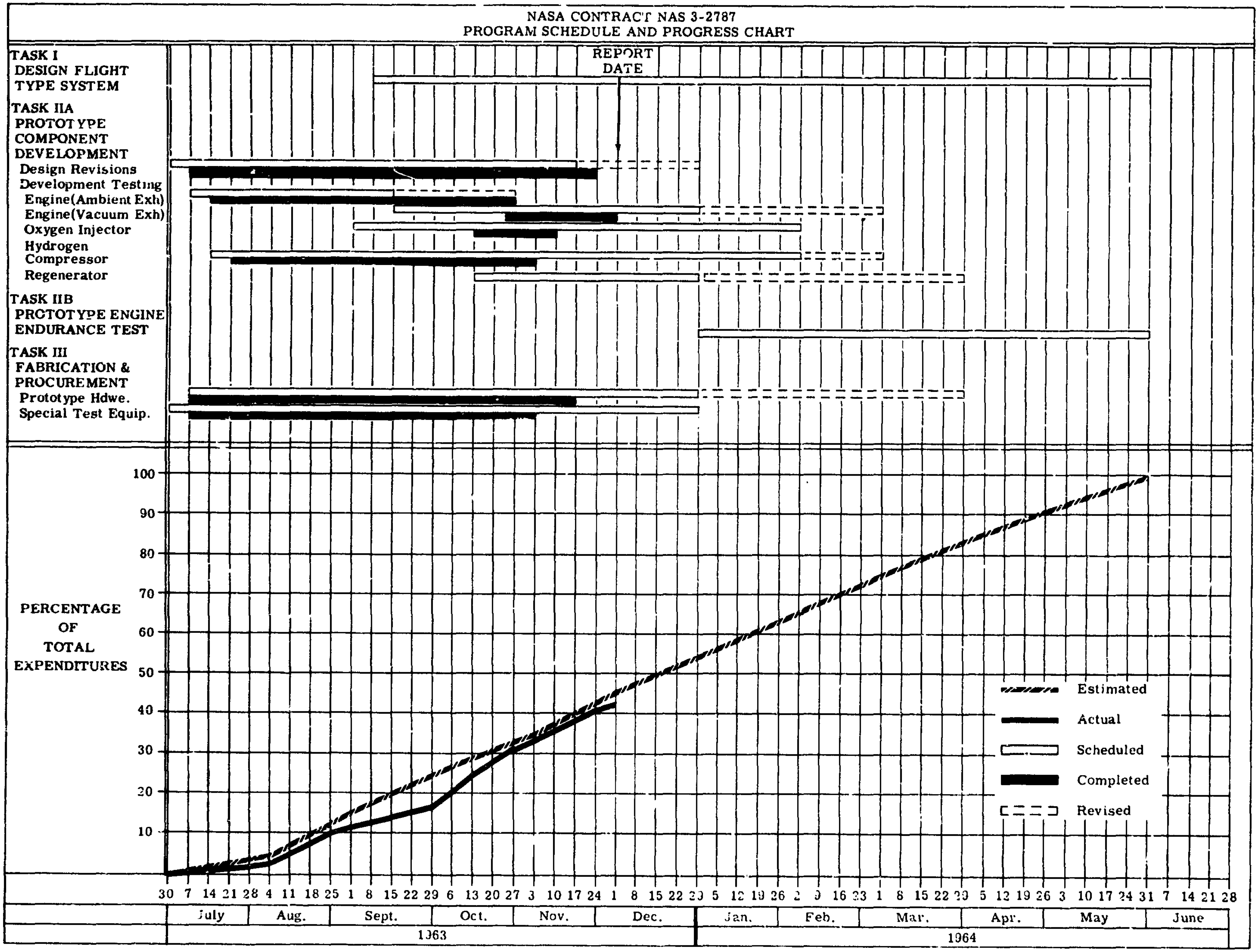

Fig. 1 - Program Schedule

of specific procedures and plan in the following areas were discussed.

a. Calibration of instrumentation and test equipment

b. Failure reporting

c. Test procedures

d. Control of suppliers

e. Prototype component buildup and parts records

f. Drawing control procedures

g. Inspection system and Material Review Board action

It was agreed that detailed written procedures and controls would be prepared for the above mentioned areas as supplements to the Reliability Program Plan submitted to NASA on October 10, 1963.

Plans for Instrumentation Control, and Failure Reporting are included in the Appendix of this report. The detailed procedure for the remaining areas will be prepared as scheduled.

Reliability & Quality Assurance Function for Task I - (Flight Type Power System Design)

Design Review

No work was accomplished during this reporting period (See Flight Type Power System paragraph).

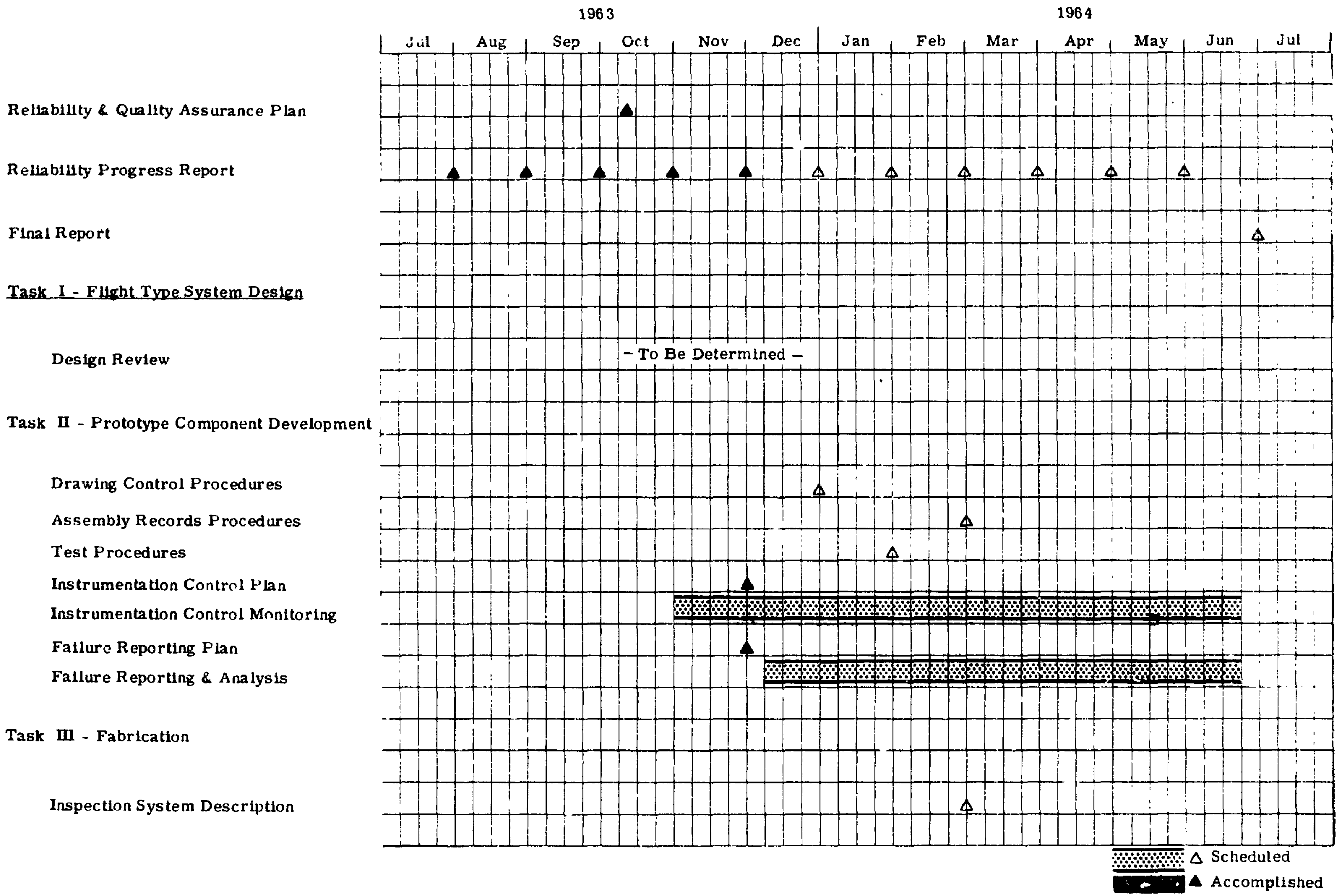

Fig. 2 - Reliability and Quality Assurance Program Plan Milestone Chart

Reliability & Quality Assurance Functions for Task II - (Prototype Component Development)

Drawing Control Procedures

A detailed written description of drawing control procedures now in use will be prepared during the month of December, and submitted in the December Progress Report.

Assembly Buildup & Parts Records

A written description of the assembly and parts record procedures now in use for the engine and compressor will be prepared during the month of February, and submitted in the February Progress Report.

Test Procedures

As agreed upon with NASA during the meeting of the 19th and 20th of November, 1963, the Test Procedures will consist of a check list and operating procedure which will permit a competant test engineer to learn to operate and maintain a particular prototype component test stand. Test procedures for the engine and compressor will be prepared during the month of January.

Instrumentation Control

The Instrumentation Control Plan, shown in Appendix A, was completed November 18, 1963. Engine and compressor test stand instrumentation information is being tablulated on calibration status sheets. These status sheets will be kept current by periodic monitoring.

The accuracy column of the calibration status sheet will be used to calculate the accuracy of reduced data.

Failure Reporting & Analysis

The proceduralized plan was completed November 22; a copy is included in the Appendix B. To assure a consistency of approach throughout the program, a copy of this plan will be retained by the reliability engineer assigned to the project, in the same file with the failure reports and summary sheets.

The Failure Report and Summary Sheet for the prototype engine has been brought up to date.

Reliability & Quality Assurance Function for Task III (Fabrication)

Inspection & Material Review Board Action

As a result of the November 19th and 20th, 1963, meeting with NASA it was decided that since only a few parts of a particular design are fabricated, a formal inspection plan showing in-process inspection stations was not practical or appropriate for this program. All parts purchased from outside sources are inspected for 100% compliance to detail drawings by Receiving Inspection which is part of the Quality Control Department. All parts fabricated in Vickers prototype shop are also inspected for 100% compliance to detail drawings. In-process inspection in the prototype shop is performed at the discretion of the prototype foreman in conjunction with close liaison with engineering.

When discrepant parts are accepted for use by the project engineer and the MRB, a copy of the inspection report is retained by the project engineer.

PROTOTYPE COMPONENT DEVELOPMENT

Engine

Design and Fabrication

The following design and fabrication was accomplished during this reporting period.

1. Fabrication of two hydrogen valves of the redesigned configuration (shown in Fig. 2 of PR 91570-510-2) has been completed.

2. Fabrication of new detail parts for the split-housing oxygen injector (layout drawing assembly shown in Fig. 2 PR 91570-510-4) has been completed. Two new quill shafts are being flame plated with aluminum oxide and two torsion tube-quill shaft weld assemblies are being prepared.

3. Fabrication of two new oxygen injector seat-guide configurations, one with an angled slot shaped port and one with three angled ports is complete.

4. The combustion chamber shape of the head insert (Fig. 4 of PR 91570-510-3) has been machined onto the cooled cylinder head (Fig. 6 of PR 91570-510-3).

5. Two new piston dome blanks of L605 (Haynes 25) have been fabricated. The L605 has a lower heat transfer coefficient than the T.D. nickel (material of present piston domes).

6. Two O_2 injector cam blanks are being machined to the cam configuration (described on Page 6 of PR 91570-510-2).

7. One cylinder head insert, of the configuration shown in Fig. 4 of PR 91570-510-3, has been flame sprayed with a .005" coating of Zirconium Oxide.

8. Ten new cylinder head insert blanks, which can be machined to different desired combustion chamber configurations, are being fabricated. One of these blanks has been machined to a new configuration.

9. The O_2 injector rocker shaft drawing has been changed to center the cam follower pivot point with respect to the new wide O_2 cam.

10. A second piston has been reworked to the configuration shown in Fig. 2 of PR 91570-510-3.

11. New X-609982 hubs are being fabricated to a drawing change which requires a tolerance that will produce greater concentricity and squareness of the timing gear with respect to the crank shaft axis.

12. Fabrication of Haynes 25, and molybdenum removeable oxygen rocker arm bearing is complete. A drawing for the removal tool has been released for fabrication.

13. Fig. 3 is a layout drawing showing the current status of the new piston and cylinder design study. Some of the improvements provided by the new design are:

a. The possibility of leakage through the piston between the dome and the piston body is eliminated.

b. The piston design allows for interchangeability of parts, thus reducing the possibility of loss of the whole assembly during fabrication and test and facilities ring and dome experimentation.

c. The cylinder liner and cooling jacket are separate pieces. This allows interchangeability and reduces the risk of total loss of the assembly during fabrication and test.

d. Exhaust porting is improved and exhaust manifold area is increased.

e. The exhaust manifold may be ceramic coated.

f. Improved coolant passage area at top and bottom of the cylinder wall.

g. Less restricted coolant passages

Detailing of the new piston design is approximately 80% complete.

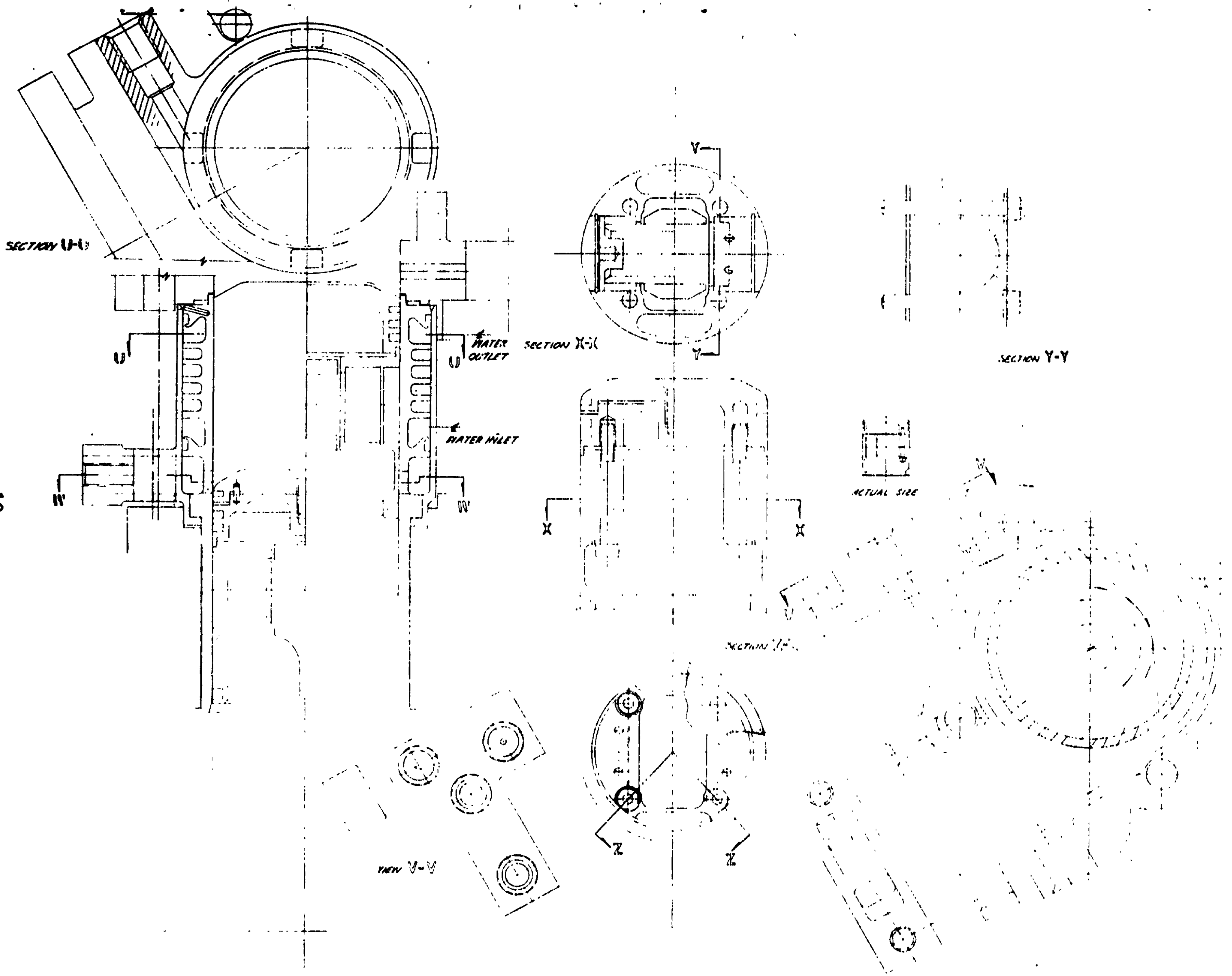

Fig. 3 - Layout Drawing of New Piston and Cylinder Design

Assembly

Disassembly of the first buildup of Engine No. I is complete. The condition of parts at teardown was recorded. Engine No. I is being rebuilt with the new hydrogen valve and with other new and reworked parts.

Engine No. II was removed from the stand, disassembled, and re-built with the following changes:

1. New compression rings were used
2. The oil drain holes in the piston were plugged and a solid cast iron compression ring was used in place of the oil ring to reduce oil consumption during tests with vacuum exhaust.
3. The diameter of the piston dome was decreased to increase the exhaust blowdown area.
4. The cylinder was re-honed and the rings lapped-in.
5. The new design O_2 cam was used.
6. The redesigned cam shaft was used.

The second oxygen injector built to the new configuration was disassembled after it exhibited leakage on the injector test stand. The flame plating on the poppet was found to be defective in the seat area. See Fig. 4. The poppet had been lapped to the seat with 1/4 micron diamond paste. It is believed that the diamond lapping particles were forced into the seat by the harder flame plated surface of the poppet and that the flame plated surface was cut and weakened during the lapping operation. During the second build-up the seat was lapped by a separate unplated poppet.

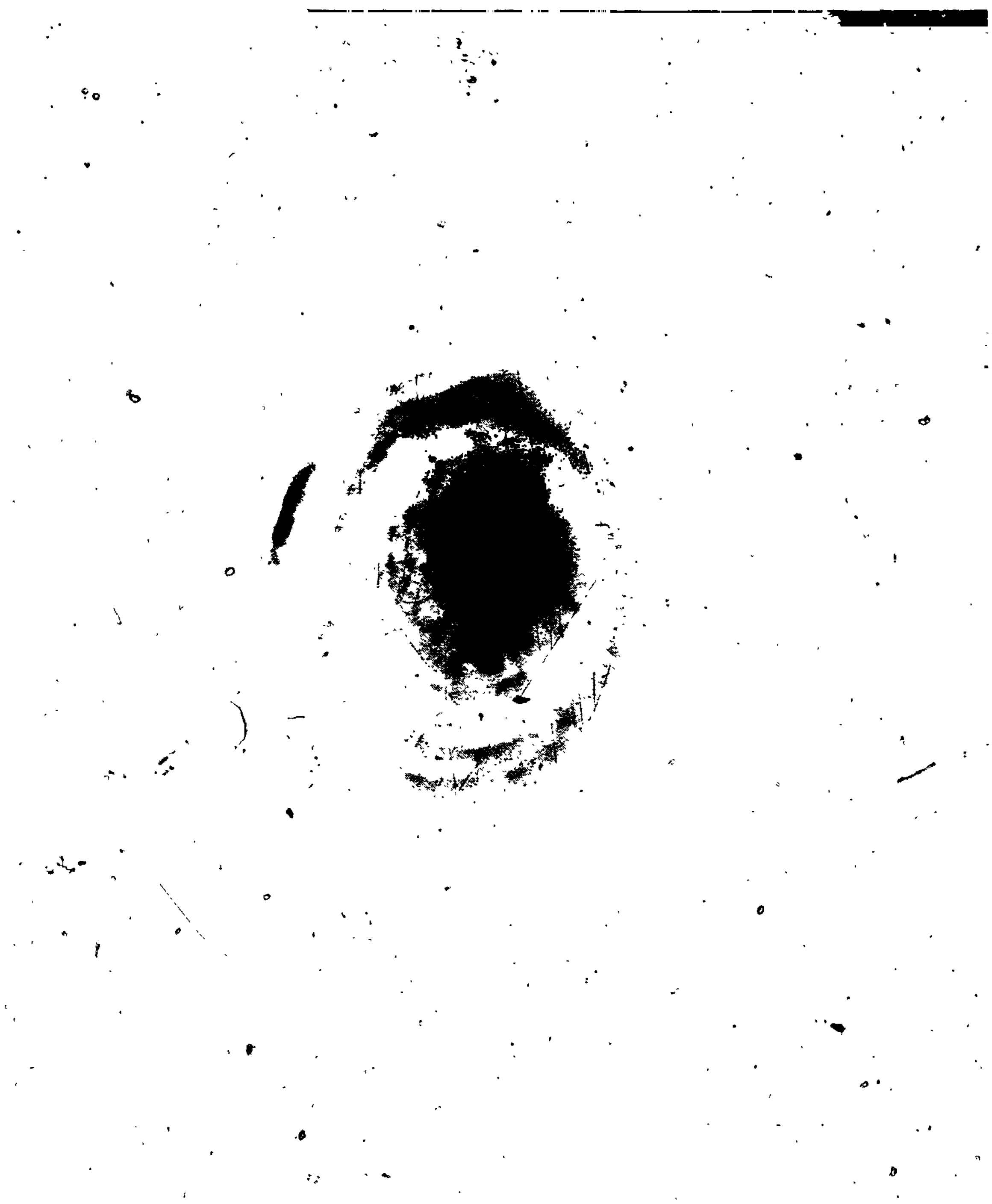

Fig. 4 - Failed Seating Area of Flame Plated Poppet

The second build up of this injector was disassembled after it malfunctioned during engine operation (but after successful operation on the injector test stand). The seating surfaces of both the seat and poppet were in good condition but the guide surfaces of both were worn. Fig. 5 is a photograph of the worn guide surface of the poppet. The guide surface of the seat was damaged around the complete circumferance, thus indicating that the poppet was rotating in the seat.

During the third build up of this injector, extreme care will be taken to assure that the poppet tip has freedom of motion (when not constrained by the guide) with respect to the rocker arm to reduce the possibility of mechanical loading between the poppet and guide during hot operation. The clearance between the guide and seat will be increased to reduce the possibility of seizure due to differential expansion.

Performance Testing

Performance data accumulated on the H_2-O_2 engine during the month of November, 1963, are given in Tables I and II. All data was taken with the Engine No. II which was given a calibration run on October 31, 1963 (See Page 24 in the October Progress Report). Table I lists data on the first assembly and Table II gives data for the second assembly of this engine. Several oxygen injector nozzle configurations, cylinder head configurations, and oxygen and hydrogen valve settings were used in both assemblies. Each condition was given an "Operating Condition No." in Tables I and II which is described in Table III.

The engine was operated for a total of 11.25 hours, 5.0 hours on the first assembly and 6.25 hours on the second assembly. A total of 7.5 hours cold motoring was also accumulated this month.

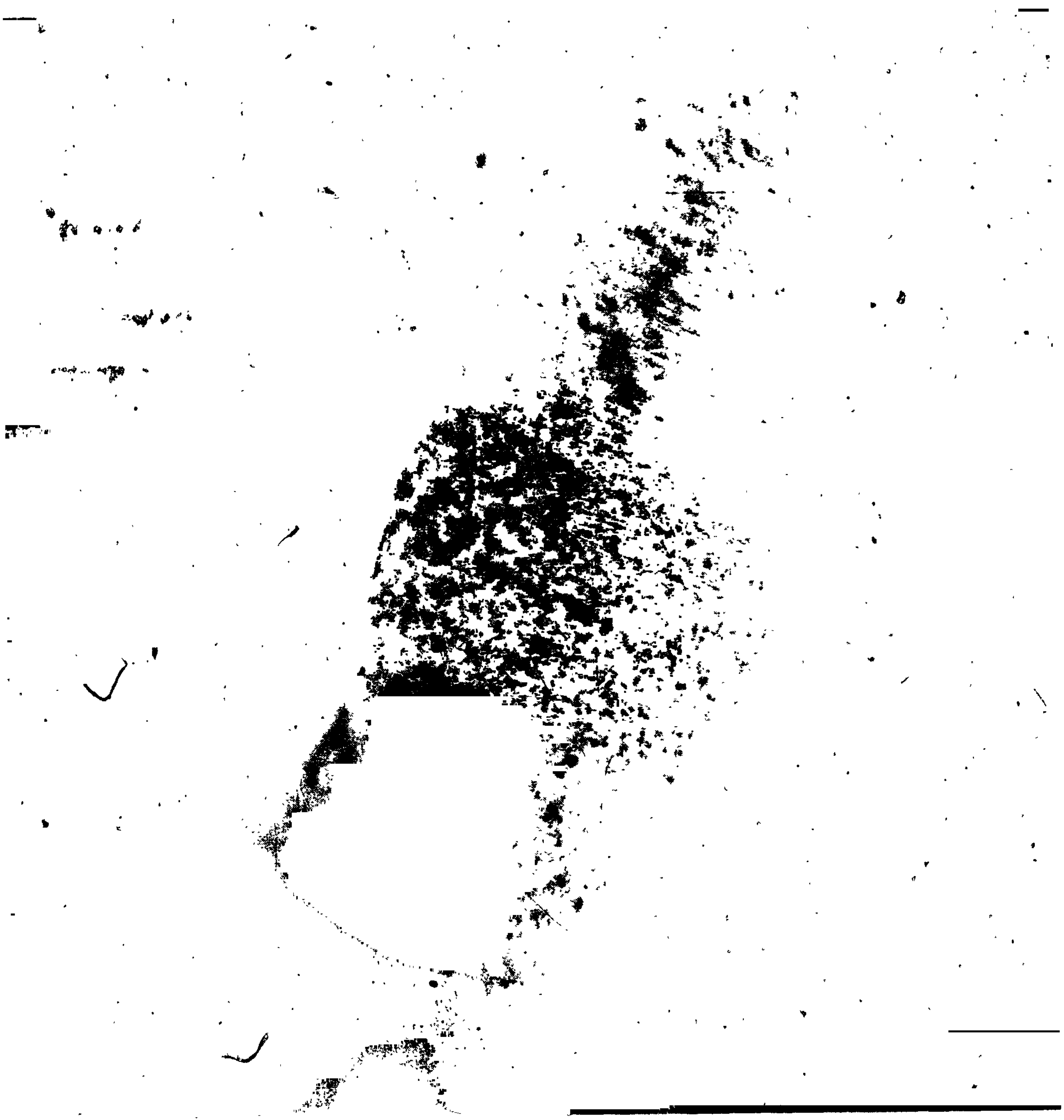

Fig. 5 - Failed Guide Area of Flame Plated Poppet

A BSPC of 1.74 lb/hp-hr has been achieved (Entry 18, Table I) and represents the best performance to date. A BSPC of 1.90 lb/hp-hr has been achieved under ambient back pressure and ambient temperature inlet hydrogen. (Entries 6 and 7, Table II). A BSPC of 2.10 has been achieved under design inlet pressures and power levels (Entry 26, Table II). This last figure should be considerably bettered at a somewhat greater BMEP, achievable with a slightly greater clearance volume in the 7 - 8% range.

Pressure-time and pressure-volume traces, and photographs of engine components are given in Figs. 6 to 27. A discussion of these figures follows.

The engine mounted on the test stand is shown in Fig. 6. This view shows the line leading to the vacuum pump and the hydrogen heater (the foil-covered assembly at top center). A close up of the engine showing the exhaust manifold is given in Fig. 7. This manifold was replaced with a more open design on November 22, 1963.

The piston dome and cylinder head after the runs of November 1 are shown in Figs. 8 and 9. Highly stratified combustion accuring in a band across the center of the combustion chamber can be seen. The oxygen swirls and creates turbulence when it strikes the opposite wall.

It was believed that top center combustion would yield the best results. A typical trace with considerable valve overlap and only 1% admission is shown in Fig. 10. Much better results were achieved, however, switching to 4% admission and less overlap of the oxygen and hydrogen valves. (Figs. 11 and 12).

TABLE I

PERFORMANCE DATA - FIRST ASSEMBLY, ENGINE NO. 2

Entry	Time Date	Time Hour	Oper. Cond. No.	H_2 Inlet Temp °F	H_2 Inlet Press psig	O_2 Inlet Press psig	Speed rpm	BMEP psi	Power HP	BSPC lb/hp-hr	O/F lb/lb	% Heat Rejected	Vacuum In. Hg.
1.	11/1/63	4:46	1	Amb.	600	615	3000	77	1.58	3.05	1.32	133	0
2.	11/1/63	4:51	1	Amb.	600	650	3660	107	2.38	2.48	0.96	76	21
3.	11/1/63	4:58	1	Amb.	600	650	3737	105	2.68	2.57	0.93	43	26
4.	11/1/63	5:08	1	Amb.	600	660	4018	102	2.83	2.48	0.95	78	26.5
5.	11/2/63	2:49	2	Amb.	600	630	4010	115	3.23	2.36	0.86	70	26.2
6.	11/2/63	2:54	2	Amb.	600	620	3020	128	2.65	2.33	0.75	66	26.5
7.	11/2/63	5:24	2	Amb.	450	510	3760	88	2.28	2.47	1.00	82	27
8.	11/2/63	5:28	2	Amb.	450	510	3010	101	2.09	2.53	1.05	98	27
9.	11/2/63	5:32	2	Amb.	450	600	3030	101	2.10	2.62	1.29	105	27
10.	11/4/63	2:18	3	Amb.	450	520	4050	73	2.04	2.57	1.21	81	27
11.	11/4/63	3:42	3	Amb.	750	850	3010	144	2.96	2.30	0.96	57	26.2
12.	11/4/63	3:47	3	Amb.	750	900	3040	149	3.09	2.27	1.10	31	27
13.	11/4/63	3:53	3	Amb.	750	800	3030	144	3.00	2.32	0.81	57	27
14.	11/4/63	3:59	3	Amb.	750	935	3010	152	3.13	2.29	1.18	-	27
15.	11/7/63	3:20	4	Amb.	750	800	2980	194	3.99	2.06	0.97	61	0
16.	11/7/63	3:28	4	Amb.	750	790	3070	218	4.89	1.86	0.97	40	26
17.	11/7/63	3:40	4	Amb.	750	980	3020	233	4.84	1.87	1.17	62	26.5
18.	11/7/63	3:45	4	540	750	800	3010	212	4.46	1.74	1.03	58	26.5
19.	11/7/63	3:52	4	510	600	685	2980	173	3.54	1.81	1.17	74	27
20.	11/8/63	11:38	4	100	600	650	3010	166	3.43	2.10	0.91	55	26.5
21.	11/8/63	11:45	4	100	600	820	3040	183	3.81	2.00	1.30	76	26.5
22.	11/8/63	11:49	4	100	600	645	3000	160	3.36	1.93	1.11	75	26.5
23.	11/8/63	11:53	4	540	600	620	2990	139	4.09	1.83	1.17	94	27

TABLE II

PERFORMANCE DATA - SECOND ASSEMBLY, ENGINE NO. 2

Entry	Time Date	Time Hour	Oper. Cond. No.	H_2 Inlet Temp °F	H_2 Inlet Press psig	O_2 Inlet Press psig	Speed rpm	BMEP psi	Power HP	BSPC lb/hp-hr	O/F lb/lb	% Heat Rejected	Vacuum In. Hg.
1.	11/16/63	5:32	5	90	750	1050	4360	171	5.12	1.94	0.74	36	0
2.	11/16/63	5:45	5	500	600	1000	3000	137	2.82	2.15	1.20	86	0
3.	11/16/63	5:49	5	520	600	1000	4320	116	3.43	2.00	1.08	72	0
4.	11/16/63	5:54	5	150	600	1000	3020	163	3.40	2.07	1.20	68	0
5.	11/18/63	3:12	6	95	750	1000	3060	225	4.73	2.09	0.92	23	0
6.	11/18/63	3:17	6	100	750	1000	4310	217	6.43	1.90	0.85	44	0
7.	11/18/63	3:21	6	100	600	1000	4340	175	5.21	1.90	1.10	46	0
8.	11/18/63	3:27	6	100	600	850	3020	189	3.90	2.00	1.31	71	0
9.	11/18/63	3:31	6	480	600	750	3040	163	3.40	1.99	1.28	22	0
10.	11/18/63	3:36	6	525	600	850	4320	140	4.16	1.91	1.26	67	0
11.	11/18/63	3:41	6	500	600	850	2960	192	3.91	1.94	1.23	64	26
12.	11/18/63	3:48	6	500	600	1000	4320	168	4.98	1.78	1.32	72	24
13.	11/19/63	4:20	7	500	450	500	3030	132	2.74	1.78	1.22	87	28
14.	11/19/63	4:25	7	510	450	560	4330	110	3.25	2.05	1.17	86	27
15.	11/19/63	4:31	7	520	600	630	3000	176	3.63	1.84	1.10	77	27
16.	11/19/63	4:52	7	520	600	610	2990	174	3.57	1.86	1.26	84	27
17.	11/23/63	1:16	8	450	300	450	3020	74	1.54	2.27	1.64	132	30
18.	11/23/63	1:48	8	115	600	670	3040	165	3.44	2.08	1.08	71	24
19.	11/23/63	1:53	8	120	450	500	3010	118	2.43	2.16	1.04	90	24
20.	11/26/63	11:21	9	450	300	1000	3030	103	2.14	2.32	2.12	116	24.5
21.	11/26/63	11:26	9	475	300	1000	4300	81	2.38	2.28	2.00	119	24
22.	11/26/63	11:30	9	465	300	1000	3050	103	2.15	2.28	2.09	104	28
23.	11/26/63	11:40	9	460	300	1000	3050	97	2.04	2.38	2.17	114	24.5
24.	11/26/63	11:43	9	460	300	1100	4300	82	2.41	2.18	2.18	109	24
25.	11/27/63	2:05	10	460	300	900	3050	102	2.12	2.21	2.10	112	28
26.	11/27/63	2:17	10	490	300	1000	4290	89	2.61	2.10	2.10	117	28
27.	11/27/63	2:23	10	470	450	1000	3030	150	3.11	2.08	1.60	106	28
28.	11/27/63	2:28	10	490	450	1000	4290	127	3.72	1.97	1.62	93	28

TABLE III

OPERATING CONDITIONS

Number	Clearance Volume	Valve Timing	Remarks
1.	4.6%	H_2 20° BTDC - 10 ATDC O_2 TDC - 30° ATDC	0.054 in. injector nozzle, solid 4.4% head
2.	5.0%	H_2 20° BTDC - 10° ATDC O_2 TDC 30° ATDC	Same as No. 1
3.	5.0%	H_2 20° BTDC - 10° ATDC O_2 10° BTDC - 20° ATDC	Same as No. 1
4.	4.2%	H_2 10° BTDC - 20° ATDC O_2 10° ATDC 40° ATDC	Same as No. 1
5.	5.5%	H_2 10 BTDC - 15° ATDC O_2 4° ATDC - 44° ATDC	Second buildup, with new oxygen valve cam, greater blowdown area, flame-plated poppet, 0.054 in. injector nozzle
6.	5.5%	H_2 10 BTDC 20° ATDC O_2 4° ATDC 44 ATDC	Same as No. 5
7.	5.0%	Same as No. 6	Solid 4.4% head installed
8.	5.0%	Same as No. 6	New exhaust pipe installed 0.035 in. oxygen injector nozzle orifice.
9.	5.0%	Same as No. 6	Water cooled head 0.054 in. injector nozzle
10.	5.0%	Same as No. 6	Same as No. 9, Dowtherm "A" used as coolant.

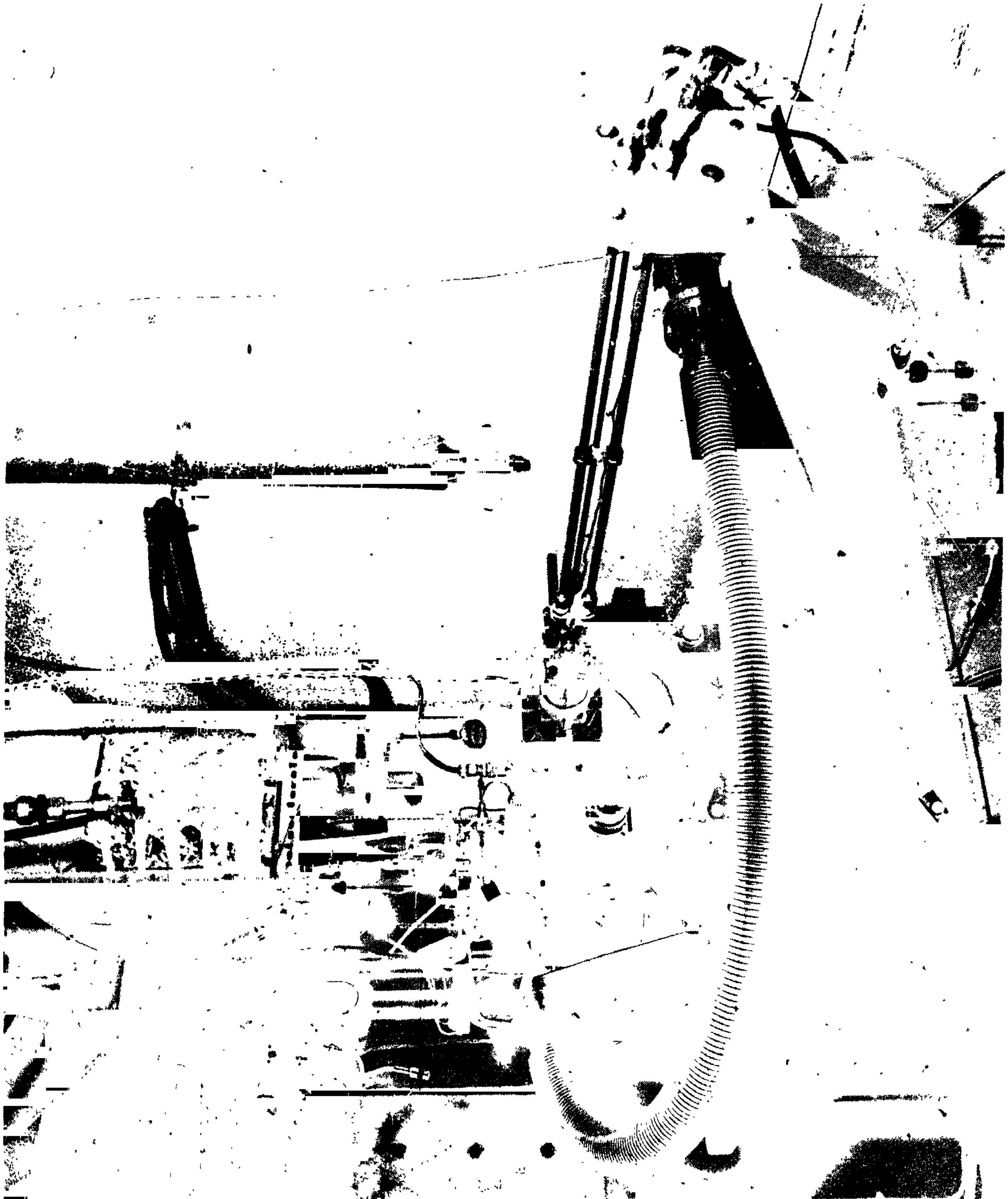

Fig. 6 - Engine on Test Stand, with Vacuum Exhaust Line & Hydrogen Heater Installed

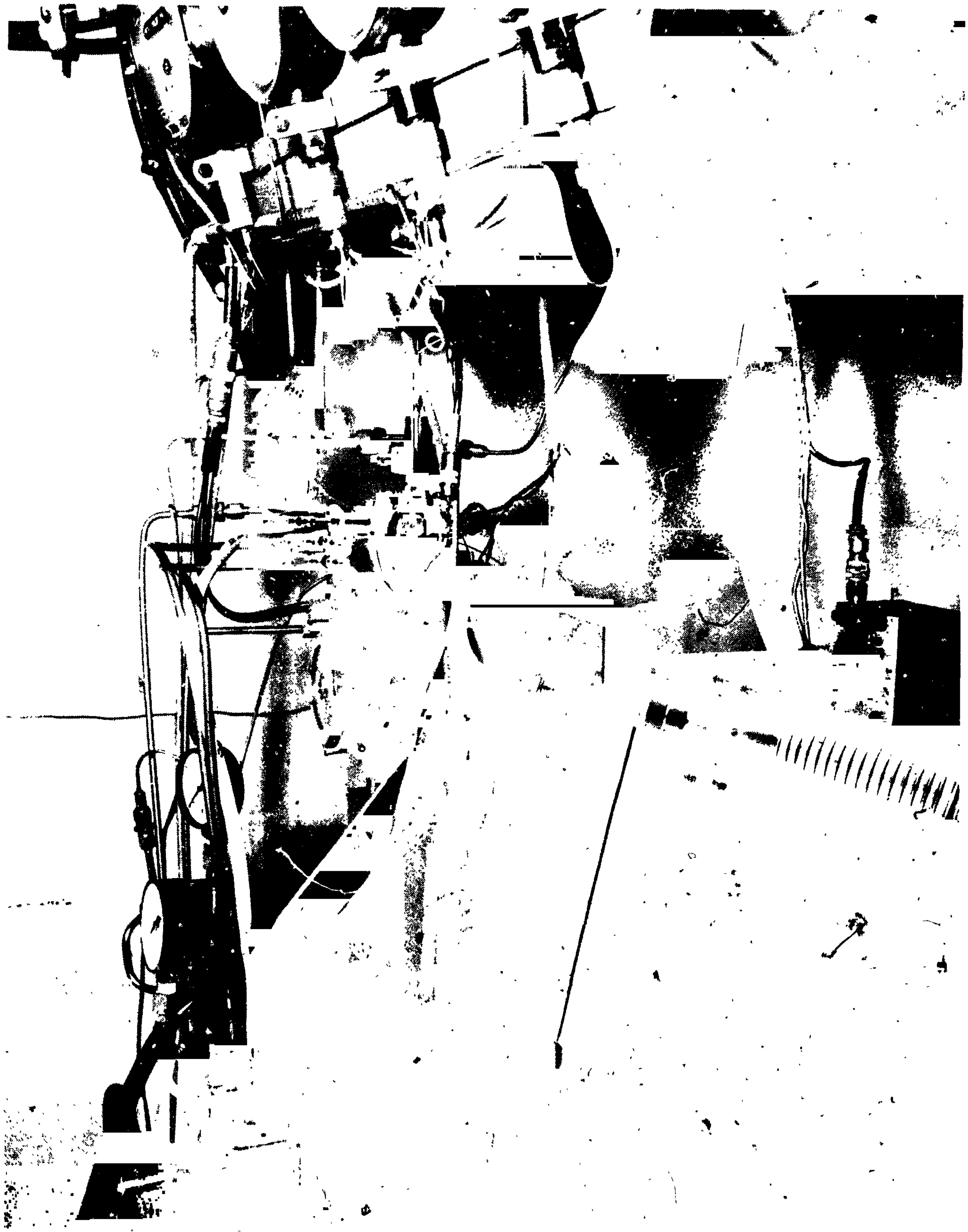

Fig. 7 - Close Up of Old Exhaust Manifold

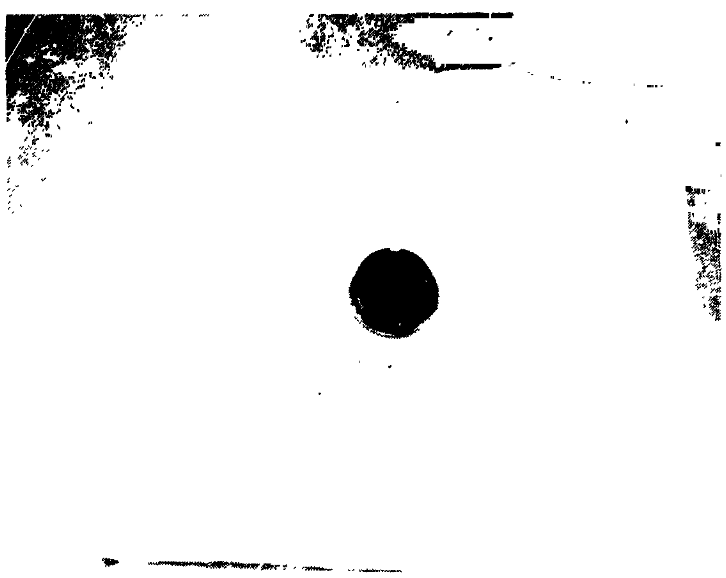

Fig. 8

Cylinder Head After the Run on Nov. 1, 1963

Fig. 9

Top of Engine Showing Exposed Piston Dome, Taken After the run on Nov. 1, 1963

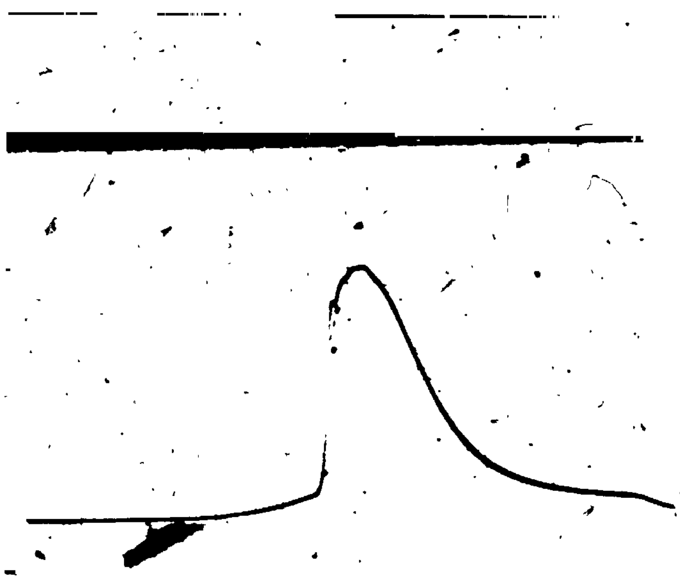

Fig. 10

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Entry No. 13, Table I

H_2 Inlet Press = 750 psi

O_2 Inlet Press = 800 psi

Vacuum = 27 in. Hg

H_2 Inlet Temp. = Ambient

Speed = 3030 rpm

Power = 3.00 hp

BSPC = 2.32 lb/hp-hr

% Heat Rejected = 57%

O/F = .81

BMEP = 144 psi

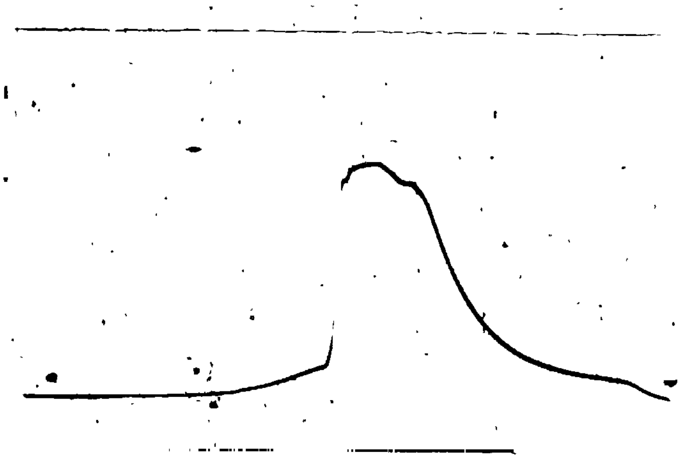

Fig. 11

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Entry No. 18, Table I

H_2 Inlet Press = 750 psi

O_2 Inlet Press = 800 psi

Vacuum = 26.5 in. Hg

H_2 Inlet Temp. = 540 °F

Speed = 3009 rpm

Power = 4.46 hp

BSPC = 1.74 lb/hp-hr

O/F = 1.03

% Heat Rejected = 58%

BMEP = 212 psi

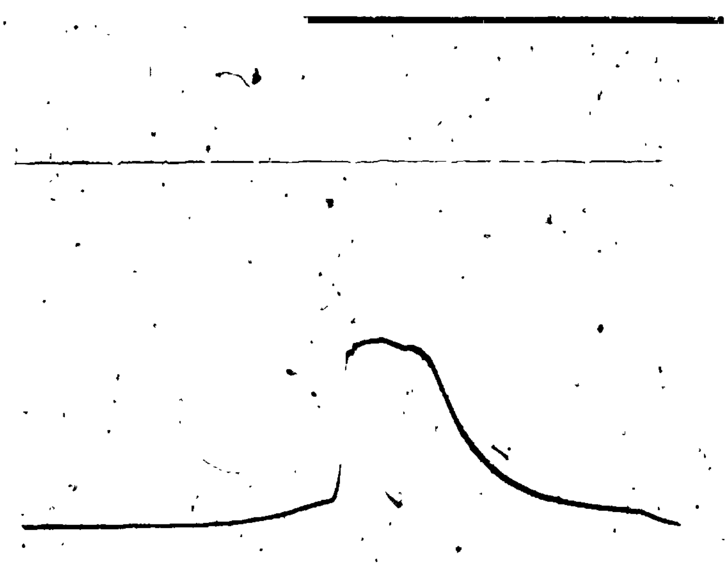

Fig. 12

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Entry No. 19, Table I

H_2 Inlet Press = 600 psig

O_2 Inlet Press = 685 psig

Vacuum = 27 in. Hg

H_2 Inlet Temp. = 510°F

Speed = 2980 rpm

Power = 3.54 hp

BSPC = 1.17

O/F = 1.17

BMEP = 173 psi

% Heat Rejected = 74%

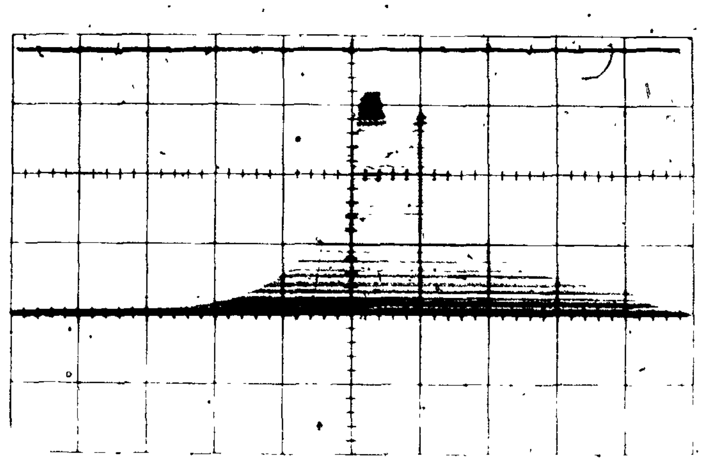

Fig. 13

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Entry No. 1, Table II

H_2 Inlet Press = 750 psig

O_2 Inlet Press = 1050 psig

Vacuum = Ambient

H_2 Inlet Temp. = Ambient

Speed = 4356 rpm

Power = 5.12 hp

BSPC = 1.94 lb/hp-hr

O/F = 0.74

BMEP = 171 psi

% Heat Rejected = 36%

This conclusion may not be valid for other combustion chamber shapes or clearance volumes, or for another oxygen injector valve nozzle configuration.

At very high BMEP's, the performance improvement from a vacuum exhaust and heated inlet hydrogen became less noticeable. Figs. 13, 14, and 15 give the results of an ambient pressure run at 750 psi hydrogen inlet and 4300 rpm, on the second buildup. The excellent blowdown of this engine is clearly evident. The best performance under ambient conditions which has been achieved to date is illustrated in Fig. 16, Entry No. 12 of Table II. Here a BSPC of 1.90 lb/hp-hr was achieved with a hydrogen inlet pressure of 600 psig. A vacuum exhaust and 500°F inlet hydrogen lowered the BSPC to 1.78 lb/hp-hr (Fig. 17). This BSPC was again achieved at 450 psig inlet hydrogen pressure and a BMEP of 132 psi, which represents the best relative performance to date (Fig. 18).

A test plan for this program through December, 1963, is given in Appendix C. This plan has been reviewed by NASA and presumes an adequate supply of hardware will be available.

Balanced Diaphragm Pressure Measurement System

Only a few good balanced diaphragm system pressure time traces were obtained this month. The best trace was plotted as pressure vs. volume using linear and log log coordinates, shown in Figs. 13, 14, and 15. Misfiring and pressure spikes experienced during the transition from ambient to vacuum operation at some valve settings tended to rupture or deform the diaphragm so that system failure occurred early in a test and we were forced to rely on the Kistler pressure transducer. Consequently, no balanced diaphragm

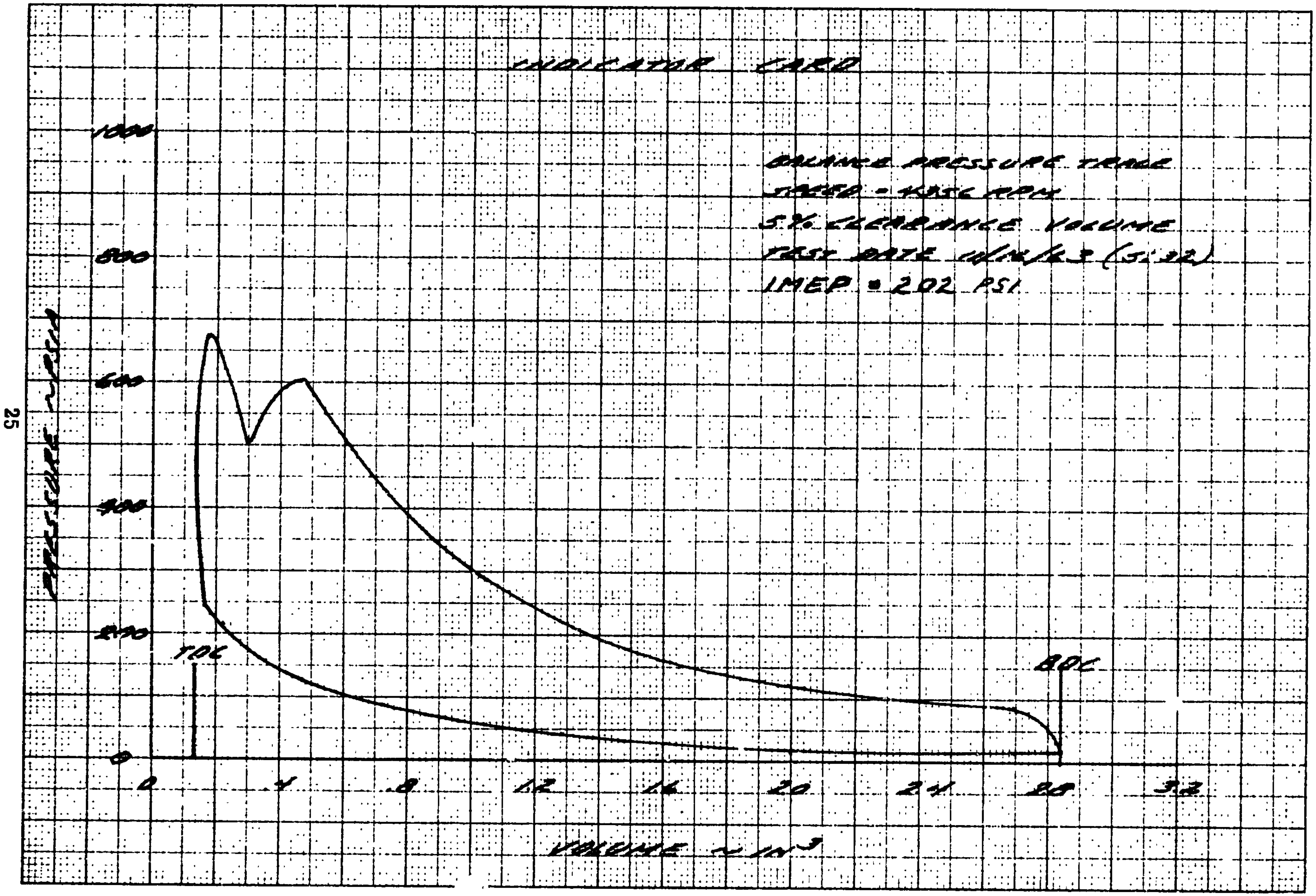


Fig. 14 - Linear Pressure Volume Curve
Dated 11-16-63 5:32 P.M.

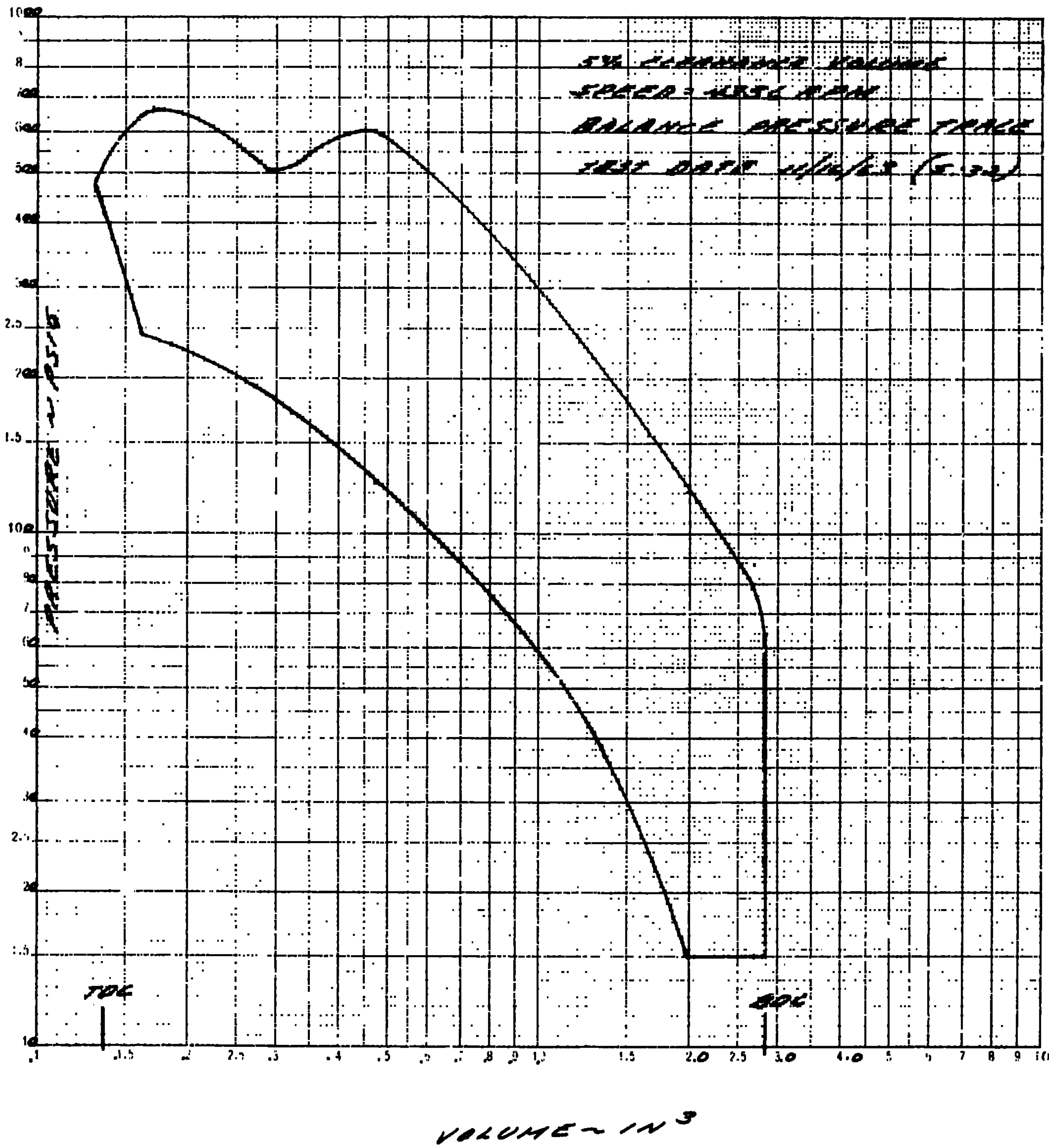


Fig. 15 - Log-Log Pressure-Volume Curve
Dated 11-16-63 5:32 P.M.

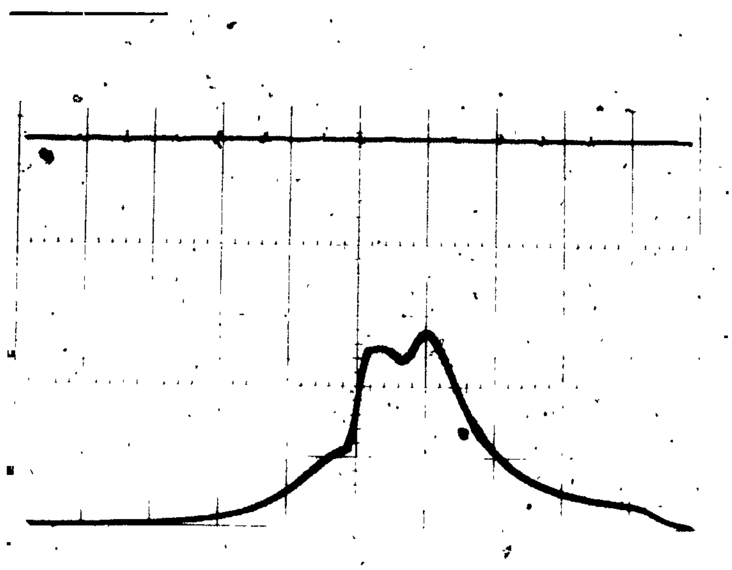


Fig. 16

11-18-63 3:21

Entry No. 7, Table II

H_2 Inlet Press = 600 psi

O_2 Inlet Press = 1000 psi

Vacuum = Ambient

H_2 Inlet Temp. = Ambient

Speed = 4335 rpm

Power = 5.21 hp

BSPC = 1.90 lb/hp-hr

% Heat Rejected = 46%

O/F = 1.10

BMEP = 175 psig

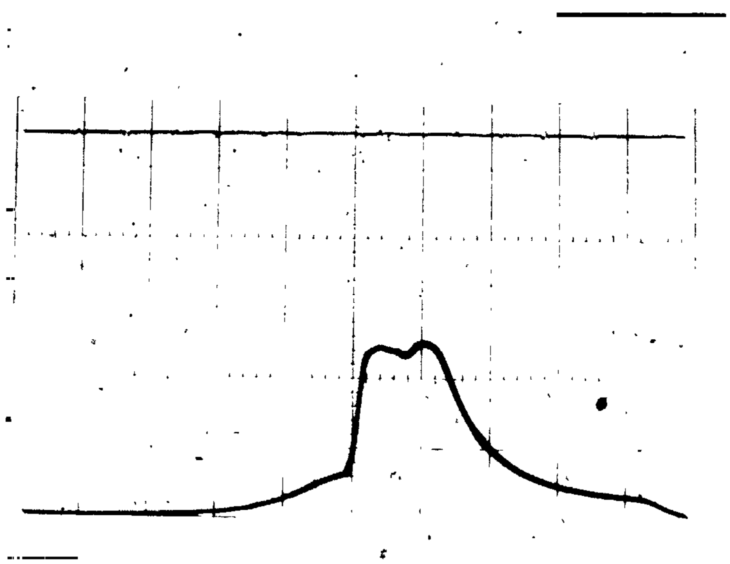


Fig. 17

11-18-63 3:48

Entry No. 12, Table II

H_2 Inlet Press = 600 psig

O_2 Inlet Press = 1000 psig

Vacuum = 24 in. Hg

H_2 Inlet Temp. = 500°F

Speed = 4320 rpm

Power = 4.98 Hp

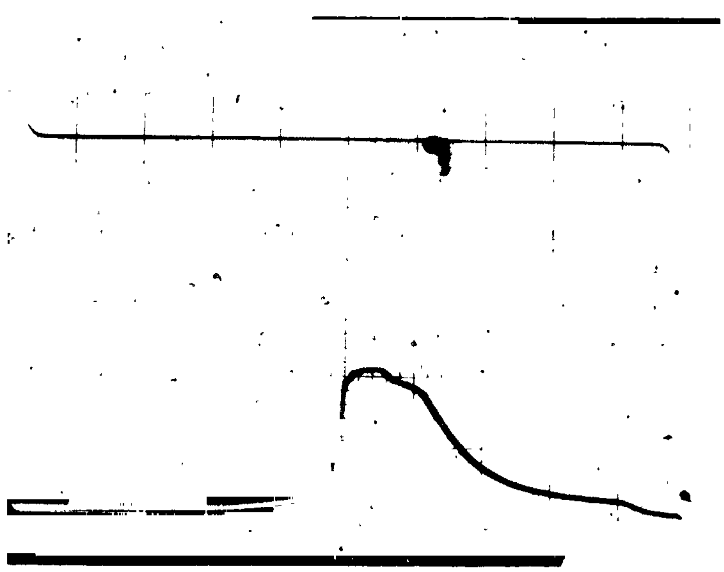
BSPC = 1.78 lb/hp-hr

% Heat Rejected = 72%

BMEP = 168 psig

O/F = 1.32

Fig. 18



11-19-63 4:20

Entry No. 13, Table II

H_2 Inlet Press = 450

O_2 Inlet Press = 500

Vacuum = 26 in. Hg

H_2 Inlet Temp. = 500 °F

Speed = 3027 rpm

Power = 2.74 hp

BSPC = 1.78 lb/hp-hr

BMEP = 132

O/F = 1.22

% Heat Rejected = 87

traces were obtained during vacuum operation. The Photocon switch failed due to overheating on November 18, (See Fig. 19), halting the balanced diaphragm pressure measurements. The system will be made operable again as soon as a replacement transducer is obtained.

Balanced diaphragm pressure measurements are believed to be much more accurate than the results obtained by the Kistler pressure transducer. For this reason no Kistler pressure-time traces are being plotted as pressure-volume indicator cards.

Since the Photocon switch was watercooled it introduced a cold spot in the center of the head which was found to influence head temperature and combustion characteristics. For example, there is a 300-400 psi pressure difference between oxygen and hydrogen inlet pressures in the runs on November 18, but only 20 - 100 psi difference in the runs on the following day, which used the solid 4.4% cylinder head. A photograph of this head after the run is shown in Fig. 20. The low pressure oxygen inlet is probably responsible for the feathery appearance of the combustion marks on the underside of the head.

Blowdown Effects and Vacuum Operation

Considerable difficulty has been experienced with misfiring during vacuum operation. Blowdown has been improved in two ways on this engine: first, by increasing the effective exhaust area through the use of a smaller piston dome, on the second buildup; and second, by installing a more open exhaust manifold. It is now possible to achieve an exhaust pressure of less than 1 in. Hg. The almost complete scavenging creates ignition difficulties which appear to be independent of mixture ratio and can be overcome only by keeping head temperatures above about 900°F. If the head temperatures exceed 1400°F, the phenomenon of knock occurs which is illustrated in Fig. 21. This

Fig. 19

Cylinder Head After The Run on Nov. 18, 1963. The Photocon Pressure Switch Due to Overheating

Fig. 20

Cylinder Head After The Run On Nov. 19, 1963

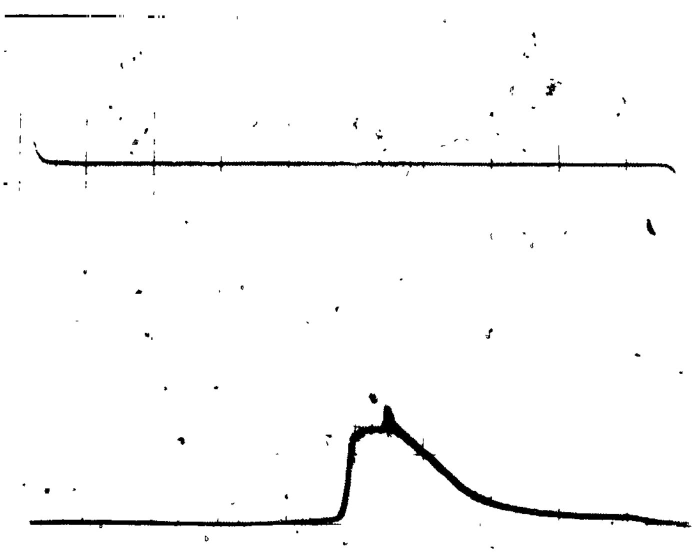


Fig. 21

11-23-63 1:16

Entry No. 17, Table II

H_2 Inlet Press = 300

O_2 Inlet Press = 450

Vacuum = 30 in. Hg

H_2 Inlet Temp = 450 °F

Speed = 3024 rpm

Power = 1.54 hp

BSPC = 2.27 lb/hp-hr

BMEP = 74 psi

O/F = 1.64

% Heat Rejection = 132%

knock disappeared when ambient back pressure was restored. It also disappeared under lower mixture ratios and lower head temperature, but misfiring or extinction of combustion then occured.

A photograph of the cylinder head after this run is shown in Fig. 22. It was thought that cylinder head orientation may be contributing to the problem due to excessive shrouding of the hydrogen inlet passage, so the head was rotated as far as possible without covering the catalyst ports. No change was noticed in performance. Knock was again present during vacuum operation. A photograph of the head after the second run is shown in Fig. 23.

Cooled Cylinder Head Operation

The difficulties which arose with the solid 4.4% cylinder head and the restricted range of experimentation due to temperature limits of a radiation cooled head prompted the change to a liquid cooled cylinder head. With this head it was possible to run at the design mixture ratio of 2:1. Pressure time traces for these runs are given in Figs. 24 and 25. Regardless of mixture ratio or inlet pressure, misfiring would occur at head temperature dropped below 900 °F. Knocking was never present, even as a transient condition.

These runs were repeated during a checkout of the recirculating cooling system using Dowtherm "A" as a coolant instead of water. While coolant temperatures and flow ratios were not optimized, a higher cylinder wall temperature was possible, which is believed to be responsible for the slight improvement in performance (From 2.28 lb/hp-hr to 2.10 lb/hp-hr). Pressure-time traces are given in Figs. 26 and 27.

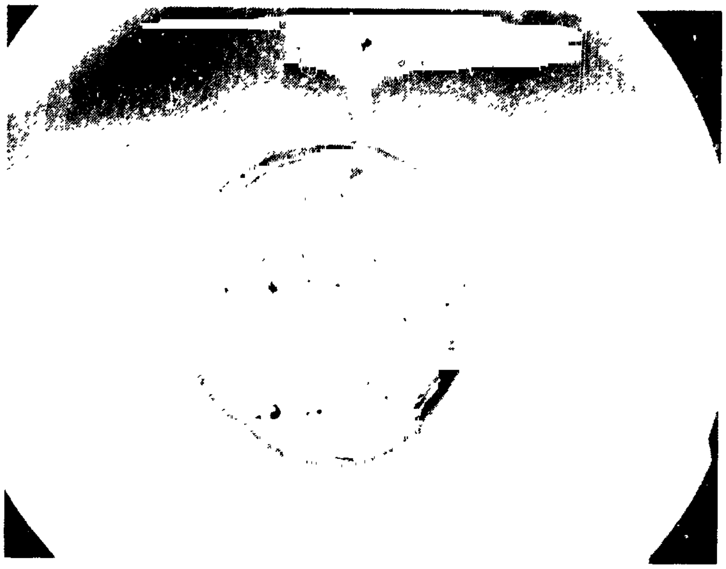


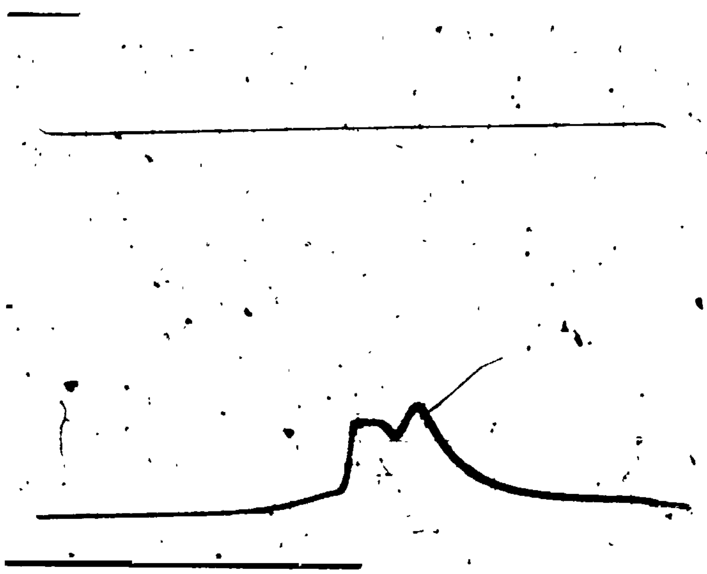
Fig. 22

Cylinder Head After The Run on Nov. 23, 1963 (Early Afternoon)

Fig. 23

Cylinder head after a check out run on Nov. 23, 1963, in which the head was rotated 5° from the orientation used in Fig. 22. This rotation was in the direction to uncover more of the hydrogen port. (counterclockwise in the picture). No change in performance was evident.

Fig. 24



11-26-63 11:26

Entry No. 21, Table II

H_2 Inlet Press = 300 psig

O_2 Inlet Press = 1000 psig

Vacuum = 24 in. Hg

H_2 Inlet Temp = 475 °F

Speed = 4298 rpm

Power 2.38 hp

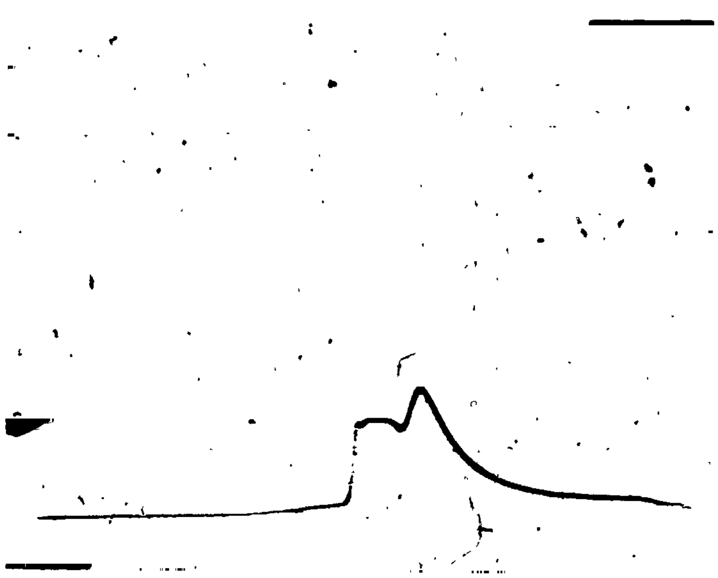
BSPC = 2.28 lb/hp-hr

BMEP = 81 psi

O/F = 2.00

% Heat Rejected = 119%

Fig. 25



11-26-63 11:30

Entry No. 22, Table II

H_2 Inlet Press = 300 psig

O_2 Inlet Press = 1000 psig

Vacuum = 28 in. Hg

H_2 Inlet Temp = 465 °F

Speed = 3047 rpm

Power = 2.15 hp

BSPC = 2.28 lb/hp-hr

BMEP = 103 psi

O/F = 2.09

% Heat Rejected = 104%

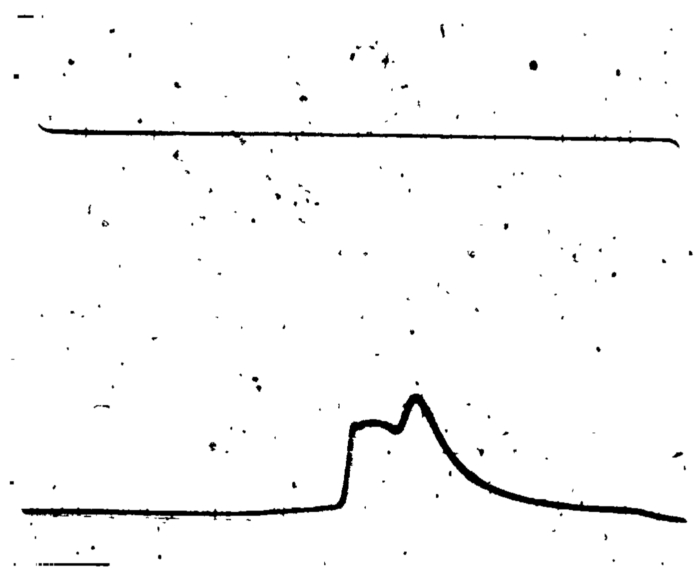


Fig. 26

11-27-63 2:05
Entry No. 25, Table II
H_2 Inlet Press = 300
O_2 Inlet Press = 900
Vacuum = 28 in. Hg
H_2 Inlet Temp = 460 °F
Speed = 3051 rpm
Power = 2.12 HP
BSPC = 2.21 lb/hp-hr
BMEP = 102 psi
O/F = 2.10
% Heat Rejected = 112%

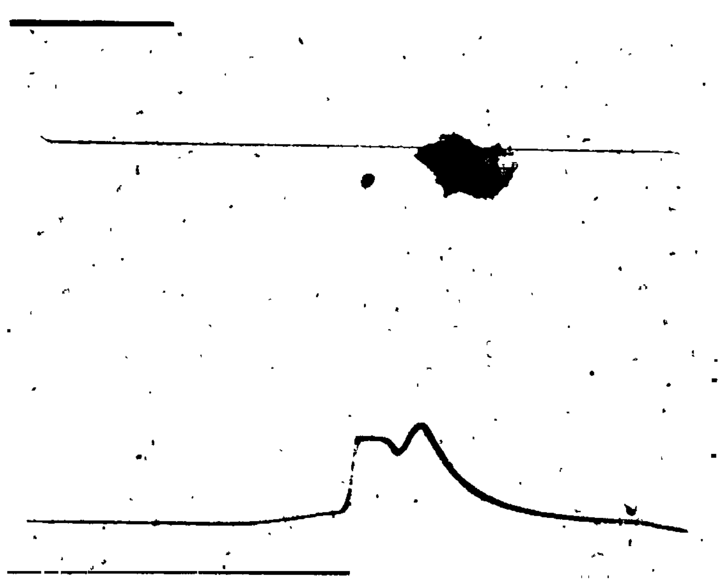


Fig. 27

11-27-63 2:17
Entry No. 26, Table II
H_2 Inlet Press = 300
O_2 Inlet Press = 1000
Vacuum = 28 in. Hg
H_2 Inlet Temp = 490
Speed = 4291 rpm
Power = 2.61
BSPC = 2.10 lb/hp-hr
BMEP = 89 psi
O/F = 2.10
% Heat Rejected = 117%

Performance Conclusions

There has been enough data obtained during this test program to draw some general conclusions as to the performance of the H_2 O_2 engine. These conclusions are:

1. BSPC improves with increasing BMEP up to approximately 150 psig. This is illustrated in Fig. 28, in which BSPC is plotted vs. BMEP for data obtained on the second buildup of Engine No. II.

2. Vacuum exhaust improves BSPC beyond the effect of merely increasing BMEP. (Due to the greater charge of hydrogen admitted when recompression pressure is lowered). This is shown by the lower of the two curves on Fig. 28.

3. Engine performance is relatively insensitive to mixture ratio over the limits 0.8:1 to 2.5:1.

Test Equipment

1. Installation of the high temperature recirculating cylinder wall cooling system, with manual controls, is complete and in use.

2. Fabrication of a new vacuum system engine exhaust manifold adaptor to reduce pressure drop is complete and in use.

3. Fabrication of the new O_2 injector test block is 80% complete.

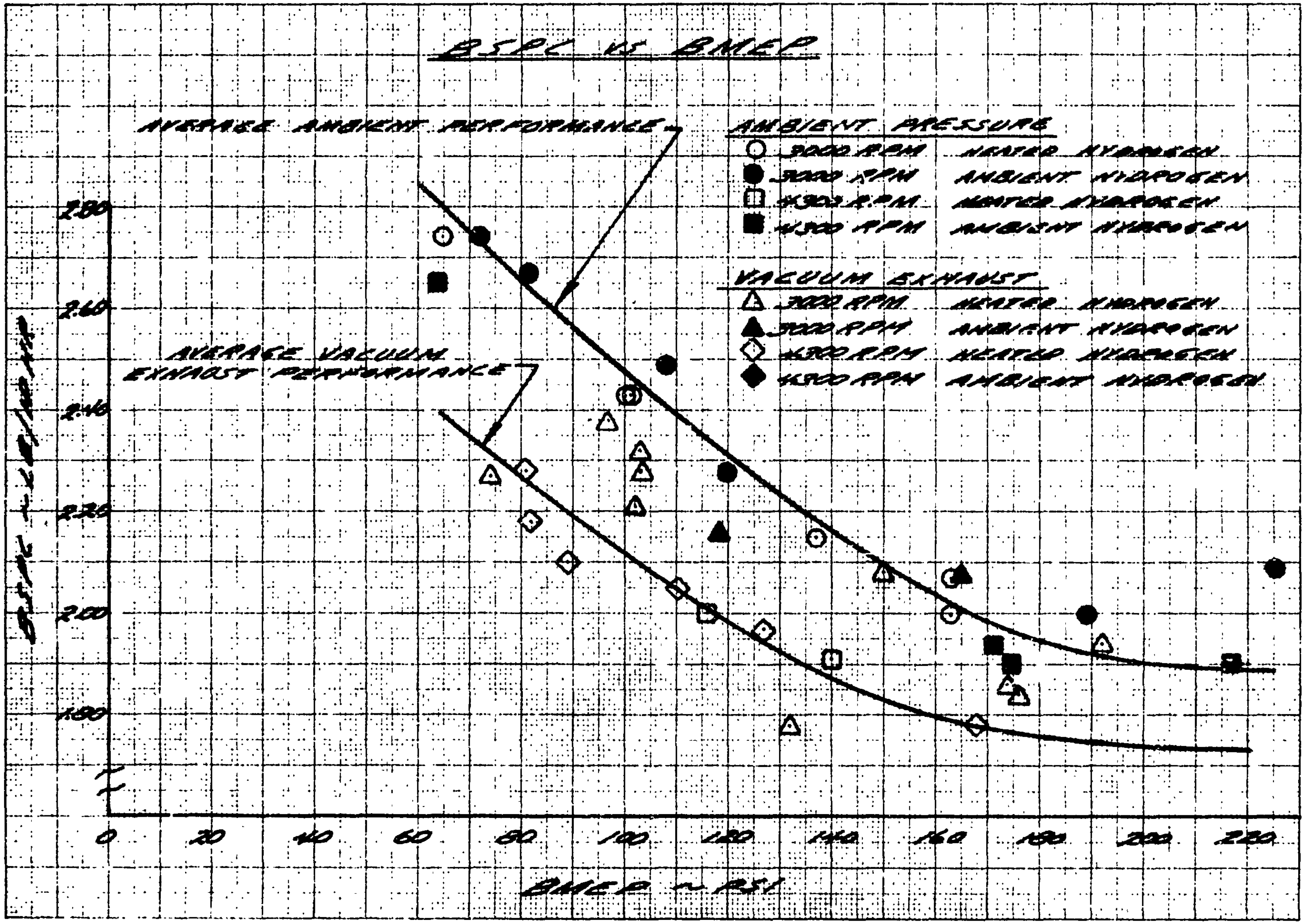


Fig. 28 - BSPC VS. BMEP

REGENERATOR

No work scheduled this reporting period.

COMPRESSOR

Design & Fabrication

1. New parts for teflon bellow assembly (shown in Fig. 21 PR 91570-510-4) are being fabricated.

2. Detail drawing for the new first stage valving shown in Fig. 29 has been completed. Release of drawings for fabrication is being withheld for consideration of current tests.

3. Rulon material rings of the Koppers configuration are being procured.

Assembly

Two compressor units have been assembled. Complete records of parts conditions during post test disassembly are being maintained. The piston for Mace Corp. design ring is used in assembly No. I and the piston for Koppers design rings is used in No. II. The redesigned first stage cylinder head assembly (shown in Fig. 6, PR 91570-510-1) is now in use. Rulon bearing material is being used in the drive linkage of each unit.

Floroloid was originally used as the bearing material in compressor No. I. This material has been rejected because of plastic deformation in operation. Fig. 30 shows Floroloid bearing

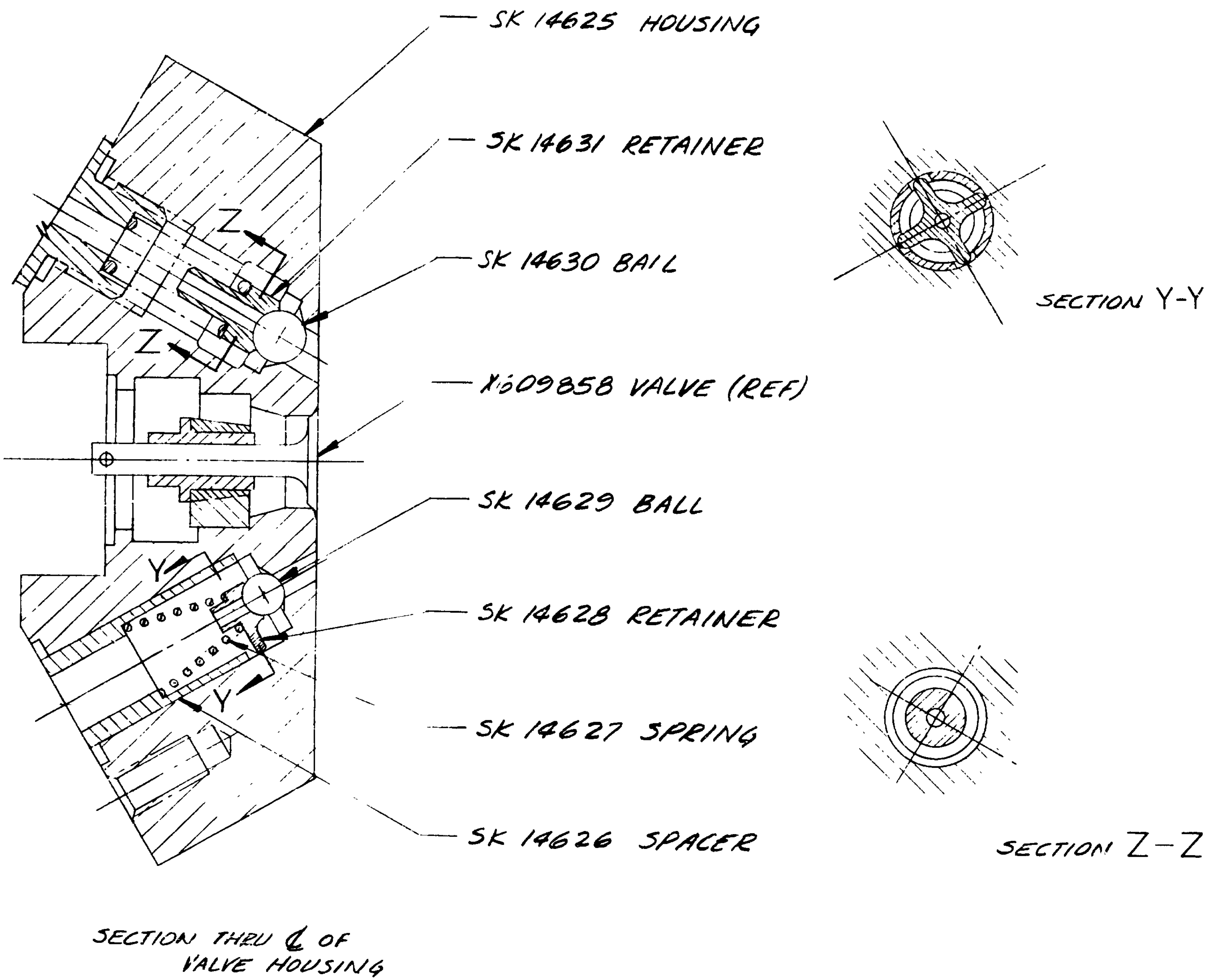


Fig. 29 - New First Stage Valving

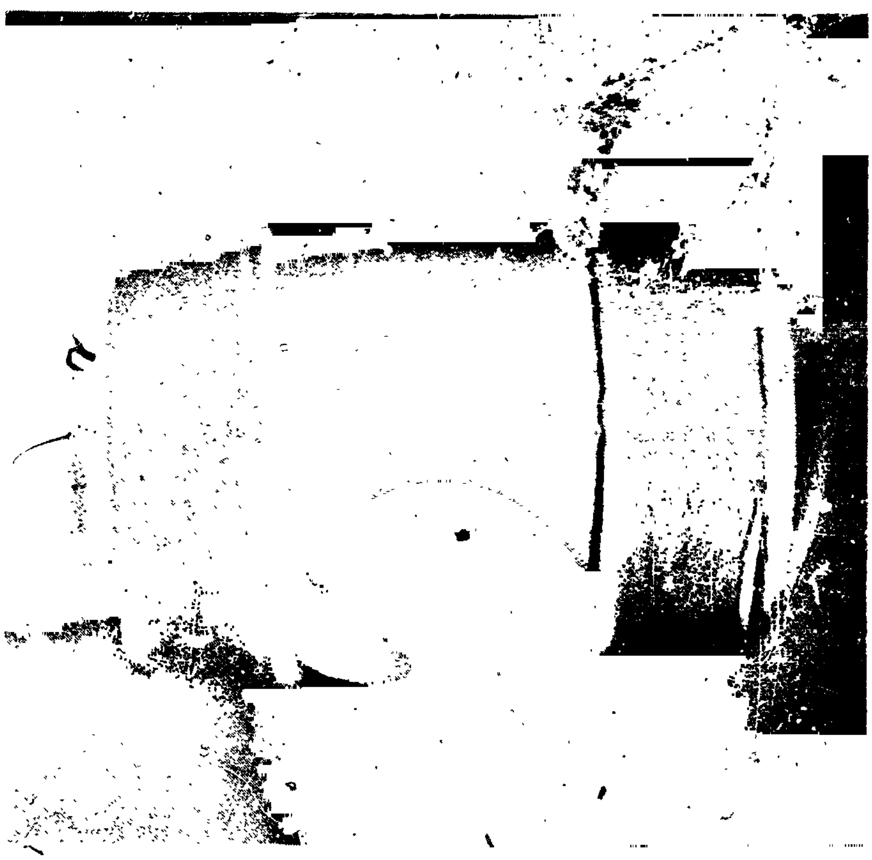


Fig. 30 - Failed Drive Linkage Bearing

surfaces after 3.1 hours of running. Thus far, the Rulon material appears to be a satisfactory bearing material. After initial run-in, surfaces appeared to have been polished and minor powder residue was present. After additional running no further change was observed.

Slight ring residue was present on the cylinder head and cylinder and some times between valves and seats each time compressor No. I (with the Mace ring) was disassembled.

Performance Testing

Compressor No. I has been run for a total of 6 3/4 hours. The time includes run-in with heads removed, and single and two stage operation with LN- cooled H_2, and N_2. Two sets of Mace rings were used in the second stage and one set in the first stage. The first set of second stage rings were removed after overheating. Two different sets of Floroloid drive linkage bearings were used for the first 3 1/4 hours, and Rulon bearings were used for the remainder of time. Initial testing with compressor No. II will start during the next week.

The accuracy of data obtained to date is uncertain due to difficulty in maintaining steady state conditions while all run points were being taken. However, condition changes were maintained sufficiently steady so that the data may be used for comparisons purposes. Variation of ring performance with temperature is believed to be a major factor contributing to eratic performance.

Te s were run-in which the cylinders were precooled with LN_2 boiloff. During the test the cylinder cooling gas flow was turned off and parameters observed as a function of cylinder temperature rise. Performance was extremely poor until the cylinder temperature reached approximately 40 °F at which time a sudden increase in output pressure and flow was observed. Flow and discharge pressure remained high at cylinder temperatures above 40 °F. The torque input to the compressor began to increase slightly at a cylinder temperature of 60 °F and sharply at a cylinder temperature of 80 °F.

Information learned from the test program to date is summarized as follows:

1. The new internal drive with Rulon bearings functioned satisfactorily for a total of 3 1/2 hours a both with and without cooling.

2. The new Mace design rings have superior sealing properties (above 40 °F cylinder temperature) than rings tested during the last program, but generate higher friction. The highest first stage volumetric efficiency observed to date are approximately 75% with a pressure ratio of 3 (CF = .95, Pin = 18 psia, H_2 gas) and 45% with a pressure ratio of 5 (CF = .91, Pin = 18.5 psia, H_2 gas).

3. Valve performance problems during compressor operation have not been isolated due to the more pronounced ring effects. However, it is suspected the poor seating, has been caused by ring residue. Based upon experience with Rulon as drive bearings, it is anticipated that the Rulon ring will reduce this problem. Static pressure drop vs. flow testing of valving will be performed during the next month.

Test Equipment

A view window has been installed in the wall between the control room and the test cell. The control panel and instrumentation read-out equipment has been moved to this window area. The discharge flow tube has been replaced with a sonic orifice.

The gas supply line between the LN_2 cooling Dewar and the compressor has been insulated.

Plumbing has been added so that the first and second stage cylinders and crankcase can be independently cooled with LN_2 boiloff.

PROTOTYPE ENGINE ENDURANCE TEST

No work scheduled during this reporting period.

APPENDIX A

INSTRUMENTATION CONTROL PLAN

NASA CONTRACT NAS 3-2787

1. All functions to be instrumented will be numbered and defined from the Test Data Sheet for the following:

   Mark I H_2-O_2 Engine, Model EA 1570-515
   Prototype Compressor, Model EA 1570-516
   Engine Exhaust to Hydrogen Regenerator

2. All the above functions will be listed on separate Calibration Status Sheets for the engine, compressor, and regenerator.

3. The following information will be documented after each instrumentation function on the Calibration Status Sheets:

   Device Name and/or Description - the name of the instrument
   Manufactured by - the name of the manufacturer
   Model No. - from the manufacturer
   Serial No. - from manufacturer
   Scale Div. - instrument scale calibration divisions
   Scale Range - the extremes of the calibration divisions
   Scale Units - the basic unit of measurement
   Accuracy - the deviation of the instrument as rated by the manufacturer in terms of % full scale or similar rating
   Calibration Period - the frequency of instrument calibration
   Calibration Next Due - the next date of instrument calibration

4. Monitoring activities to implement the Control Plan will be to assure:

   a. That calibration decals are attache . on each measuring device in a conspicious place.

   b. That the calibration decal is noted with the date at which next calibration is due.

   c. That each measuring device is labelled with the function that it performs, and the item number from the test data sheet. This will facilitate quick and accurate data read-outs during the testing procedure.

   d. That all instrumentation is reasonably easy to view for the full range of the scale in the interests of reducing the human error to a minimum.

   e. That calibration activities are carried out periodically, dependent upon the nature of the instrumentation. That the calibration is carried out by a certified agency when necessary, and that the standards used in calibration are traceable back to the National Bureau of Standards, whenever applicable.

   f. That the Calibration Status Sheets for instrumentation for the engine, compressor, and regenerator are maintained and updated periodically.

   g. That the results of instrumentation calibration activities are reported in the Monthly Progress Reports.

APPENDIX B

FAILURE REPORTING PLAN

NASA CONTRACT NAS 3-2787

1. All failures will be documented on the Failure Report And Summary Sheet and analyzed on the Failure Analysis Report. Failures will conform to a mechanical definition of failure as follows:

   Any distortion of size or shape, or any change of physical property of a part, or integral assembly of parts, from the designed configuration which renders this component unable to perform its intended function.

   When a component material loses its ability to perform its intended function due to physical property changes, this shall also be considered as a failure.

   The above limited definition of failure is used with Contract NAS 3-2787 due to the particular nature of the program. Functional failures; as an example, when a gasket is leaking, or when a part is not functioning properly, will be identified, but not documented to the same extent of detail as mechanical failures, in keeping with the limited program scope.

2. The Failure Report and Summary Sheets are retained in a folder, maintained by the reliability engineer assigned to this project. Columns will be notated with the following data.

   a. Failure No. - will be sequentially numbered from data acquired from the Engine Test Log (retained on the desk of the engine test engineer) whenever a mechanical failure is noted. Functional failures are noted and numbered on separate sheets.

b. Data Sheet No., Time and Date of Failure - This column will be noted with the number of the Test Data Sheet, date of failure, and time when applicable.

c. Part No. and Serial No. - This column will be notated with the part drawing number and Vickers serial number.

d. Description of Failure - This will briefly describe the failed part condition in accordance with the failure definition.

e. Description of Conditions - This will briefly describe the conditions (i.e. the type, and lengths of test run) active on the part prior to failure.

f. Failure Mode No. - This column will be notated with a failure mode code derived from the Failure Mode Analysis form.

g. Cumulative Time on Part - The total time in minutes that the failed part was functioning in all tests prior to failure.

h. Corrective Action - The corrective action taken to assure that the similar failure will not occur again will be briefly noted.

i. Failure Analysis Report No. - The number of the Failure Analysis Report form used in the analysis of the particular failure will be entered in this column.

3. The Failure Report and Summary Sheet forms will be initially notated in pencil, then typed on vellums. and retained for NASA review. Copies will be submitted to NASA upon request. Separate sets of Failure Report and Summary Sheet forms will be compiled for the following.

   Prototype H_2-O_2 engine, Model EA 1570-515
   Prototype compressor, Model EA 1570-516
   Prototype regenerator.

4. Failure Analysis Report forms will be prepared for failures where detailed analysis is required to determine corrective action.

5. Failure reporting and analysis activities will be carried out on a continuous scheduled basis, and will be periodically summarized for the Monthly Progress Reports.

APPENDIX C

TESTS TO BE CONDUCTED

NASA SPICE H_2-O_2 ENGINE

11-15-63 to 1-1-64

ASSUMPTIONS

1. Thirty hours of hot testing will be conducted on four separate engine buildups: (6 to 10 hours hot time between buildups). About ten hours of cold running.

2. Testing will be limited to the minimum running time necessary for warmup, obtaining and verifying data, and determining the effects of changes in the engine, instrumentation and test setup. Several 30-minute runs will be made. A 6 - 8 hour endurance run will be scheduled if feasible. Tests will be run over a full power range.

TESTS

1. Checkout Tests
   Number of Tests: 6 - 10

   Description: Calibration runs on new engine buildups or new test stand innovations. There will be four buildups, plus two checkouts of the recirculating cooling system, on manual control and automatic control; and checkout runs of radical timing changes.

   Operating Parameters: Two engine speed settings (3000 and 4200 rpm) and two hydrogen pressure settings, with other parameters held to values where plenty of past data is available. On checkout runs of radical timing changes, a full range of engine speeds will be covered. (2500 - 4500 rpm).

Estimated Running Time: 6 hours

2. Injector Nozzle Calibration Tests:

Number of Tests: 4 or 5

Description: Hydrogen pressure and rpm will be held constant while oxygen pressure is varied in steps over a wide range, to be limited by permissible operating temperatures. Hydrogen timing: 10° BTDC - 20° ATDC (4% admission). Oxygen timing: Start at 10° ATDC - 40° ATDC, and try a couple of other settings as dictated by performance results and the appearance of pressure-time traces. Hydrogen pressures will depend on the results of oxygen injector bench tests. (Sc that a mixture ratio between 1. 1:1 and 1. 5:1 can be investigated without overheating, and with an adequate differential between the oxygen and hydrogen inlet pressures).

Operating Parameters: Vacuum exhaust will be used. Hydrogen may or may not be preheated. Each injector nozzle configuration will be run at 3000 and 4300 rpm and two hydrogen inlet pressure levels. As many oxygen pressure levels as possible between the limits of misfirings and overheating will be investigated.

Estimated Running Time: 6 hours

3. Combustion Chamber Tests:

Number of Tests: 2 or 3

Description: Runs will be made over a wide range of hydrogen and oxygen inlet pressures for 3000 and 4300 rpm, at timings to give BMEP's between 150 and 225 psi. An oxygen injector configuration whose characteristics are well known will be used. Vacuum and ambient exhaust will be used as necessary to facilitate operation.

Operating Parameters:
1. 3000 and 4300 rpm
2. Vacuum and Ambient Exhaust
3. Heated (500 °F) and Ambient Hydrogen
4. H_2 Inlet Pressure of 300, 450, 600. and 750.
5. Matching O_2 Inlet Pressures to give O/F ratio of 1.2:1.
6. Different clearance volumes

Estimated Running Time: 4 hours

4. Heated Inlet Tests

Number of Tests: 2 - 4

Description: The engine will be stabilized at the lowest possible mixture ratio and hydrogen inlet temperature will be raised in steps to the highest allowable value.

Operating Parameters:
1. 4% H_2 Admission (10° BTDC 20° ATDC)
2. H_2 Inlet Temperatures Ambient, 200 °F, 400 °F, 600 °F, 800 °F, 1000 °F.
3. Mixture Ratio 1:1 or less 3000 and 4300 rpm

Estimated Running Time: 3 hours (this time includes heated hydrogen expansion tests)

5. Exhaust Blowdown Tests

Number of Tests: 2

Description. Indicator cards of the region between 50° BBDC 50° ABDC will be taken using the balanced diaphragm system. Both pressure bleeddown and point-by-point measurements will be taken.

Operating Parameters: Two engine speeds (4300 and 3000 rpm) at about 150 - 175 psi BMEP, and 1.2:1 O/F. Other conditions of interest may be checked.

Estimated Running Time. 4 hours

6. Cooled Cylinder Head Tests

Number of Tests 2 or 3

Description: Engine will be run with a calibrated injector using the automatically controlled cooling system and the cooled cylinder head. High coolant and engine temperatures will be attempted at a 2 1 mixture ratio.

Operating Parameters.
1. Full Range of Speed 2500 - 4500 rpm
2. 400°F Coolant Temperature
3. O/F - 2.1
4. 4% H_2 Admission
5. Two H_2 Pressure Levels (BMEP 125 - 200 psi)

Estimated Running Time 4 hours

7. <u>Advanced Hydrogen Timing</u>

Number of Tests 2 or more

<u>Description</u> Hydrogen will be admitted near BDC at a low pressure and temperature and compressed, with the oxygen admitted near TDC. Length and number of tests will be determined by the success of this combustion technique.

<u>Operating Parameters</u>

1. H_2 40° ABDC 60° ABDC
   Approximately 50 psi
2. O_2 Midpoint at TDC 500
   1000 psi cooled cylinder head

<u>Estimated Running Time</u> 3 hours