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TECHNICAL MEMORANDUM

X-417

PERFORMANCE OF A SMALL GAS GENERATOR USING

LIQUID HYDROGEN AND LIQUID OXYGEN

By Loren W. Acker, David B. Fenn,
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Lewis Research Center
Cleveland, Ohio

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SUMMARY

The performance and operating problems of a small hot-gas generator burning liquid hydrogen with liquid oxygen are presented. Two methods of ignition are discussed. Injector and combustion chamber design details based on rocket design criteria are also given. A carefully fabricated showerhead injector of simple design provided a gas generator that yielded combustion efficiencies of 93 and 96 percent.

INTRODUCTION

Small gas generators using the primary vehicle propellants have many applications such as providing power for turbopumps and turboelectric generators, supplying hot gas for attitude control jets, or heating the propellant-tank pressurizing gas. An investigation was conducted at the NASA Lewis Research Center to study the problems associated with the design and operation of small liquid-hydrogen, liquid-oxygen gas generators. This investigation was part of a rocket systems research study in which the function of the gas generator was to provide hot gas to a heat exchanger that heated the pressurizing gas required for the main propellant tanks. The gas generator was designed to supply 300 Btu per second. The design of the gas-generator injector and chamber was based on the information used in the design of rockets as presented in reference 1. The data of this reference state a relation between chamber exit velocity, chamber length, chamber pressure, and propellant droplet size.

The present report presents the steady-state combustion efficiency, characteristic exhaust velocity, and exhaust temperature obtained from several different configurations. The gas generators were varied in chamber length from 6 to 17.6 inches and were operated over a range of

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*Title, Unclassified

oxidant-fuel weight ratios from 0.4 to 1.2 at chamber exit Mach numbers of 0.35 and 0.47. This report also points out some of the operating problems, namely, chamber pressure oscillations, ignition of propellants, and burnout of the combustor wall. Possible solutions to such problems are discussed.

APPARATUS AND PROCEDURE

The gas-generator research facility, the operating procedure, the propellant flow control, and the method of instrument calibration are described in detail in appendix A.

Gas Generator

The gas generator was designed to supply 0.16 pound per second of hot gas at a pressure of 220 pounds per square inch absolute and a temperature of 1823° R. This temperature is reached, ideally, at an oxidant-fuel weight ratio of 1.0 as shown in table I, where some physical properties of the products of combustion of liquid hydrogen and liquid oxygen are presented. Based on these conditions and a chamber exit (nozzle inlet) Mach number of 0.35, a cylindrical chamber 0.61 inch in diameter was required.

The analytic correlation of reference 1 was applied to the design conditions of the gas generator even though experimental verification existed only for the range of conditions encountered in rocket combustors. Reference 1 relates the length of the combustion chamber required to vaporize a given percent of propellant to the chamber exit velocity, droplet diameter, chamber pressure, and propellant injection conditions. The droplet diameter of the slower vaporizing propellant, oxygen in this case is the largest single factor in determining the chamber length. Therefore, to minimize the combustion chamber length, the oxygen injection holes had to be made as small as practical to produce the required small droplets.

A plot (fig. 1) of mass of the oxygen unvaporized as a function of chamber length was obtained from this correlation of droplet diameter and chamber length. Oxygen droplet diameters of 0.004 and 0.006 inch were assumed. These curves indicated that a chamber length between 4.5 and 8 inches would be sufficient for 99-percent vaporization. If the propellants burn instantaneously upon vaporization, as reference 1 assumes, nearly 100-percent combustion efficiency would be achieved. However, this chamber may not be long enough because of the relatively low temperatures in the gas generator as compared with the temperature in rocket combustors; and, furthermore, the liquid-oxygen injector may not produce

uniformly small droplets. Consequently, in this investigation the chamber length was varied from 6 to 17.6 inches.

A sectional drawing in figure 2 shows one configuration used in this study. All parts were fabricated from Inconel and were nickel-brazed in a vacuum furnace. Two different sonic-flow discharge nozzles were used to establish chamber exit Mach numbers of 0.35 and 0.47. The liquid-oxygen injector face (fig. 3) that formed the end of the combustion chamber had 21 holes, 0.0135 inch in diameter. They were equally spaced on two concentric circles of 10 holes each with the remaining hole located in the center of the face on the combustion chamber centerline.

The liquid-hydrogen injector, which was fed by an annular plenum, had 20 holes, 0.033 inch in diameter, evenly spaced around the chamber, 0.05 inch downstream of the liquid-oxygen injector face. The liquid-hydrogen spray was directed radially into the combustion chamber so as to impinge at 90° on the liquid-oxygen spray. This injection method should promote rapid mixing of the fuel and oxidant, and limit oxygen contact with the wall of the chamber.

Ignition System

Ignition was accomplished by a pilot flame formed by injecting gaseous oxygen on a spark plug during the fuel lead period. Both the gaseous oxygen and the spark were turned on and off simultaneously. The ignition was left on 4 to 5 seconds after both propellants started to flow.

Because the gas generator was designed to operate with a fuel-rich mixture of hydrogen and oxygen to obtain low-temperature combustion products, the liquid-hydrogen flow in the combustion chamber was established before the liquid-oxygen flow. Some of the hydrogen burned with the oxygen gas to provide the hot pilot flame that vaporized the liquid oxygen and started the primary combustion. The gaseous oxygen flow in the igniter was approximately one-hundredth of the main liquid-oxygen flow.

The igniter is shown downstream of the exhaust nozzle in figure 2, but in some configurations it was installed in the combustion chamber proper. Ignition was detected by a thermocouple located adjacent to the gaseous-oxygen injector tube.

Range of Conditions

Each gas-generator configuration was operated at a constant hydrogen flow of 0.08 pound per second. Oxygen flow was varied to give a range of oxidant-to-fuel weight ratios from 0.4 to 1.2. A description of the

automatic flow control used for this investigation is presented in appendix A. The combustion chamber length was varied from 6 to 17.6 inches, and two different exhaust nozzles were used. The nozzles were sized with a chamber diameter of 0.61 inch to give nominal chamber exit Mach numbers of 0.35 and 0.47.

INSTRUMENTATION

The pressures were sensed with linear variable-reluctance-type transducers. The largest timelag element in the measuring system for combustion chamber pressures was the tubing between the transducer and the combustion chamber wall, combined with a small orifice in the wall. Calculations based on a simple "RC" electrical analogy indicate less than 25-percent attenuation in amplitude of 50-percent pressure perturbations ($\Delta P/P$) for frequencies up to 4 cycles per second. This response at 5-percent amplitudes extends to frequencies of 16 cycles per second. The data were reproduced by using a 6-cycle-per-second sharp cutoff filter.

Gas-generator exhaust gas temperatures were sensed with Chromel-Alumel thermocouples. Carbon resistors were used to measure liquid-hydrogen temperatures, while platinum resistors were used to measure liquid-oxygen temperatures. The variation of resistor resistance with temperature changes was calibrated to determine the fluid temperature. Continuous analog records of pressures and temperatures were obtained on a frequency-modulated tape-recording system that is described in detail in the appendix of reference 2.

Propellant flow rates were calculated from pressure and temperature measurements in calibrated venturi tubes located in the liquid feed lines.

RESULTS AND DISCUSSION

Steady-State Performance

The performance of each configuration was obtained over a range of oxidant-to-fuel weight ratios at a constant fuel flow of approximately 0.08 pound per second. One of the most convenient parameters describing gas-generator performance is the characteristic exhaust velocity c^*, which is defined by either of the following two equations:

$$c^* = \frac{P_A g}{w_O + w_F} \tag{1}$$

$$c^* = \sqrt{\frac{gRT}{\gamma M}\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{1-\gamma}}} \qquad\qquad (2)$$

(All symbols are defined in appendix B.)

The characteristic exhaust velocity presented in figure 4(a) as a function of oxidant-to-fuel weight ratio was calculated from equation (1) by using the measured nozzle inlet static pressure and total propellant flow rates. It must be noted that in converting from static to total pressure the ideal value of the isentropic exponent γ was used. This assumption, however, results in a negligible error in c^* at high combustion efficiencies. No correction for the momentum pressure loss due to combustion was necessary because the chamber pressure was measured at the chamber exit. The data shown in figure 4(a) indicate that the ideal c^* was not attained over the range of mixture ratios investigated. For example, at a ratio of 1.0 the ideal c^* was 6990 feet per second, the 17.6-inch length was nearest the ideal with a value of 6710 feet per second, and the other configurations were 6500 feet per second.

Since the ideal c^* is a property of the completely burned propellants, the ratio of actual to ideal c^* can be used to indicate the level of combustion efficiency. Figure 4(b) shows the combustion efficiency of the various configurations investigated over a range of oxidant-to-fuel weight ratios from 0.4 to 1.23. The additional scale of total weight flow is based on a hydrogen flow of 0.08 pound per second. In general the efficiency was independent of oxidant-to-fuel weight ratio over the range of conditions investigated, and the scatter in the data obscured any trends with chamber exit Mach number that may have been present. The data scatter was attributed to inaccuracies of the measurements. The efficiencies of all the configurations except the 17.6-inch length lie within ±2 percent of a mean value of 93 percent. The 17.6-inch gas generator had a 96-percent combustion efficiency apparently due to its longer length. These high values of c^* efficiency indicate that good results can be obtained in a small low-temperature gas generator without resorting to complex injector designs.

Although thermocouples were installed in the combustion chamber and at several locations downstream of the exhaust nozzle, no actual measured gas temperatures can be reported because of repeated thermocouple failures. The thermocouple probes in the chamber were usually burned off flush with the wall and those downstream either bent, lost their radiation shields, or failed in numerous other ways. It is believed that the burned probes were either consumed in raw oxygen or were burned off by hot streaks of gas. In the absence of measured values, the chamber exit total temperature was calculated from the c^* values of figure 4(a)

and equation (2). The ideal values of the molecular weight and isentropic exponent were used. The calculated nozzle inlet total temperature is presented in figure 4(c) as a function of oxidant-to-fuel weight ratio. At a mixture ratio of 1.0, the exhaust temperature was 1680° R for the 17.6-inch length and 1570° R for the others, while the ideal was 1823° R.

Figure 5 shows a typical plot of combustion chamber exit static pressure against oxidant-to-fuel weight ratio for a fuel flow of 0.08 pound per second and a chamber exit Mach number of 0.35. At a mixture ratio of 1.0, the chamber pressure was 212 pounds per square inch absolute.

Operating Problems

Combustion stability. - The foregoing results were based on average readings of chamber pressure during the last 6 to 10 seconds of operation at each mixture ratio. Some degree of disturbance was always present in the chamber pressure measurements. Figure 6 shows sample oscillograph traces of recorded chamber pressure time histories. Traces are shown at the highest and lowest mixture ratios for four individual runs. The chamber pressure always appeared smoothest at the highest mixture ratio and roughest at the lowest mixture ratio. The data show magnitudes of disturbances in the order of 15 to 35 percent of the mean chamber pressure at the lowest mixture ratios, and only 2 to 15 percent at the highest mixture ratios. It is believed that smoother operation at the higher mixture ratios is not necessarily related to the mixture ratio, but rather to the higher oxidant injector pressure drop. Mixture ratio was varied directly with oxidant flow, and the chamber pressure level varied accordingly (fig. 5). Oxidant injector pressure drops were about one-half the chamber pressure at the higher mixture ratios and about one-third at the lower. It is not known whether a different oxidant feed system would improve or aggrevate the oscillations.

The pressure oscillations shown in figure 6 should not impose a severe structural problem at the combustion chamber walls. The values shown are peak to peak, but the stress increment in the walls is related only to a root-mean-square average of one-half the peak-to-peak value.

Fortunately, the oxidant flow of a given gas generator is not completely independent of the operating chamber pressure level. Because operation at a high chamber pressure and low oxidant flow is unlikely, the pressure oscillations may become less significant at the higher operating chamber pressures. Fuel injector pressure drop appeared to have little effect on stability, since in one case the result was the same in spite of a hole burned through the chamber wall into the fuel plenum.

It is difficult to discriminate a single frequency of the disturbances by simple observation of the traces. The frequencies appear to vary randomly from 2 to 3 cycles per second with some very low amplitudes at 9 cycles per second. Pressure disturbances above 3 cycles per second may be neglected when observing the traces because the amplitudes are less than 2 percent of the chamber pressure level. It is believed that the instrumentation yielded good reproductions of the actual pressure disturbances.

Failures. - During the series of operations, several combustion chambers were burned through the fuel plenum. However, one model (fig. 7) was operated for approximately 24 minutes with ten starts and stops. Only a slight deterioration of the wall was observed. Figure 8 shows photographs of two typical failures. The wall of the chamber in figure 8(a) appears to have been melted through by a zone of hot gas at a temperature above the melting point of the metal. Molten metal flowed from the cavity and solidified around the liquid-hydrogen injector holes. The cavity appears to be fairly clean and free from severe oxidation. The burn-through to the fuel plenum was not detected in the overall performance of the gas generator.

The other burnout, shown in figure 8(b), appears to have been caused by severe oxidation of the chamber wall. The warm wall must have been in direct contact with unburned oxygen from a misdirected spray from the liquid-oxygen injector. Neither of these two models was operated more than 3 minutes.

The major difference between the injectors that resulted in burnout and the one that did not was in the method of assembly. The successful injector was fabricated as a single piece and machine-indexed. The poor ones had a separate liquid-oxygen injector face plate that was alined by eye and brazed into the body. This fabrication technique could easily cause misalinement of the impinging jets in addition to misalinement of the face plate to the chamber walls. Thus, excellent alinement between the fuel spray and oxygen spray is apparently required to prevent burnout with the type of injection system used in this investigation.

Igniters. - Two different ignition systems were tried during the investigation, a simple glow plug and a spark igniter (see Ignition System, p. 3). The glow plug was a coil of high-resistance wire that consumed about 100 watts and attained a temperature of about 2000° F at ambient conditions. The glow-plug igniter was unsuccessful, however, because during the fuel lead period its temperature was below 0° F. The ignition temperature required was approximately 1500° F (ref. 3). Further investigation of the glow-plug igniter would require an automatic temperature control to maintain a high temperature in liquid hydrogen without imposing so high a current flow at atmospheric conditions as to cause a glow-plug failure. The spark igniter, on the other hand, never failed to ignite the main propellant flow at oxidant-to-fuel weight

ratios of 0.5 and 1.0. Successful ignition was obtained with the igniter located either in the combustion chamber or just downstream of the exhaust nozzle.

SUMMARY OF RESULTS

Liquid hydrogen and liquid oxygen were burned at oxidant-to-fuel weight ratios from 0.4 to 1.2 in a 0.61-inch-diameter gas generator. The gas generator was constructed with a simple showerhead oxygen injector and radial hydrogen injection around the circumference. Chamber lengths from 6 to $8\frac{1}{4}$ inches and chamber exit Mach numbers of 0.35 and 0.47 had combustion efficiencies of 93 percent, while the 17.6-inch length had 96 percent. The use of injector and chamber design principles developed for rocket engines appears satisfactory to provide high-efficiency gas-generator operation.

Combustion instability was in general related to the liquid-oxygen injection system. The chamber pressure oscillations encountered in this investigation should not severely compromise any structural requirement of the chamber walls.

Several gas-generator and thermocouple failures were encountered during the investigation. These were caused either by a localized gas temperature above the melting point of the material or by oxidation of the material with raw oxygen. Careful alinement of the fuel and oxidant injector holes seemed to prevent rapid deterioration of the chamber walls.

Successful ignition of propellants at oxidant-to-fuel weight ratios of 0.5 and 1.0 was obtained from a pilot flame formed by spark-igniting a small jet of oxygen gas in the main flow of hydrogen.

Lewis Research Center
    National Aeronautics and Space Administration
        Cleveland, Ohio, September 29, 1960

APPENDIX A

GAS-GENERATOR FACILITY AND OPERATION

Research Facility

The gas-generator research facility consisted of a test-cell area and a remote-control area. Figure 9 shows a planview of the facility. The two areas are interconnected by control and instrument cables.

The test cell shown in figure 10, which houses the test bed, is constructed of earth-filled walls 8 feet thick and 15 feet high on three sides. The open side faces downwind of the prevailing winds. The gas-generator exhaust was piped through this end. During the tank filling and gas-generator firing, the roof was opened to prevent any accidental accumulation of hydrogen gas in the cell. Vented hydrogen gas was piped about 300 feet away from the cell and was allowed to escape unburned. Vented oxygen gas was piped about 40 feet away from the open end of the cell. Similarly, the gas-generator exhaust was piped about 20 feet beyond the open end of the cell. Excess hydrogen gas in the exhaust was burned off the end of the pipe with a spark plug as an ignition source.

The control area consisted of a portable control room parked behind an earthen mound. The control room shown in figure 11 contained the operating controls and the data-recording apparatus. It also contained two television monitors for observing the gas generator and the test bed. Burnouts and propellant leaks could thus be detected without personnel in the test cell during operation.

The test bed shown in figure 12 contained the gas generator, the propellant tanks, and all the associated piping to the gas generator. Some of the instrumentation components were housed in the air-conditioned box shown on the end of the bed. Figure 13 shows a schematic diagram of the plumbing on the bed. Both propellant systems are fed by pressurized tanks. These tanks were filled with propellants from transportable Dewar tanks prior to firing. The tank volumes were 75 gallons for liquid hydrogen and 10 gallons for liquid oxygen. Both tanks were of stainless steel with a working pressure of 1200 pounds per square inch gage. The hydrogen tank was vacuum-jacketed, but the oxygen tank was left uninsulated. The propellants were discharged out of the bottoms of the tanks past antivortex baffles. The 3/4-inch-tubing hydrogen feed line was vacuum-jacketed from the tank shutoff valve to the venturi. The remainder of the hydrogen line and the entire 1/2-inch oxygen feed line were covered with closed-cell foamed-in-place plastic. Both flow-control valve bodies were submerged in an open-top liquid-nitrogen bath. A 1/2-inch-thick steel plate served as a fire wall and armor plate between the gas generator and the majority of the piping.

Operating Procedure

The liquid-hydrogen and liquid-oxygen systems were both evacuated and purged with helium gas before filling with their respective liquids.

The hydrogen tank and feed line were evacuated to 150 microns of mercury, while the oxygen tank and feed line were evacuated to 1 millimeter of mercury. Each system was then filled with helium to a pressure of 50 pounds per square inch gage and vented to atmosphere twice prior to the liquid transfer. After both tanks were filled, the supply Dewar tanks were removed and the test-cell area was evacuated of all personnel.

The facility was then ready for a "firing" operation. The first step was to purge the hydrogen feed line and injector plenum from the tank shutoff valve through the cooldown valve and control valve with helium gas at a pressure of 80 pounds per square inch. The oxygen injector plenum on the gas generator was purged with helium gas at a pressure of 150 pounds per square inch starting from the control valve. Both feed lines at this point were free of air and ready to receive their liquids.

Both tanks were pressurized to 50 pounds per square inch gage with regulated helium pressure. Both tank shutoff valves and cooldown valves were opened to allow liquids to flow out the vents. This flow precooled the venturis and remained on until the fluid temperatures had stabilized in both systems. The flow was stopped by closing the cooldown valves. The tank pressures were then increased to an operating pressure of 350 pounds per square inch gage.

The next step was to start the program timer, which was a series of timed relays. The first relay started the 0.08-pound-per-second liquid-hydrogen flow through the gas generator by opening the hydrogen flow-control valve. This relay also turned on the igniter spark and gaseous-oxygen flow. The liquid-oxygen injector plenum was purged at this time with 150 pounds per square inch of helium to prevent a backup of hydrogen into the plenum. After 4 or 5 seconds the next relay commanded the controller to start the gas generator by opening the liquid-oxygen control valve to set the first of six mixture ratios and by stopping the helium purge. After 3 or 4 seconds of operation the igniter was turned off, and the run proceeded through the six mixture ratios with a running time of 20 to 30 seconds each. The liquid-hydrogen flow was maintained at a nominal value of 0.08 pound per second.

The timing out of the sixth-mixture-ratio relay shut off the gas generator by closing the liquid-oxygen control valve. The 150-pound-per-square-inch helium purge to the oxygen injector was again turned on. The hydrogen flow was left on for about 15 seconds and then was shut off manually by closing the hydrogen control valve.

Before allowing personnel to reenter the cell, both systems were put into a "safe" state. The first step was to vent the systems through the tank vents to 50 pounds per square inch gage. Unused liquids were then discharged out the vents through the cooldown lines. After all the liquids had been discharged, both systems were vented to atmospheric pressure. The hydrogen system was filled with helium to 50 pounds per square inch gage, the cooldown valve was opened for 30 seconds, and the feed line was given a flowing purge. The system was then vented to atmospheric pressure again. Three purges of this type were adequate to obtain a negative reading at the vent discharge on a combustible gas analyzer.

Propellant Flow Control

An electrohydraulic control system (ref. 4, appendix B) was used to position the flow-control valves to establish the desired hydrogen flow and oxidant-to-fuel weight ratio. This flow-control system eliminates any flow-metering effect by the injectors and combustion chamber. However, to maintain a desired flow, the tank pressure must be adequate to provide the system with more than the minimum-control valve pressure drop at the desired flow. The hydrogen and oxygen venturis were located in the liquid lines ahead of the control valves where the fluid density was constant, so that the venturi pressure drops could be used as an indication of weight flow. The control set the hydrogen flow by adjusting the hydrogen flow-control valve until a preselected value of hydrogen venturi pressure drop was attained. The oxygen flow-control valve was adjusted until the ratio of oxygen to hydrogen venturi pressure drops attained a preselected value corresponding to a desired oxidant-to-fuel weight ratio. The program timer was used to insure a fuel lead during the starting sequence and a fuel lag at shutdown.

Instrument Calibration

The analog zero and the sensitivity of each pressure channel were determined by impressing a series of known pressures on the transducers. This was done before and after each run to detect any possible shifts of zero and sensitivity during the run.

The temperature channels were treated in much the same way except that known values of precision (± 0.1 percent) resistors were substituted in the bridge circuit for the probe resistor. This method of calibration was based on the assumption that each platinum and carbon resistor maintained its initial sensitivity to temperature. The NASA method of selecting, aging, and calibrating resistors for cryogenic temperature measurements is described in reference 5. For good precision and resolution, the upper ends of the instrument ranges were limited to 200° R for the platinum resistors and 60° R for the carbon. An analog reference was established before and after each run by immersing each probe in its respective liquid under normal atmospheric pressure.

This method of calibration obviates a calibration of the playback system. Thus, the only requirement that must be met by the playback system is that it maintain a constant sensitivity of frequency deviation to analog voltage. It must meet this requirement only during the few minutes required to play the initial and final calibrations, and the data, of each data channel.

APPENDIX B

SYMBOLS

A	effective area of discharge nozzle, sq in.
c^*	characteristic exhaust velocity, ft/sec
g	gravitational conversion factor, 32.174 ft/sec^2
M	molecular weight, lb/lb-mole
P	total pressure, lb/sq in. abs
R	universal gas constant, 1544 ft-lb/(lb)($^{\circ}$R)
T	absolute total temperature, $^{\circ}$R
w_F	fuel flow rate, lb/sec
w_O	oxidant flow rate, lb/sec
γ	isentropic exponent (ratio of specific heats)

REFERENCES

1. Priem, Richard J., and Heidmann, Marcus F.: Propellant Vaporization as a Design Criterion for Rocket-Engine Combustion Chambers. NASA TR R-67, 1960. (Supersedes NACA TN's 3883, 3985, 4098, and 4219.)

2. Mulholland, Donald R., Acker, Loren W., Christenson, Harold H., and Gough, William V.: Flight Investigation of a Liquid-Hydrogen Fuel System. NACA RM E57F19a, 1957.

3. Drell, Isadore J., and Belles, Frank E.: Survey of Hydrogen Combustion Properties. NACA Rep. 1383, 1958. (Supersedes NACA RM E57O24.)

4. Otto, Edward W., and Flage, Richard A.: Control of Combustion-Chamber Pressure and Oxidant-Fuel Ratio for a Regeneratively Cooled Hydrogen-Fluorine Rocket Engine. NASA TN D-82, 1959.

5. Herr, Austin C., Terbeek, Howard G., and Tiefermann, Marvin W.: Suitability of Carbon Resistors for Field Measurements of Temperatures in the Range of 35° to 100° R. NASA TN D-264, 1960.

6. Gordon, Sanford, and McBride, Bonnie J.: Theoretical Performance of Liquid Hydrogen with Liquid Oxygen as a Rocket Propellant. NASA MEMO 5-21-59E, 1959.

TABLE I. - SOME PHYSICAL PROPERTIES OF COMBUSTION PRODUCTS

USING LIQUID HYDROGEN AND LIQUID OXYGEN[a]

Oxidant-to-fuel weight ratio	Gas temperature, ^{o}R	Characteristic exhaust velocity, ft/sec	Molecular weight, lb/lb-mole	Isentropic exponent, γ
0.30	597.1	4913	2.621	1.398
.40	778.1	5416	2.822	1.393
.60	1136.3	6134	3.226	1.385
.794	1474.3	6612	3.616	1.373
.80	1485.2	6627	3.629	1.373
1.00	1822.7	6987	4.032	1.356
1.19	2129.4	7247	4.415	1.340

[a]Extension of data given in reference 6.

TABLE I. - SOME PHYSICAL PROPERTIES OF COMBUSTION PRODUCTS

USING LIQUID HYDROGEN AND LIQUID OXYGEN[a]

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0.30	597.1	4913	2.621	1.398
.40	778.1	5416	2.822	1.393
.60	1136.3	6134	3.226	1.385
.794	1474.3	6612	3.616	1.373
.80	1485.2	6627	3.629	1.373
1.00	1822.7	6987	4.032	1.356
1.19	2129.4	7247	4.415	1.340

[a]Extension of data given in reference 6.

Figure 1. - Calculated relation of oxygen vaporization to combustion chamber length for two oxygen droplet diameters. Chamber pressure, 220 pounds per square inch absolute; oxidant-to-fuel weight ratio, 1.0; chamber exit Mach number, 0.35; injector pressure drop, 50 pounds per square inch; oxygen injector temperature, 180° R.

CD-7027

Nozzle throat	
Throat diameter, in.	Chamber Mach number
0.459	0.35
.520	.47
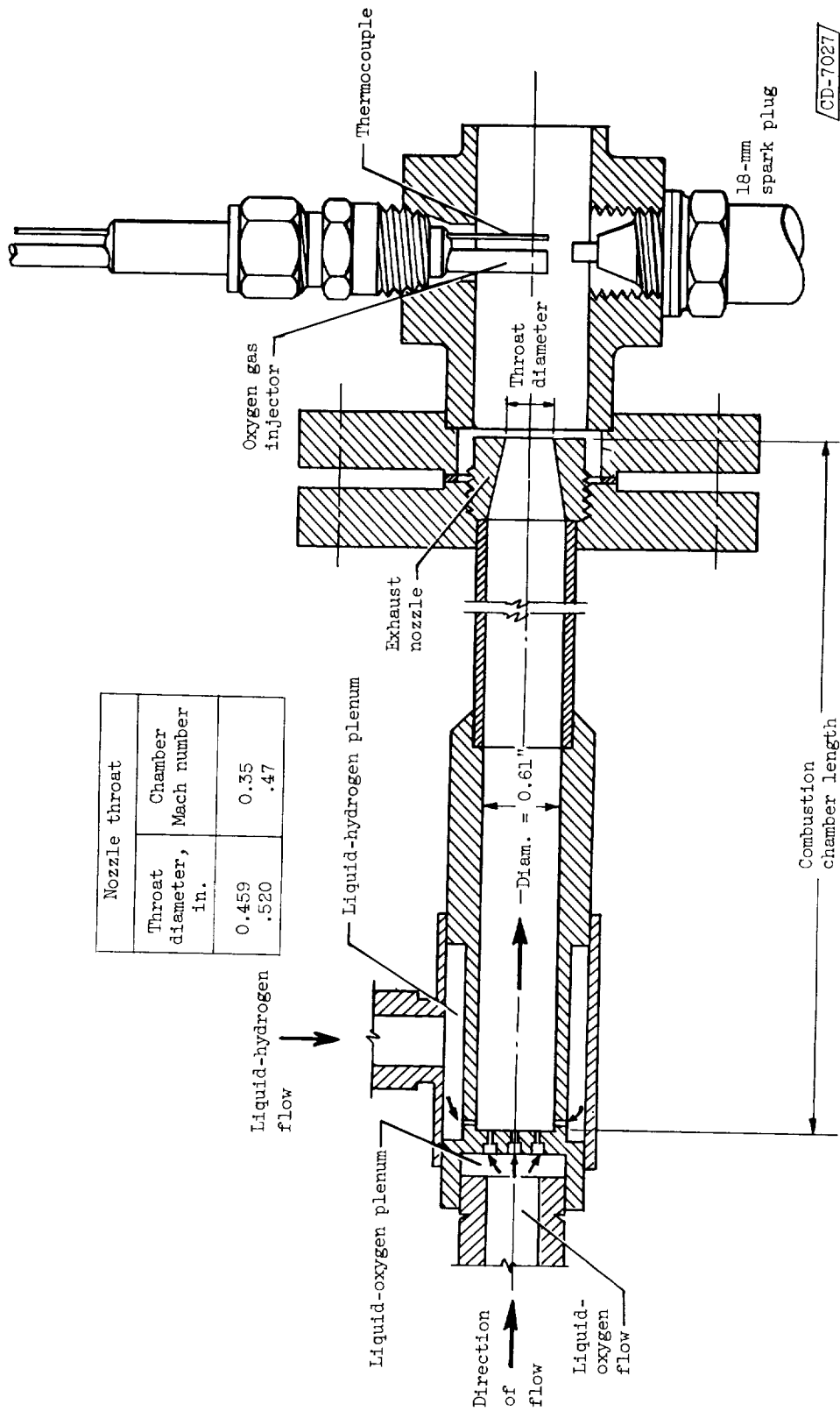
Figure 2. - Typical gas-generator and igniter configuration.

0.035" Diam. by 0.04" long
1.06" C drill
30 Holes

liquid-hydrogen plenum

0.015" Diam.
0.040" C drill (far side)
10 Holes on 0.4" diam. circle

liquid-hydrogen
injection holes

0.0135" Diam.
0.040" C drill (far side)
10 Holes on 0.25" diam. circle

liquid-oxygen
injection holes

Combustion
chamber wall

0.0135" Diam. by 0.04" long
0.040" C drill (far side)
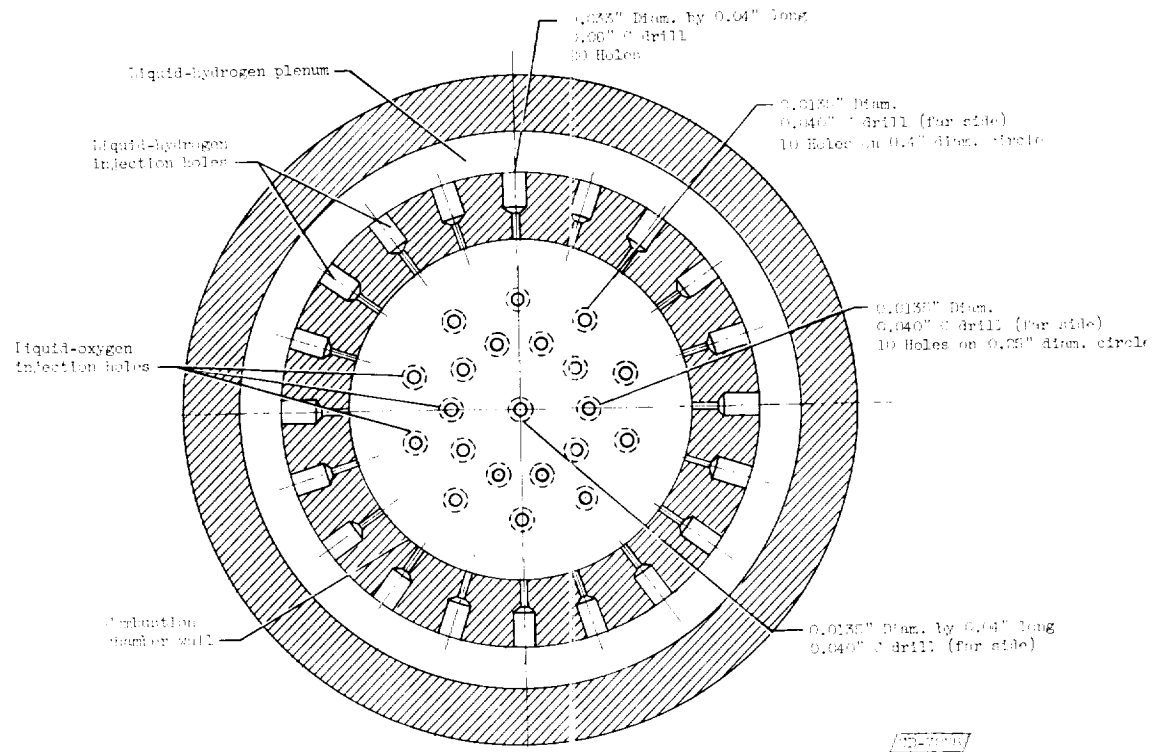
Figure 4. Injector details.
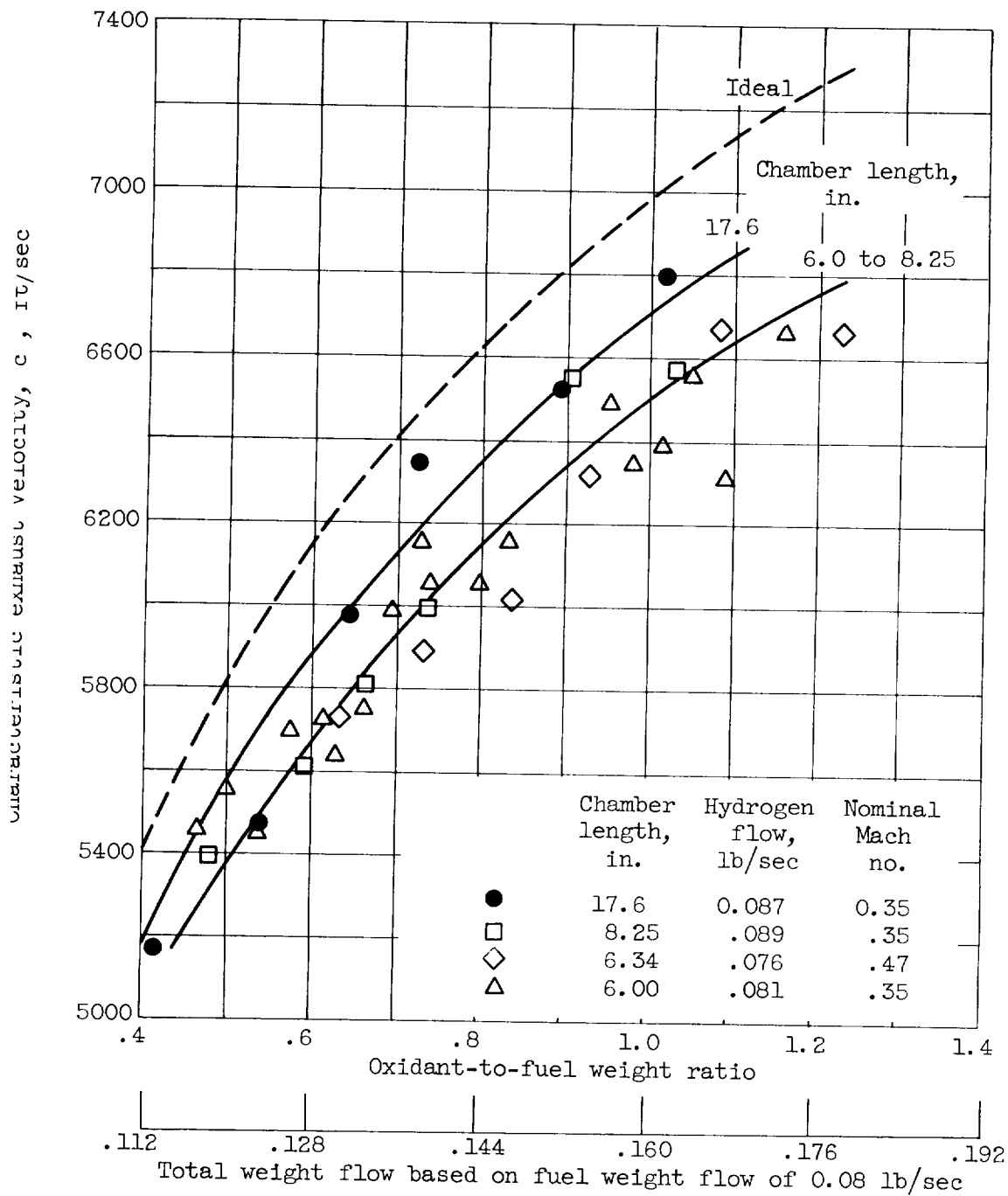
(a) Variation of characteristic exhaust velocity with oxidant-to-fuel weight ratio.

Figure 4. - Steady-state performance.
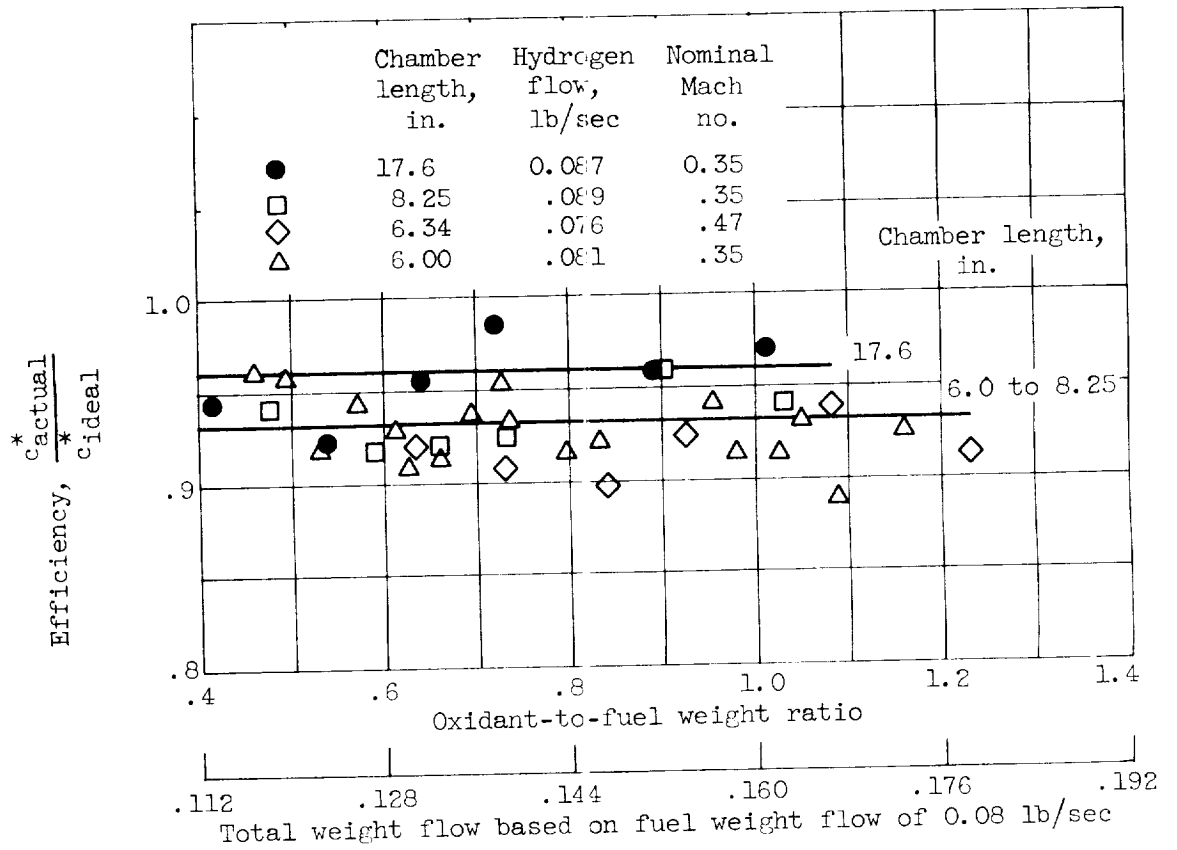
(b) Variation of combustion efficiency with oxidant-to-fuel weight ratio.

Figure 4. - Continued. Steady-state performance.
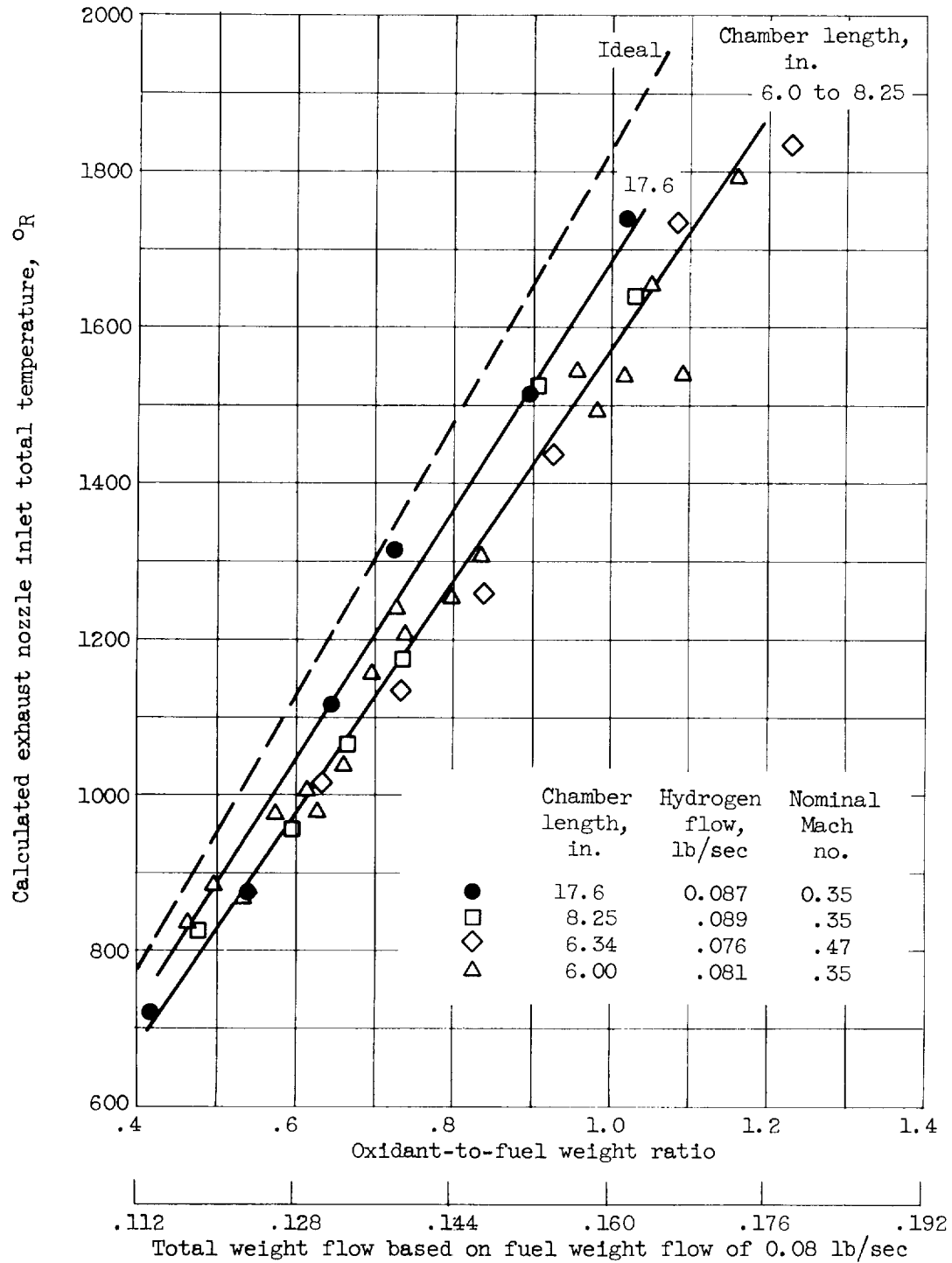
(c) Variation of calculated exhaust nozzle inlet total temperature with oxidant-to-fuel weight ratio.

Figure 4. - Concluded. Steady-state performance.
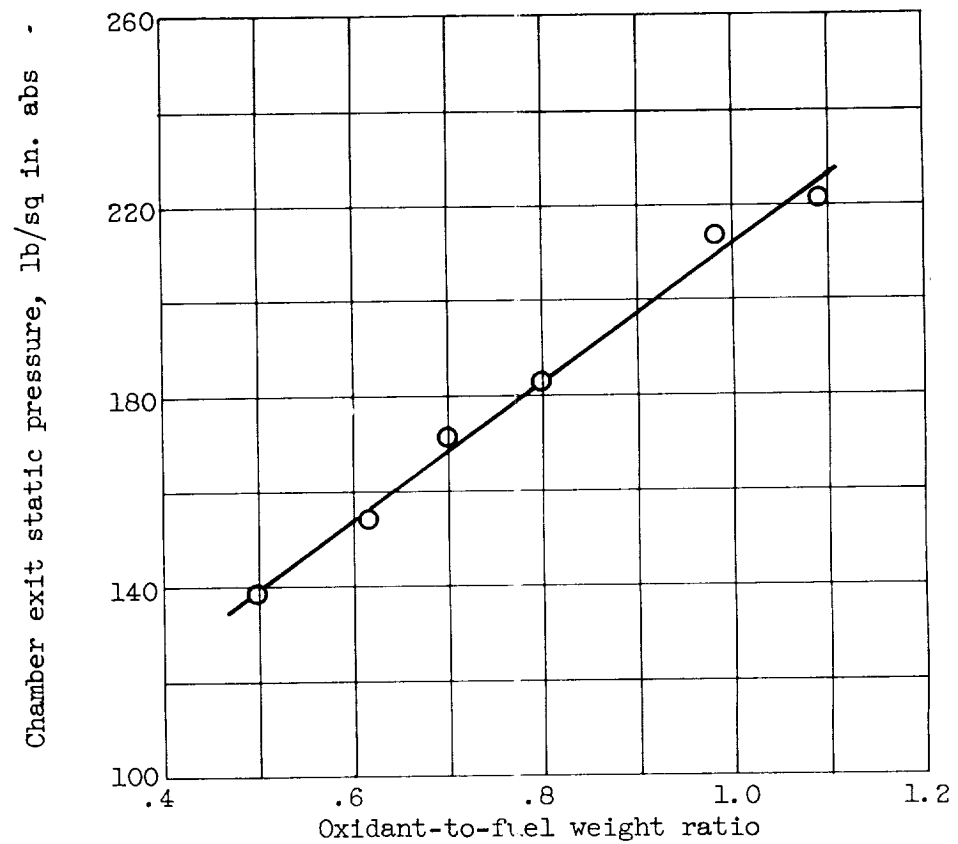
Figure 5. - Typical variation of chamber exit static
pressure with oxidant-to-fuel weight ratio. Hydro-
gen flow, 0.080 pound per second; nominal chamber
exit Mach number, 0.35; chamber length, 6 inches.
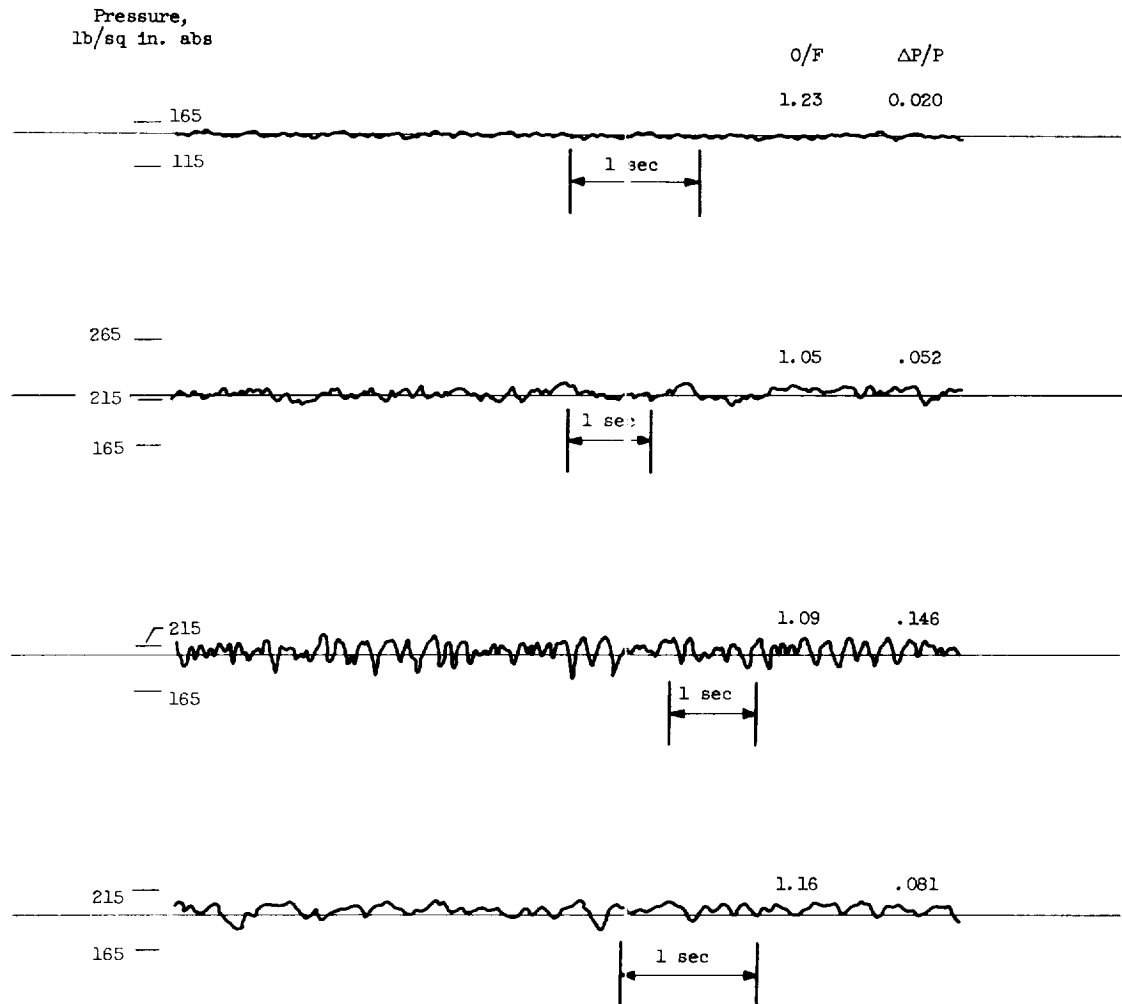
(a) Four runs at high oxidant-to-fuel weight ratios.

Figure 6. - Oscillograph time history of chamber pressure.
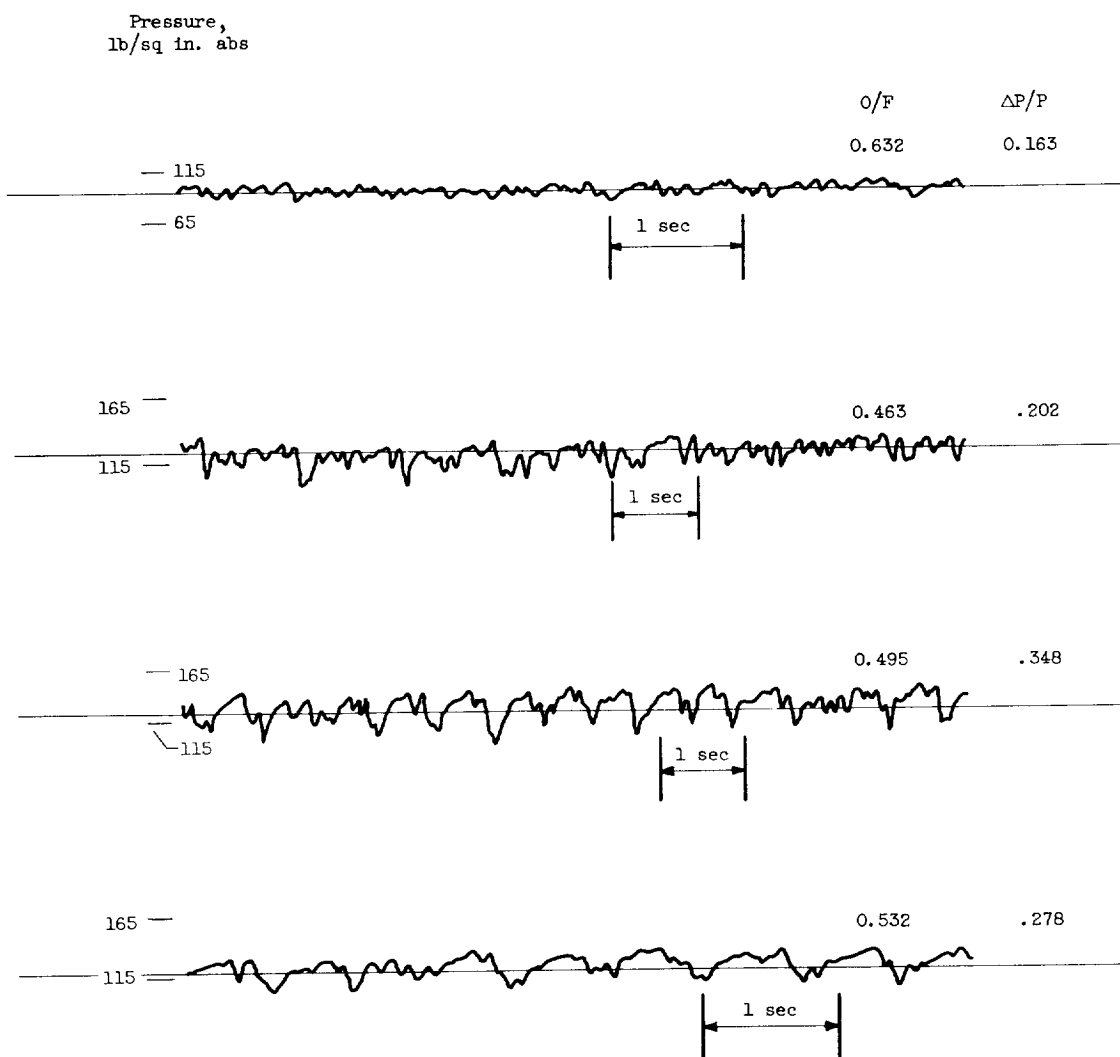
(b) Same four runs at low oxidant-to-fuel weight ratios.

Figure 6. - Concluded. Oscillograph time history of chamber pressure.
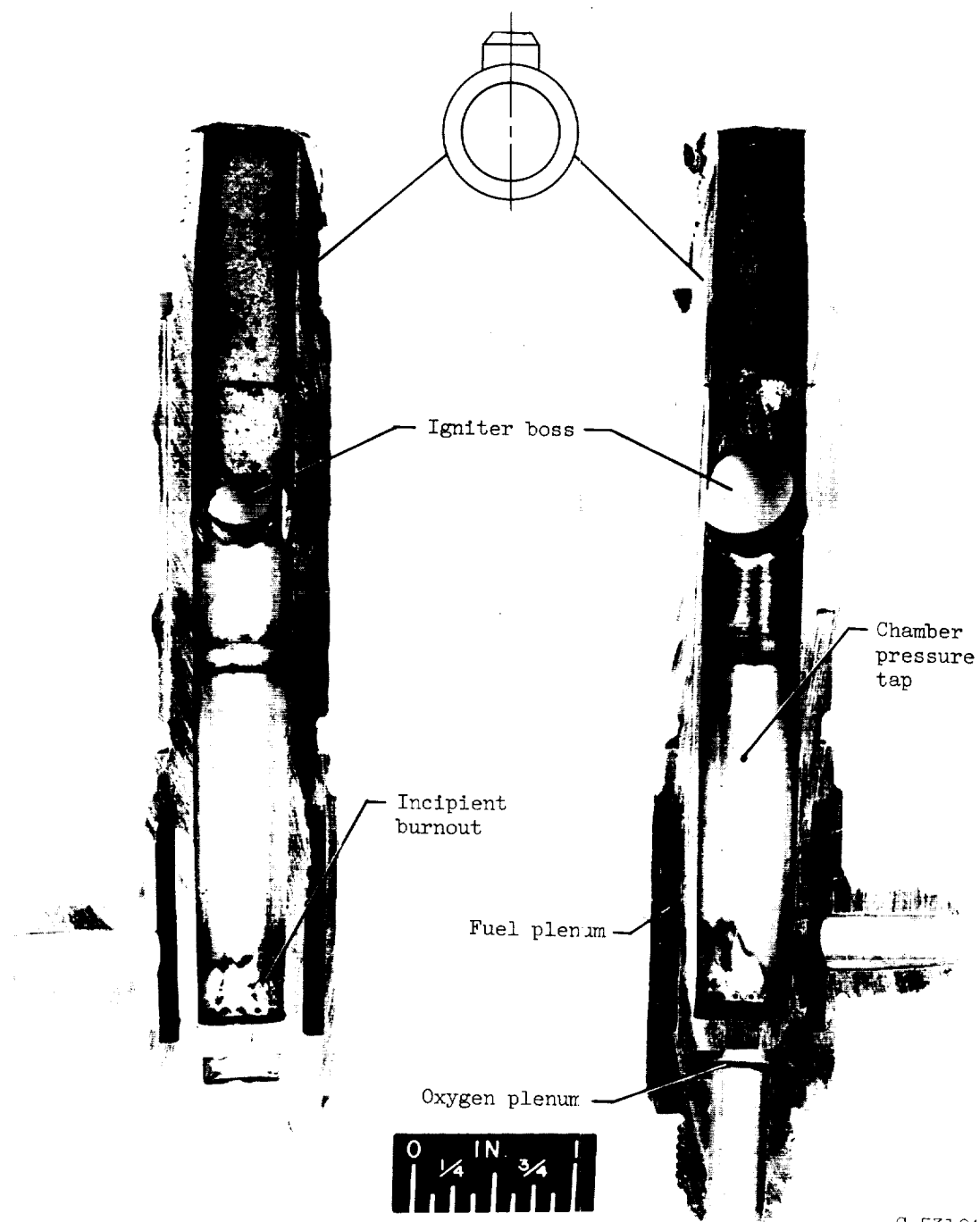
Figure 7. - Gas generator after 24 minutes operation with ten starts and stops.

Melted cavity

Fuel plenum

Oxygen plenum

0 IN. 3/4

C-53105
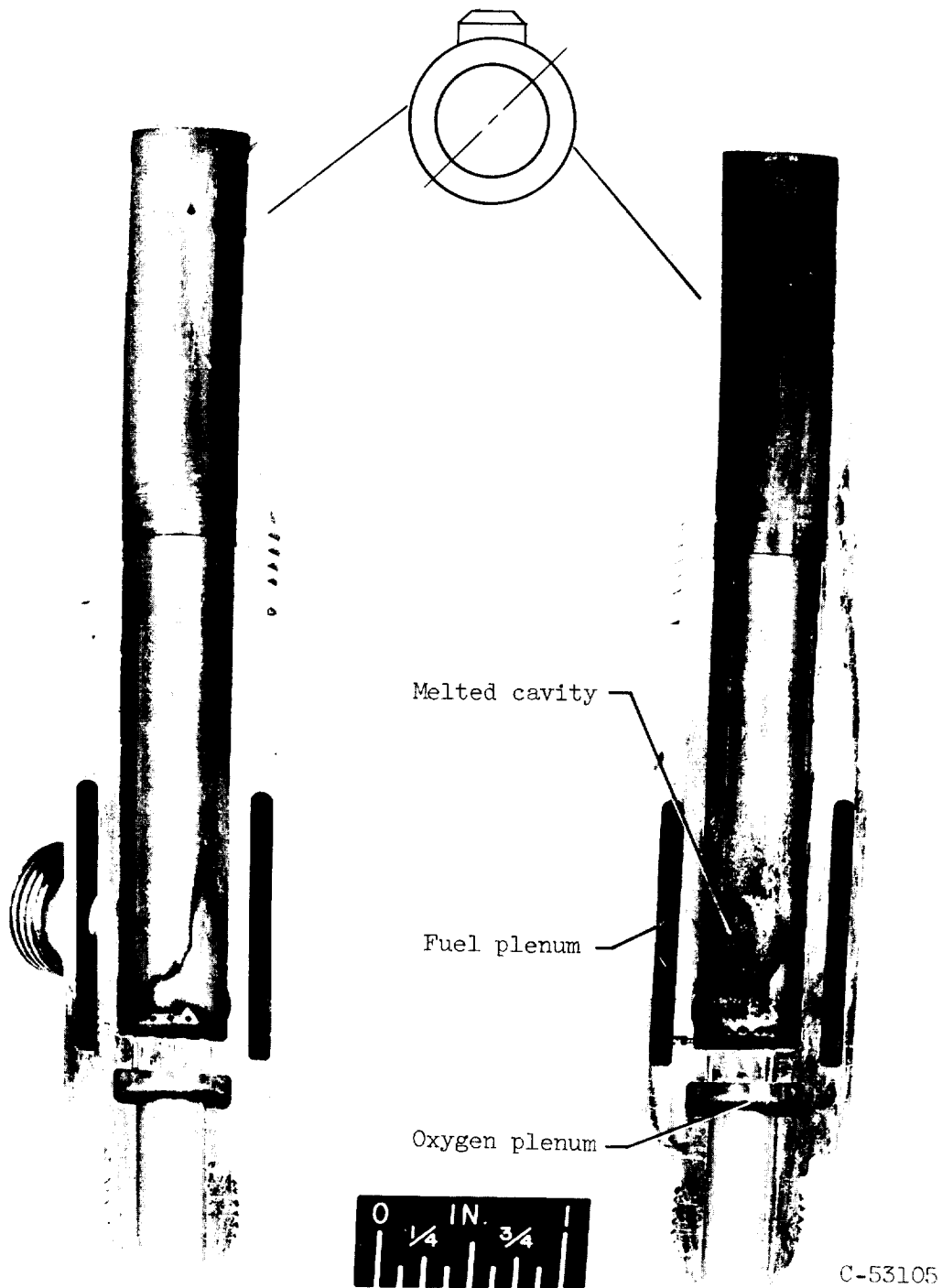
(a) Gas-generator burnout caused by local gas temperature above melting point of material.

Figure 8. - Gas-generator burnouts.

Chamber
pressure
tap

Oxidized cavity

Fuel plenum

Oxygen plenum

C-53103
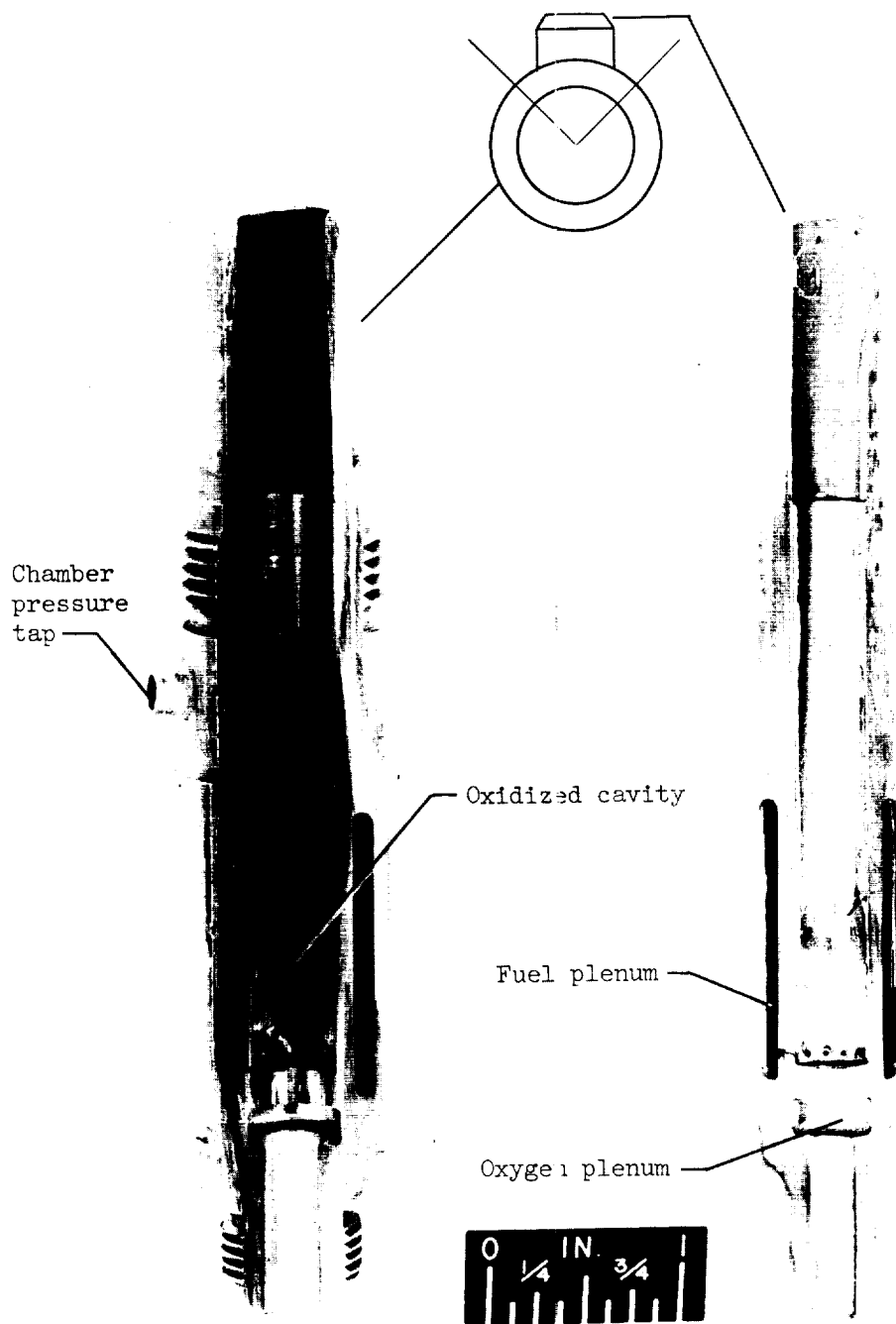
(b) Gas-generator burnout caused by contact of liquid oxygen with wall.

Figure 8. - Concluded. Gas-generator burnouts.
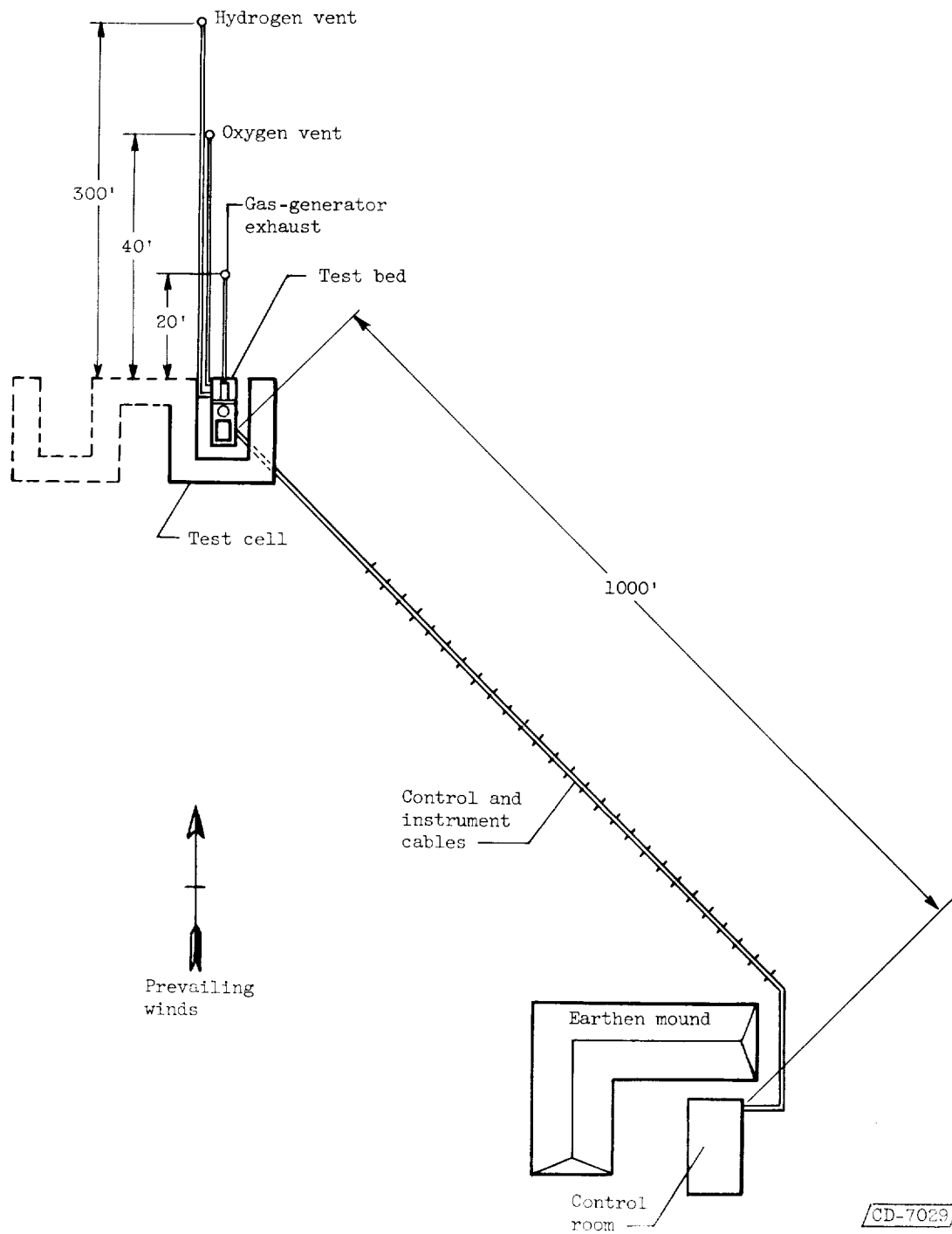
Figure 9. - Gas-generator facility planview.

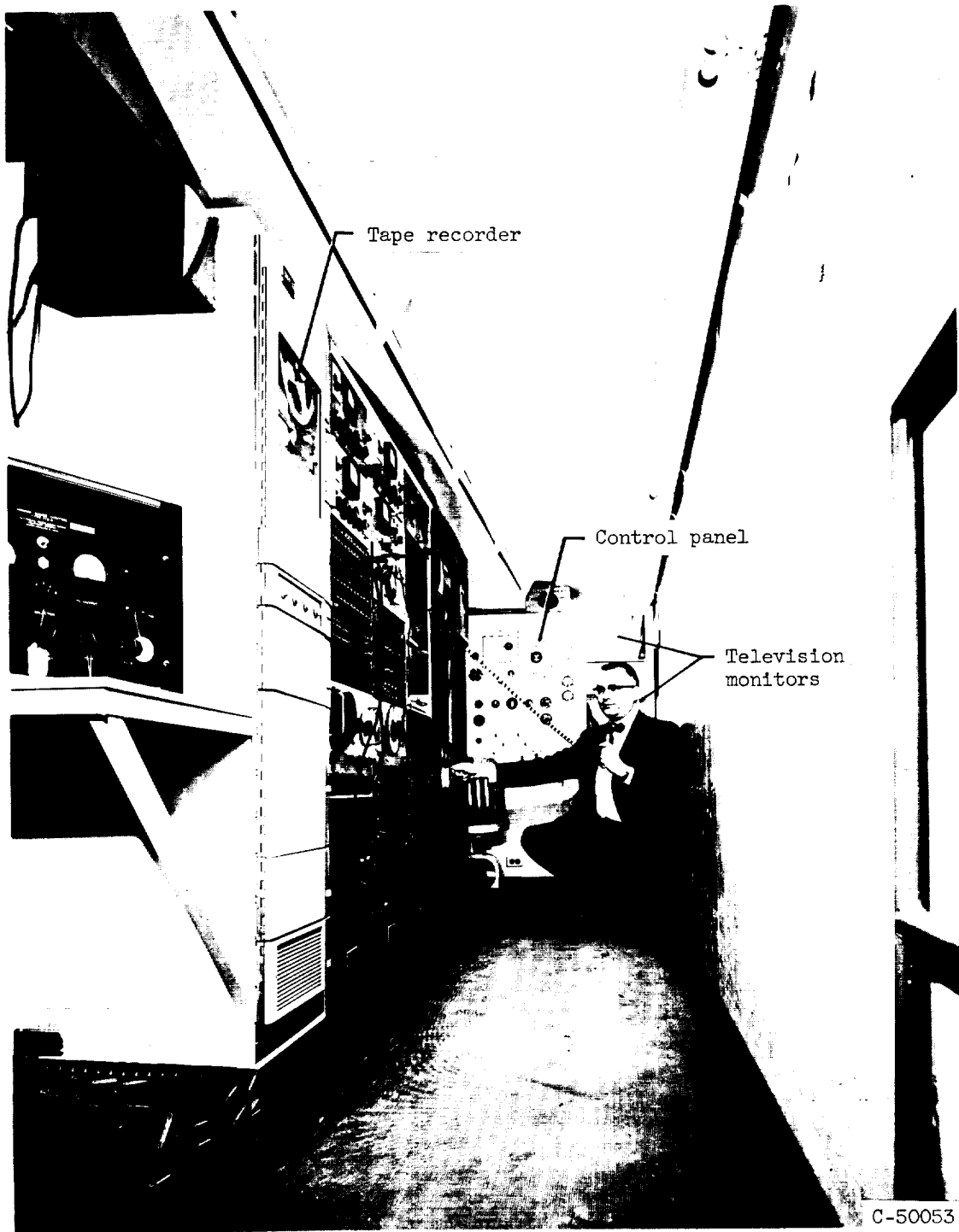Figure 10. - Aerial view of gas-generator facility.
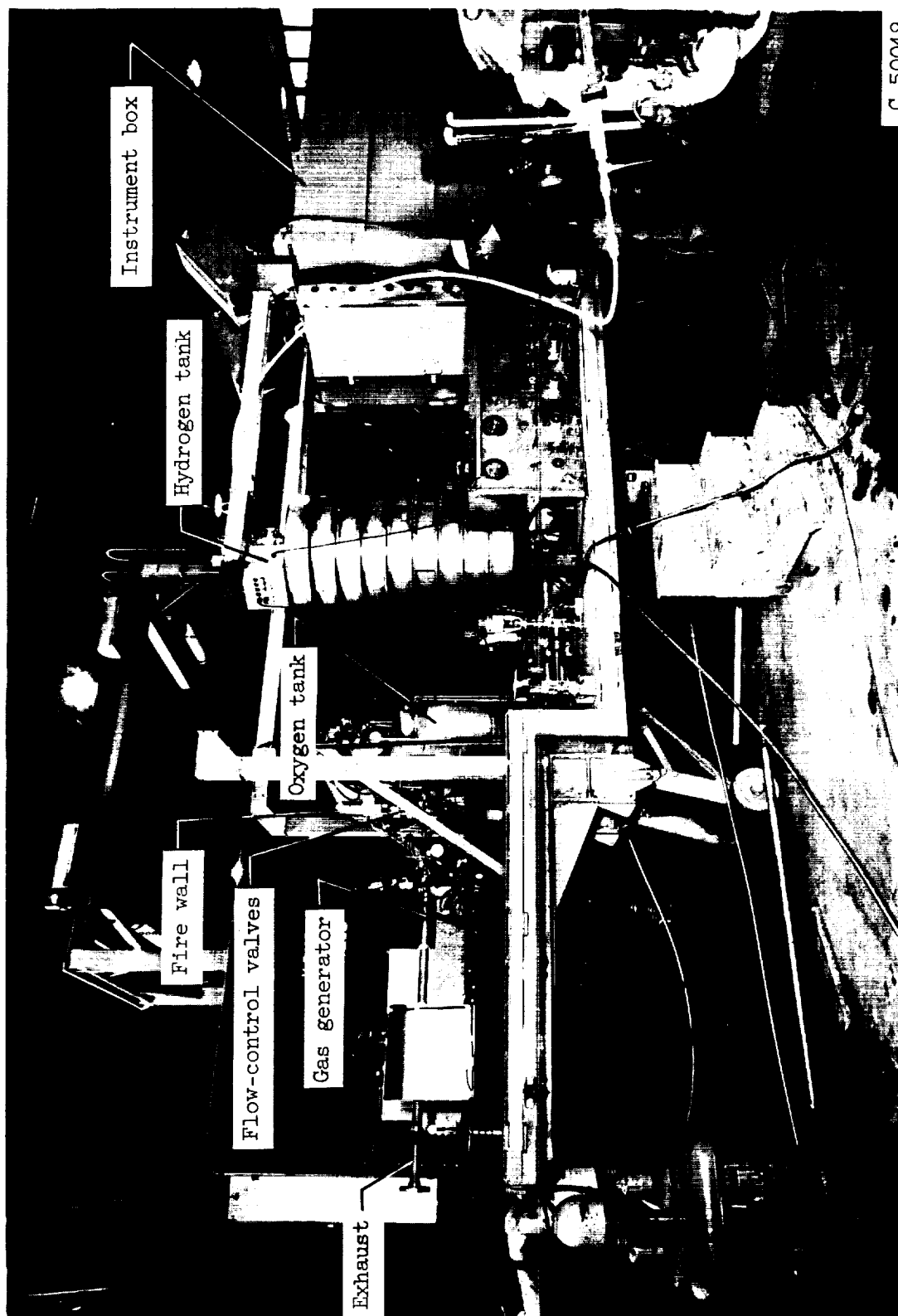
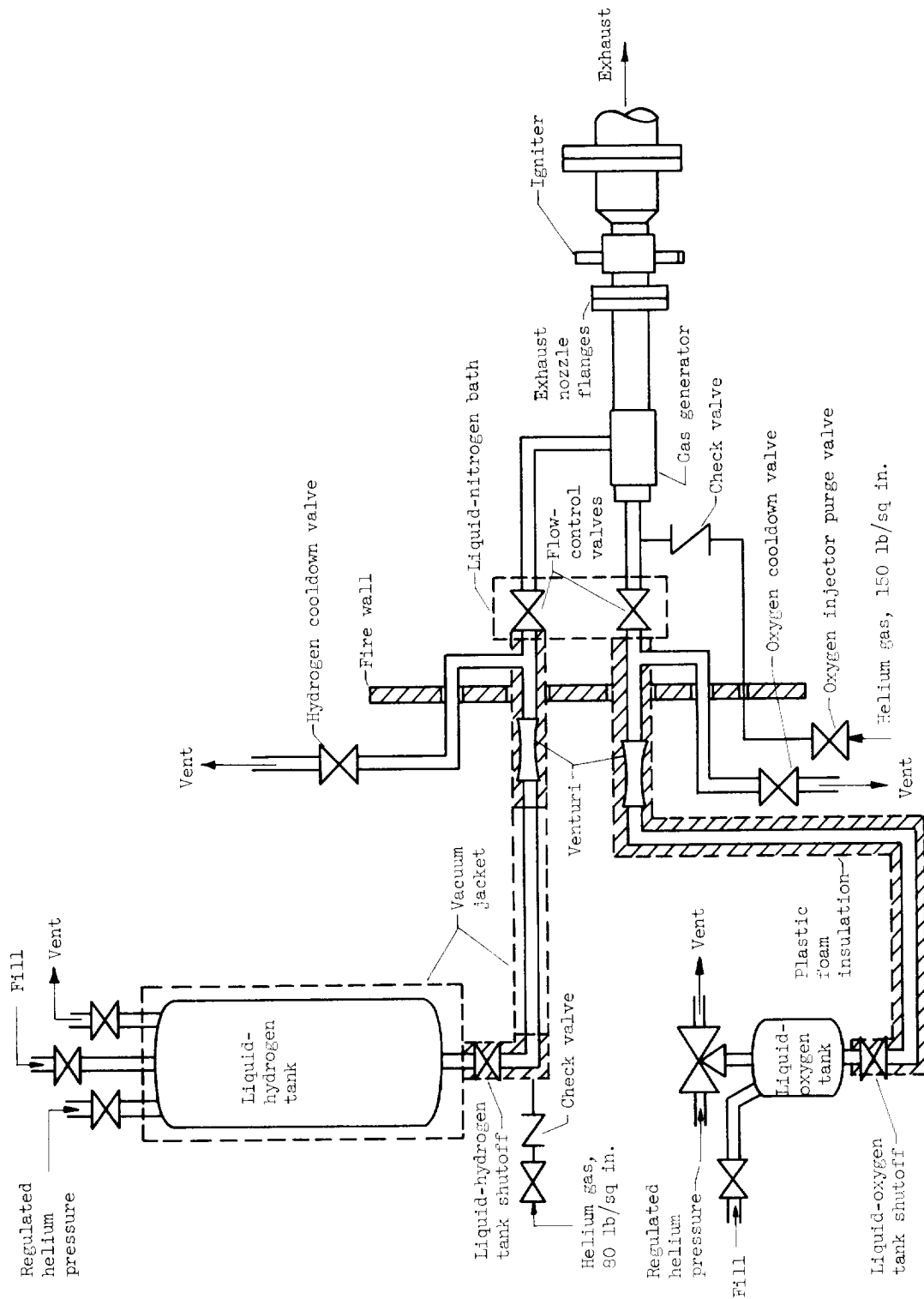Figure 11. - Gas-generator control room.

Figure 12. - Gas-generator test bed.

Figure 13. - Schematic piping diagram of gas-generator test bed.

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