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ANALYSIS OF ADVANCED FLIGHT VEHICLE HEAT EXCHANGER FIRE AND EXPLOSION HAZARDS (U)

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Bureau of Mines
U. S. Department of the Interior

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Air Force Aero Propulsion Laboratory
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FOREWORD

This report was prepared by the Explosives Research Center of the U. S. Bureau of Mines under USAF Delivery Order 33(615)64-1007, Project No. 6075, "Flight Vehicle Hazard Protection," Task No. 607504, "Fire and Explosion Hazards of Flight Vehicle Combustibles." It was administered under the direction of the Research and Technology Division, Wright-Patterson Air Force Base, with Mr. Benito Botteri as project engineer. The report covers work done during the period January 2, 1964 to April 30, 1965, and is the final report on this contract.

ABSTRACT

The use of highly compact and lightweight hydrogen heat exchangers envisaged for advanced flight vehicles has introduced problems associated with flight safety. A hydrogen leak permitting the hydrogen gas to mix with high temperature ram air can result in autoignition of the gas-air mixture with subsequent failure of the entire heat exchanger. In this work, heat exchangers were simulated by placing one or more hydrogen bearing tubes in a heated air stream. The leaks were simulated with various diameter holes (.0135-.040-inch) drilled through one wall of the tubes. Air mass velocity through the test section was varied from 1 to 38 lbs/ft^2 sec. and the temperature of the heated air was varied to obtain the minimum air temperature to effect ignition of the gas-air mixtures. Ignitions were obtained with tube holes as small as 0.0135-inch diameter and hydrogen leak rates up to 0.56 SCFM. The ignition temperature fell between 1000° and 1300°F and increased with increasing air flow rate.

This report has been reviewed and is approved.

Arthur V. Churchill

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INTRODUCTION

Advanced flight vehicles can involve new means of propulsion that introduce problems associated with flight safety. For some vehicle configurations, air-breathing propulsion systems are proposed in which hydrogen heat exchangers are to be utilized to cool high temperature ram air. Prototype heat exchangers currently being developed consist of compact tube bundles (Ref. 1). The tubes themselves are very thin-walled and of high strength material. The difficulty of sealing the tube ends to the headers has introduced the possibility of leaks and failures. A hydrogen leak in such systems could be a great hazard since the air temperatures may be sufficiently high to effect autoignition of hydrogen-air combustible mixtures formed as a result of the leak. Accordingly, the present work was conducted to investigate the fire and explosion hazards which may be associated with the leakage of hydrogen from aerospace plane type heat exchangers under expected operating conditions. Specifically, experiments were made to determine the temperatures at which hydrogen gas leaking from simulated heat exchanger tubes can ignite in a heated air stream at various air and hydrogen flow rates.

As a part of this research, a large pebble-bed heater was constructed to provide the necessary heated air for conducting ignition experiments at temperatures up to 2000° F. This report covers the classified portion (Section III) of work conducted for the Air Force under Delivery Order 33(615) 64-1007. The unclassified work done under this contract (Sections I and II) is presented in AFAPL-TR-65-28.

Manuscript released by authors August 1965 for publication as an RTD Technical Report.

EXPERIMENTAL APPARATUS AND PROCEDURE

Ignition temperature and gas leakage experiments were conducted with heated or unheated hydrogen leaking from simulated heat exchanger tubes into air under various flow conditions. The facility employed in the initial experiments is described in other reports (Refs. 2 and 3). It consisted of an air compressor, four large air receivers used as blow-down tanks (total capacity 2000 ft^3), flow metering equipment, and a pebble-bed heater for heating the air. However, because of mechanical failure of the air compressor in this facility, two air-cooled compressors were substituted; their combined capacity was 166 CFM and their pressure rating 250 psig. In addition, the pebble-bed air heater of the above unit was found inadequate for continuous use at the elevated temperature and flow conditions required in this work. Therefore, another pebble-bed heater was designed and constructed. This heater was designed to provide air at 250 psig and 2000°F and is described in the appendix of this report. An additional heater was installed in the system for heating the hydrogen. This unit consisted of a gas-fired burner which heated the hydrogen flowing through a section of coiled tubing.

Five test sections were constructed for use in the ignition and gas leakage experiments. Test Section I consisted of a 1/8-inch od stainless steel tube (hydrogen tube) that was mounted diametrically in a section of 2-inch schedule 40 pipe. To inject hydrogen, a 0.040-inch diameter hole was drilled in the 1/8-inch tube at the axis of the 2-inch pipe; the hole was also positioned to face downstream in the flowing air. Test Section II was the same except that the hole of the hydrogen tube was smaller (0.0135-inch).

Test Sections III and IV contained three and eight hydrogen tubes, respectively, mounted in a rectangular tube (1.25-inch x 0.593-inch). Here, the hydrogen tubes were constructed of Hastelloy-X material, 1/8-inch od with a wall thickness of 4 mils. Aside from the number of tubes, the structure and dimensions of both sections were the same; a drawing of Test Section III is shown in Figure 1. (The geometry of tube pattern in the multiple tube test sections is the same as specified in Exhibit A, Purchase Request No. 6918 and is also shown in Figure 1). Figures 2 and 3 are photographs of the three-tube model showing an external view and an internal view looking through the rectangular air chamber of this model. The hole for injecting hydrogen was 0.004-inch diameter and was centrally located in the middle tube, facing downstream. In the eight-tube model, the same size hole was in the center tube of the upstream row of tubes; thus, hydrogen issuing from the hole would impinge on the two downstream row of tubes. The latter tube model is of interest for determination of the damage which may result to the adjacent tubes in the event of a hydrogen leak and subsequent ignition in an air stream.

Considerable difficulty was experienced in the fabrication of Sections III and IV. Furthermore, although a set of these sections passed a static pressure test (275 psia), both units developed excessive leaks or failed structurally under the elevated temperature and flow conditions of this work. These failures were not unexpected since the same difficulties have been experienced by others (Ref. 1). The main problem is the brazing of the thin-walled Hastelloy tubes to the headers; here, the brazing was performed with a No. 52 (AMS4778) Coast Metal Powder in a hydrogen atmosphere as recommended. Although a non-oxidant atmosphere is used, it is not entirely possible to eliminate some reaction between the Hastelloy-X tube and the brazing compound. Reaction tends to weaken the tube and result in a poor bond between the brazed pieces. The tubes may then fail structurally or develop excessive leaks as observed in our work.

In a preliminary run with Test Section III, one of the side tubes failed structurally. An attempt was then made to replace all three tubes and rebraze the joints. However, in drilling out the old tubes, it was not possible to keep the hole diameters within the 0.002-inch maximum oversize and the subsequent brazing was ineffective. Upon the initial heating of Test Section IV, leaks occurred at the brazed joints and the attempt at rebrazing was unsuccessful. Because of these failures, quantitative data were not obtained in the ignition temperature experiments with Test Sections III and IV.

The fifth test section (V) used in this work is shown in Figure 4. This section was designed to determine the ease of ignition of hydrogen gas if the leak occurs in a tube surrounded by other tubes in a heated air stream. Essentially, it consisted of 10, 1/8-inch od stainless steel tubes mounted in a section of 2-inch pipe similar to the mountings in Test Sections I and II. The matrix of the hydrogen tubes was in the form of a triangle with 4 tubes in the first row and 3, 2 and 1 tubes in the second, third and last rows, respectively, the apex of the triangle being downstream. The center tube in the second row (3 tubes) was the only tube which transported hydrogen. It had a 0.0135-inch hole located on the axis of the 2-inch pipe facing downstream. To reduce large voids near the pipe walls, filler blocks were placed inside the 2-inch pipe such that the width of the air passages at the sides of the first row was equal to 1/2 the width between tubes (see Figure 4).

In the ignition experiments, ignition of the hydrogen gas escaping into the flowing air was generally detected by visual observation. Fine bare wire thermocouples were employed in some instances but these proved unsatisfactory at high flow conditions. In practice, there were sufficient impurities in the air stream so that the flame was visible to the naked eye. Ignition in Test Section V was also detected by a protected thermocouple used to determine the air temperature. It was located approximately one inch downstream from the nearest (apex) tube of this section. When ignition occurred, the hydrogen flame inpinging on the downstream tubes heated these tubes, which in turn elevated the temperature of the air noticeably - as measured by the thermocouple. Several other methods were examined for detecting the hydrogen flames. These included closed circuit television, image converter tubes sensitive to blue radiation, and a commercial ultra-violet flame detector. However, none of these proved adequate as they either could not detect the flame, or they could not be positioned close enough to the test section to be useful.

RESULTS AND DISCUSSION

1. Hydrogen Leak Rate

The volumetric rate of hydrogen issuing from the holes in heat exchanger tubes was determined as a function of differential pressure across the hole. The leak rate was determined for two hole sizes, 0.0135-inch and 0.004-inch, at a gas temperature of 70° F. With Test Section II (0.0135-inch hole) the data were obtained under essentially stagnant conditions in the heat exchanger tubes (Figure 5); that is, the flow of hydrogen was confined to that issuing from the leak. With the 0.004-inch hole, data were obtained with Test Section III under stagnant conditions as above and under flow conditions in the heat exchanger tubes (Figure 6); here, hydrogen was permitted to flow through the leak and the normal outlet of the tubes for the flow condition. The hydrogen mass flow rate for the flow condition was 16 lbs/ft^2-sec.[1/] which is approximately the rate required in mode II operation as stated in Exhibit A, Purchase Request No. 6918. There appeared to be little variation between the results found under stagnant and flow conditions with Test Section III.

From Figures 5 and 6, it can be seen that maximum hydrogen leak rate was achieved at a differential pressure of about 55 psi (0.56 SCFM) with Test Section III (0.004-inch hole). At these critical flows, the hydrogen velocity would be expected to be sonic in each of these tube holes and equal to about 4300 ft/sec. According to flammability data in the literature (Ref. 4), hydrogen concentrations between 4 and 75 volume percent in air are flammable at atmospheric pressure. Therefore, if complete mixing were to occur, an assumed leakage of hydrogen (0.56 SCFM) from a 0.0135-inch hole under sonic conditions could form uniform flammable mixtures in an air stream where the air flow rate is in the range of 0.18-13.4 SCFM or 0.013-0.96 lbs/ft^2-sec;[2/] similarly, for the 0.004-inch hole (Test Section III) and hydrogen leak rate of 0.40 SCFM, they could form at an air flow rate within the range 0.13-9.6 SCFM or 0.12-8.4 lbs/ft^2-sec. However, complete mixing is not effected immediately and all possible compositions from lean to rich exist in the zone of mixing between the issuing jet of hydrogen and the air stream; furthermore, the limits of flammability tend to widen with increasing temperature. Accordingly, ignition can result in the mixing zone at elevated temperatures, even though the hydrogen leak is less than that required to produce uniform flammable mixtures; this is the case in some of the ignition experiments discussed in the next section of this report.

1/ Based on the minimum free flow area of the hydrogen tube.
2/ Based on the minimum free flow area of the test section.

The leak rate of Test Section V (triangular matrix model) is also shown in Figure 5. Here, maximum flow was not obtained with differential pressures up to 100 psi, the difference between hydrogen tube and air chamber pressures. Although the hole diameter (0.0135-inch) is the same as for Test Section II (single tube model), free expansion of the hydrogen gas emitting from the hole apparently did not occur because of confinement by the neighboring tubes.

2. Ignition Temperature Experiments

The minimum air temperature required to achieve ignition of initially unheated hydrogen injected into an air stream was determined as a function of air flow rate ($\leq$ 27 lbs/ft^2-sec.) for Test Sections I (0.040-inch hole) and II (0.0135-inch hole). The rate at which hydrogen was injected into the air stream within a 2-inch pipe was varied by increasing the pressure within the hydrogen tube; when ignition did not occur, the pressure was increased to a maximum of 265 psia (1.4 SCFM) with Test Section I and 345 psia (0.56 SCFM) with Test Section II. These experiments were made with the normal outlet of the hydrogen tubes closed so that the flow of hydrogen was that issuing from the leak or hole in the given tube into the air stream.

Figure 7 shows the variation of ignition temperature with air mass velocity obtained in the experiments with Test Section I (0.040-inch hole). The air temperature required for ignition increased consistently with an increase in air mass velocity; this result is expected since ignition temperatures generally increase with increasing air dilution and with decreasing fuel contact time with a heat source. The following expression may be used to define the curve for the ignition temperature data obtained with Test Section I, as illustrated in Figure 7:

$$T_{air} = 76 \ln G_{air} + 1005 \qquad (1)$$

where T_{air} is the minimum air temperature for ignition in °F and G_{air} is the air mass velocity between 1 and 21 lbs/ft^2-sec. (16 and 336 SCFM).

A hydrogen flow rate of at least approximately 0.4 SCFM was required to obtain ignition at the highest air flow rate (21 lbs/ft^2-sec.) in the above experiments; the latter air flow rate corresponds to about 336 SCFM for the 2-inch pipe used here. If complete mixing of the hydrogen and air is assumed, the hydrogen concentration would have been about 0.1 volume percent and the resultant mixture would not have been flammable. Thus, ignition had to occur near the point of hydrogen injection where flammable mixtures could exist; observations made in these experiments indicated that the ignitions did indeed occur near the hydrogen leak but did not propagate throughout the hydrogen-air stream. These results were somewhat analogous to those observed by other investigators in the ignition of combustible gases by jets of hot air or other gases (Ref. 5).

The data obtained with Test Section II (0.0135-inch hole) did not vary greatly from those found with Section I (0.040-inch hole). Figure 7 shows a comparison of these data. The curve drawn to represent the datum points for the smaller size hole is shifted upward and diverges with increasing air flow rate from the curve indicated for the Test Section I data. This behavior was expected since the maximum hydrogen flow employed (e.g. sonic flow) was greater for the larger diameter hole. In addition, hot gas ignition temperatures increase with a decrease of jet diameter; although the hydrogen jets issuing from the tubes of each test section may be poorly defined, it is safe to assume that the smaller size jet would be associated with the smaller size hole. The curve for Test Section II data may be defined approximately by the following expression:

$$T_{air} = 103 \ln G_{air} + 970 \quad (2)$$

where G_{air} is between 4 and 25 lbs/ft^2-sec. (56 and 350 SCFM).

Ignition experiments with Test Section V, consisting of a triangular matrix of 10 tubes, were conducted using heated (400-550° F) and unheated hydrogen which issued from a 0.0135-inch hole in a tube located near the center of the matrix. Here, the hydrogen flow through the hole was $\leq$ 0.25 SCFM and the air mass velocity was varied between 6 and 38 lbs/ft^2-sec. (15.7 and 100 SCFM). It is evident from Figure 8 that the air temperatures required for ignition of the escaping hydrogen were not influenced significantly by heating the hydrogen to between 400° and 550° F. This is not surprising since the temperature and heat flux of the air stream were much greater than that of the hydrogen jet. The air pressure in the above experiments was between 16 and 26 psia. When the air pressure was increased to 65 psia, the ignition temperatures increased from about 1200° to 1300° F at an air mass velocity of 15 lbs/ft^2-sec. This increase is probably due to air dilution effects since the hydrogen flow was limited and the ignition temperatures would be higher at low fuel concentrations. The ignition temperatures obtained with Test Section V at 16 to 26 psia air pressures also tended to be slightly lower than those found with Test Sections I and II at approximately the same air pressure. Apparently, the air velocity and dilution effects on the ignition temperatures were less pronounced in the case of hydrogen leakage within the triangular tube matrix (Section V). Where such leakage is sufficiently isolated from the air stream, it is possible for ignition to occur under near-stagnant conditions and the ignition temperatures could be as low as about 1005° F (autoignition temperature of hydrogen in quiescent air). In any event, these data indicate that ignition of hydrogen escaping from a hole $\geq$ 0.0135-inch into a heated air stream $\leq$ 38 lbs/ft^2-sec. can occur at air temperatures between approximately 1000° and 1300° F. Of course, any leak which does occur in a tube can be expected to become enlarged with time and conditions for ignition and flame propagation will tend to be more optimum. At the same time, higher temperatures will be required for ignition as the air mass flow is increased.

CONCLUSIONS

Pin hole leaks which may develop in hydrogen heat exchanger tubes present an ignition hazard when the leakage occurs in quiescent or moving air which has been sufficiently heated. Ignition can be obtained with a tube hole or leak at least as small as 0.0135-inch diameter, depending on the hydrogen flow rate, air flow rate, and air temperature; here, hydrogen leak rates up to 0.56 SCFM (sonic conditions) and air mass velocities between 1 and 38 lbs/ft^2-sec. were employed. Although ignitions occurred under these flow conditions, flame did not propagate throughout the hydrogen-air stream because of air velocity and dilution effects. The ignition temperatures fell between about 1000° and 1300° F and they increased with increasing air flow rate and air pressure.

REFERENCES

1. Development of Manufacturing Processes for a Lightweight Heat Transfer System. AirResearch Manufacturing Co., Interim Engineering Progress Report, IR 8-258(II), January 31, 1965.

2. Zabetakis, M. G., G. S. Scott, A. Imhof and S. Lambiris. Research on the Flammability Characteristics of Aircraft Hydraulic Fluids, Part II. Wright Air Development Center, WADC Technical Report 57-151, March 1959.

3. Furno, A. L., J. Corry and M. G. Zabetakis. Evaluation of Proposed Dyna-Soar Hydrogen Disposal System. Aeronautical Systems Division, AF(33-657)-62-403, Final Report No. 3869, November 30, 1962.

4. Coward, H. F. and G. W. Jones. Limits of Flammability of Gases and Vapors. Bureau of Mines Bull. 503, 1952, 155 pp.

5. Vanpee, M. and A. Bruszak. The Ignition of Combustible Mixtures of Laminar Jets of Hot Gases. Bureau of Mines RI 6293, 1963, 84 pp.

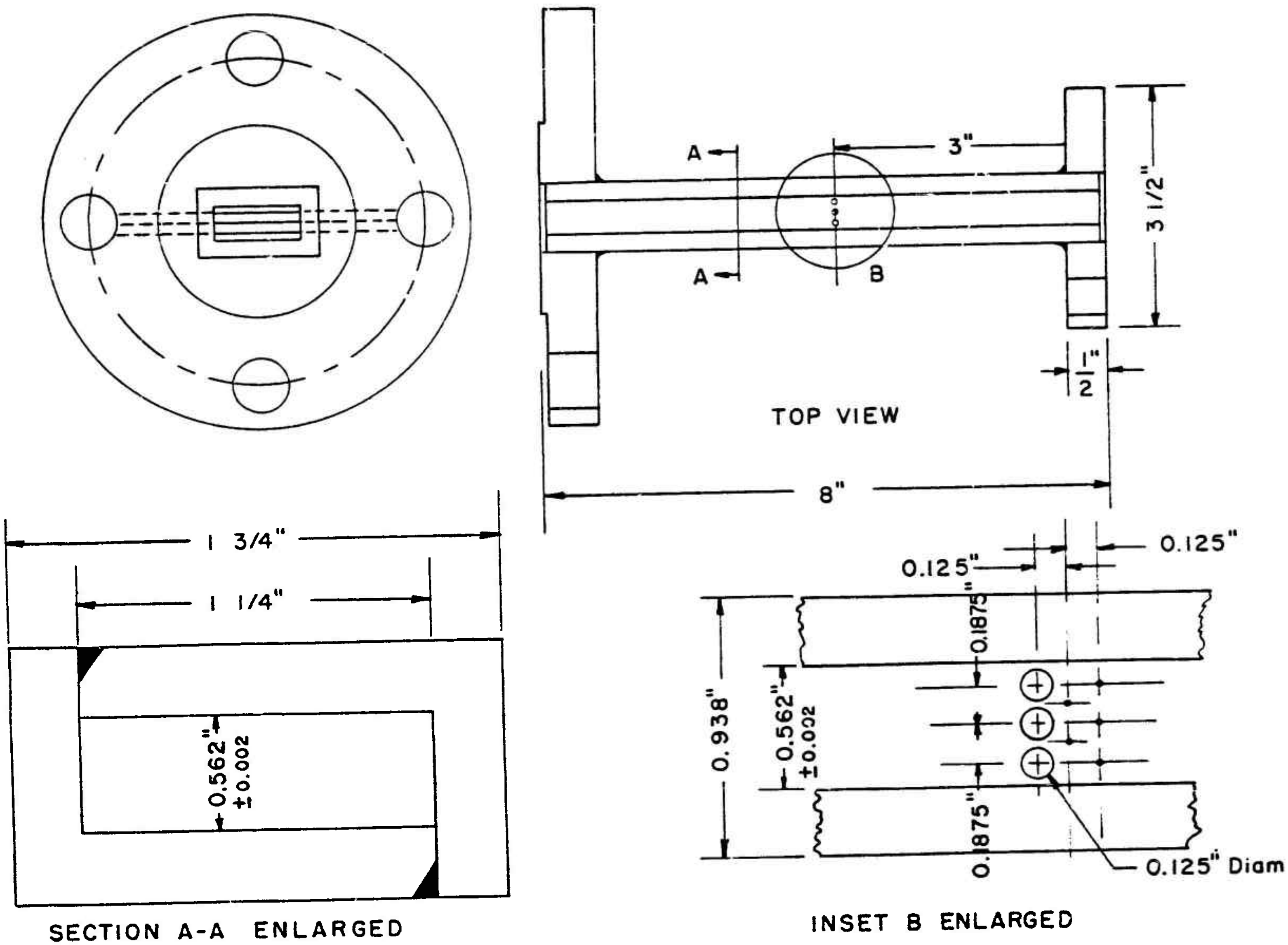

Figure 1. Drawing of simulated heat exchanger test section III.

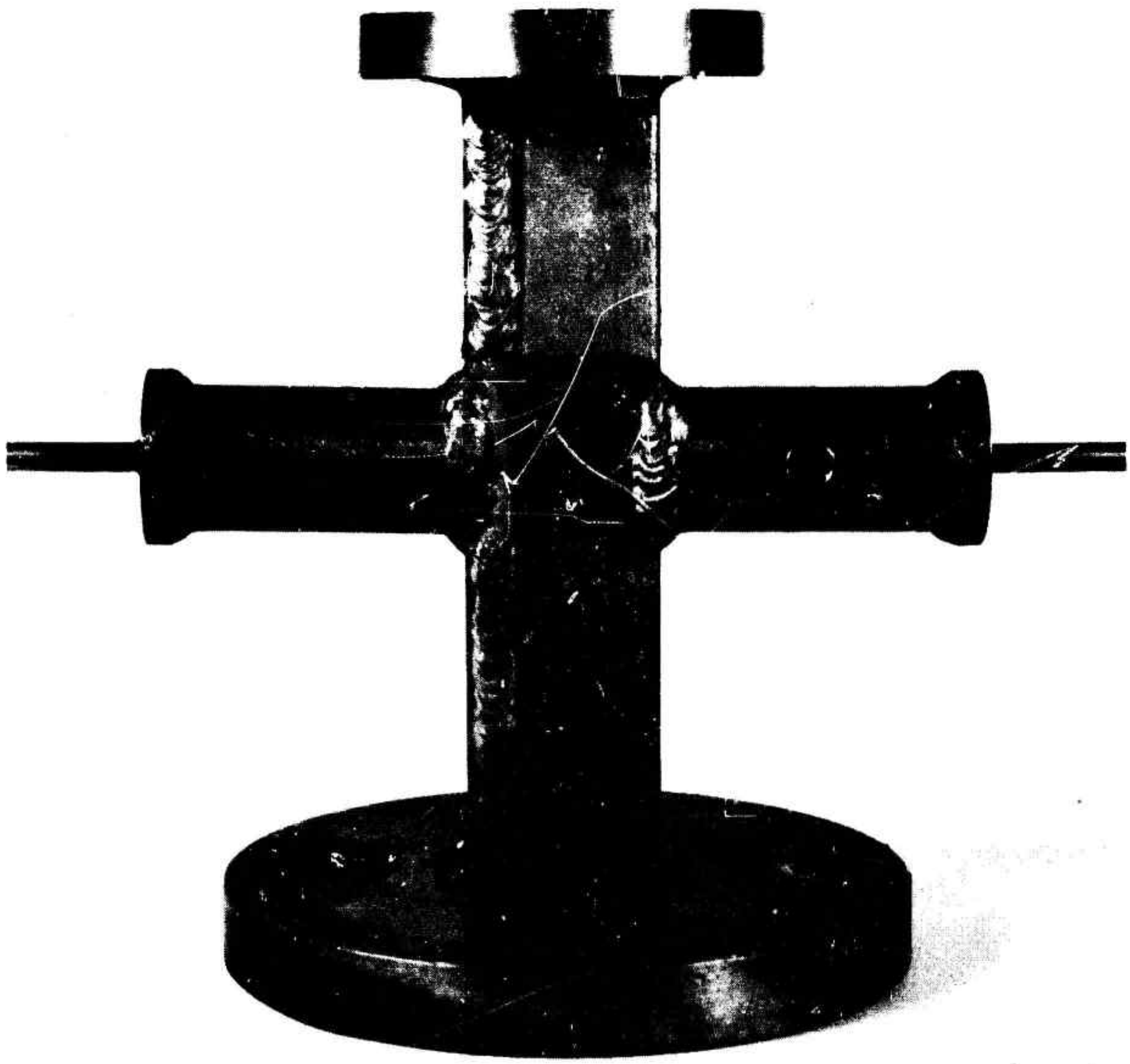

Figure 2. Test section III for simulating hydrogen heat exchanger.

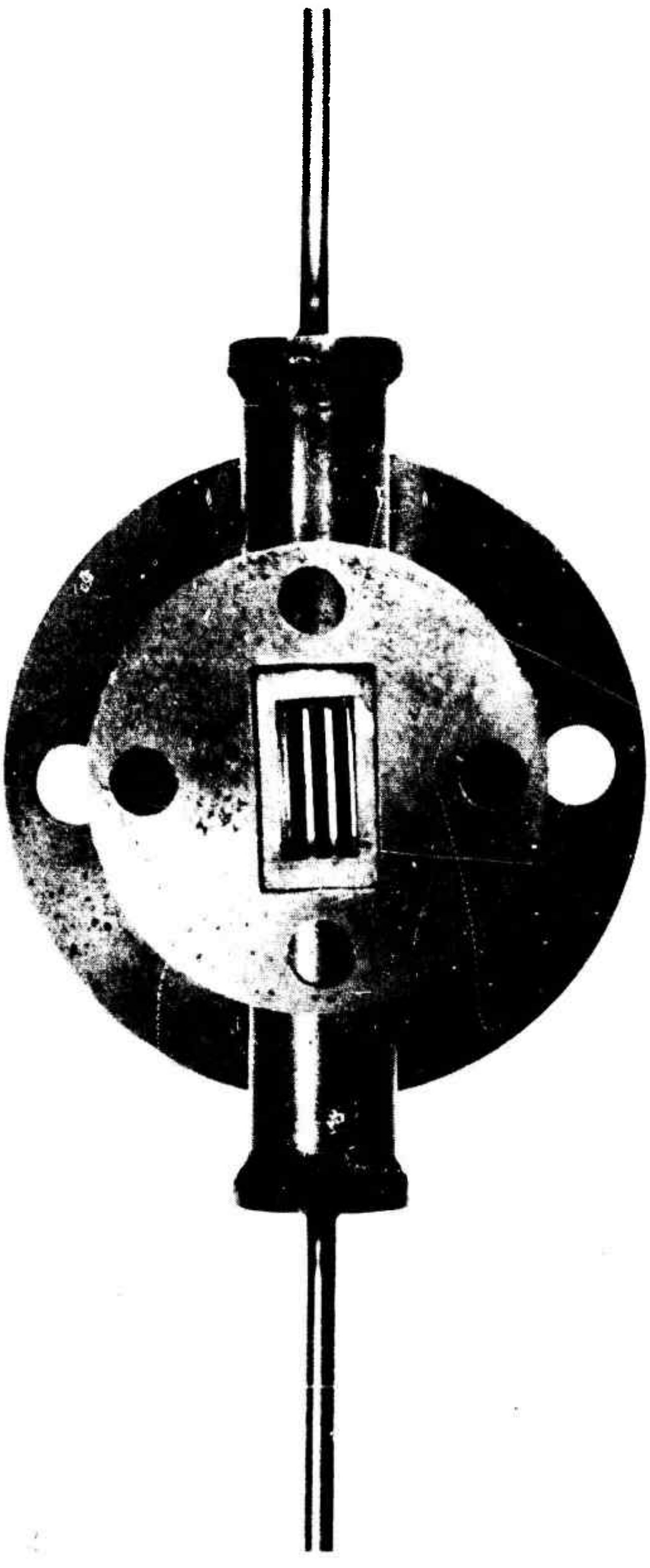

Figure 3. Internal view of test section III showing three hydrogen tubes.

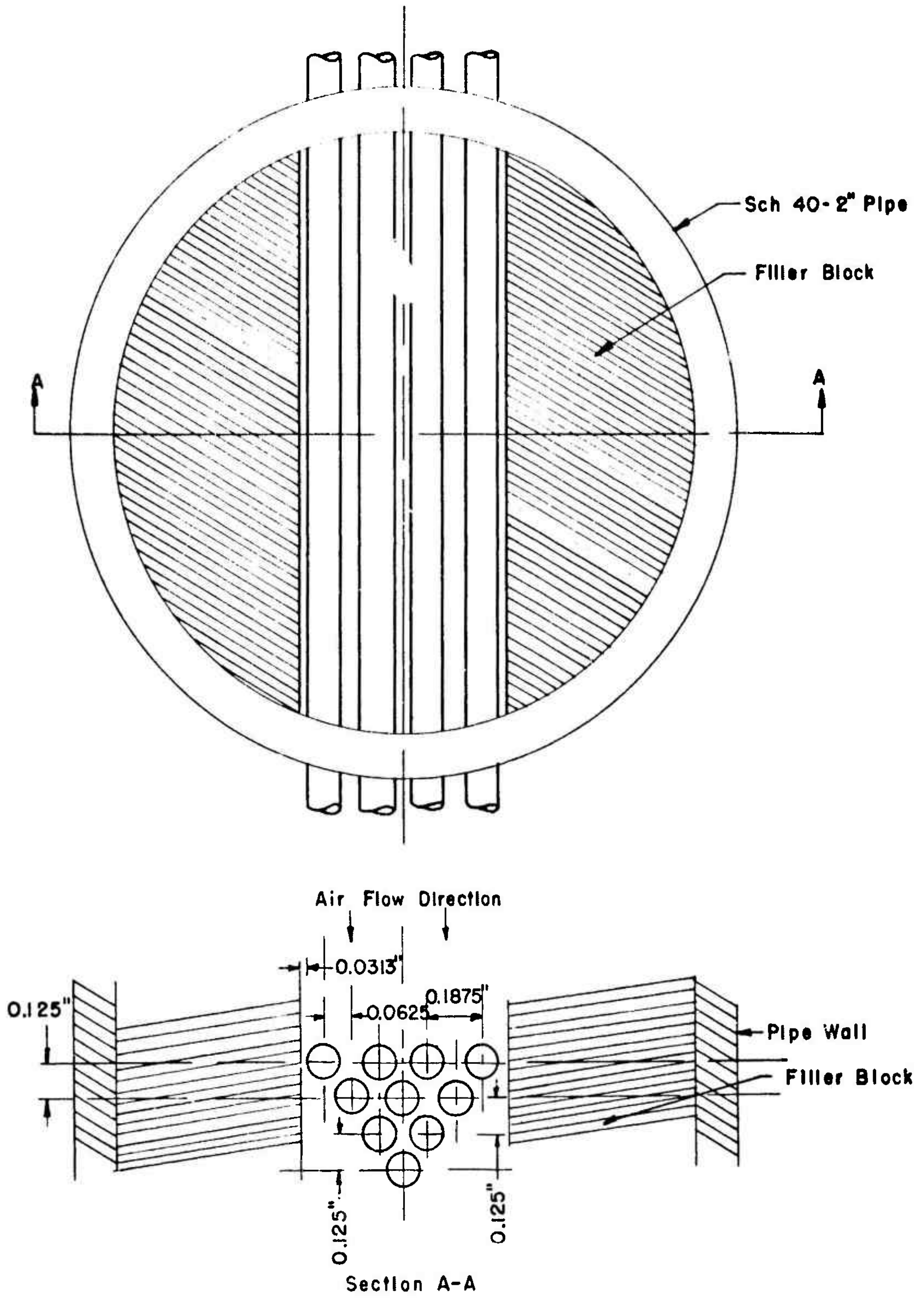

Figure 4. Drawing of simulated heat exchanger test section V.

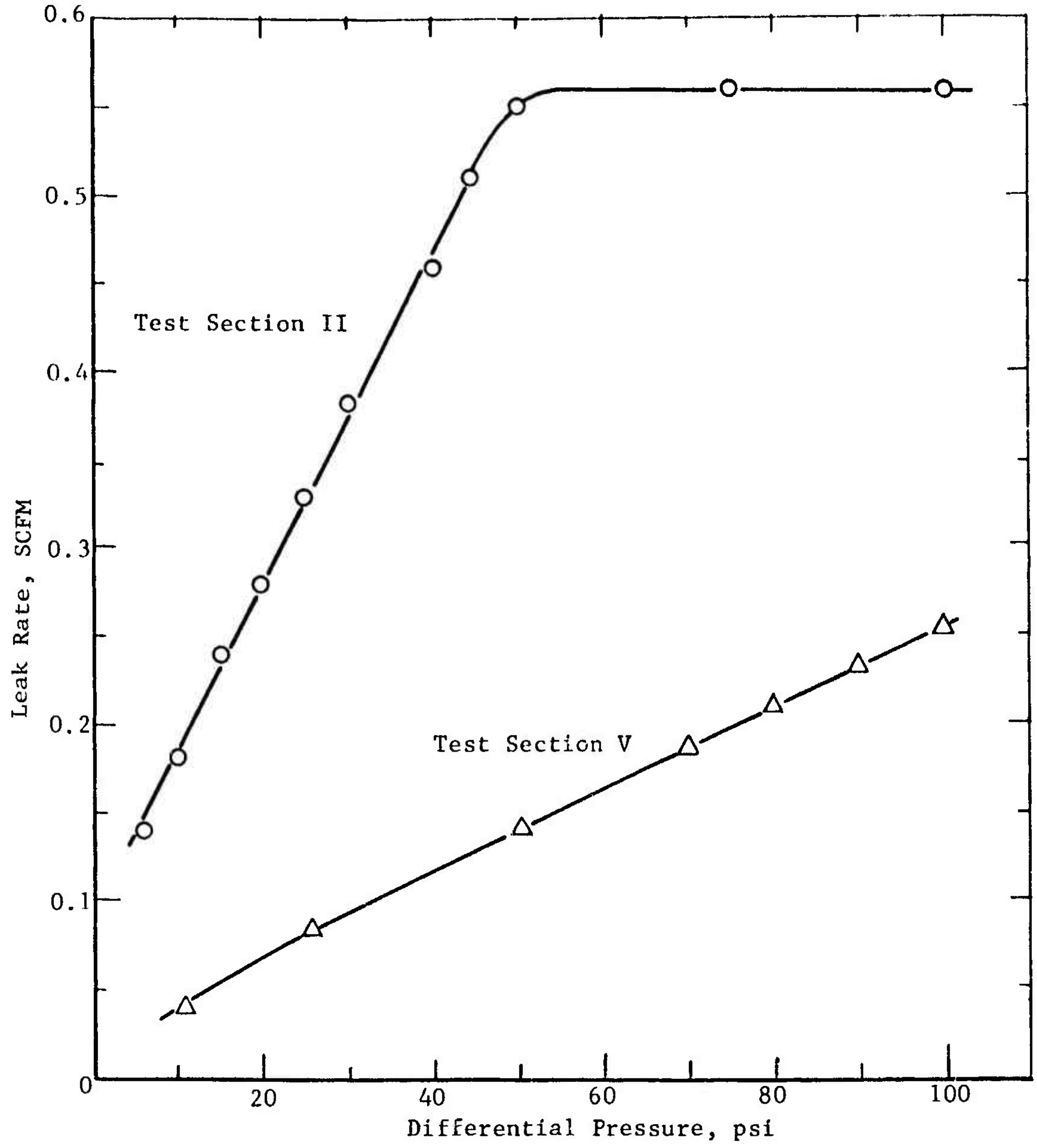

Figure 5. Hydrogen leak rate versus differential pressure for a 0.0135-inch hole with single tube test section II and multiple tube test section V under static conditions in the hydrogen tubes. Hydrogen gas temperature 70°F.

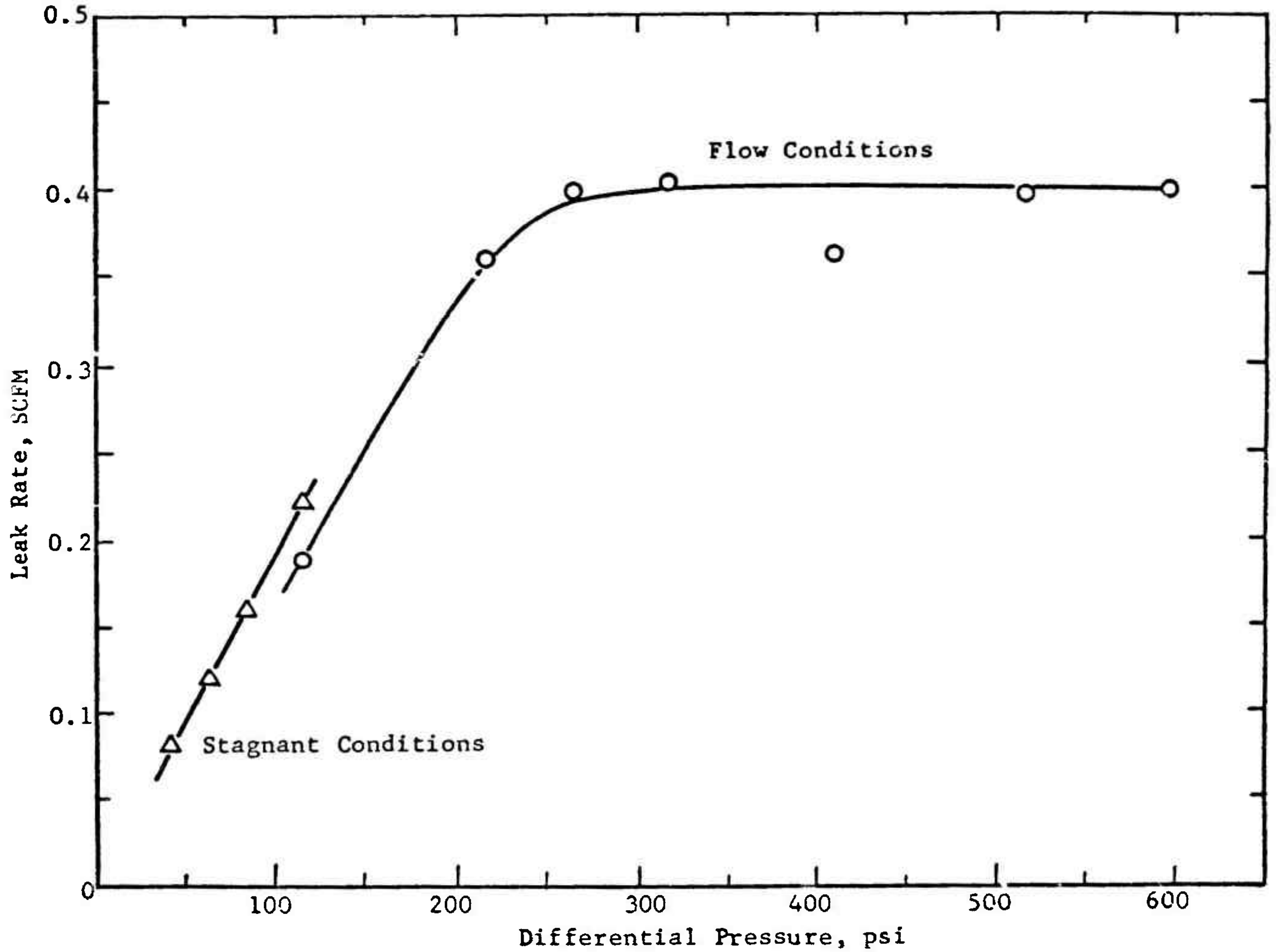

Figure 6. - Hydrogen leak rate versus differential pressure with test section III (.004-inch hole) under flow and stagnant conditions in the hydrogen tubes. Hydrogen gas temperature 70°F.

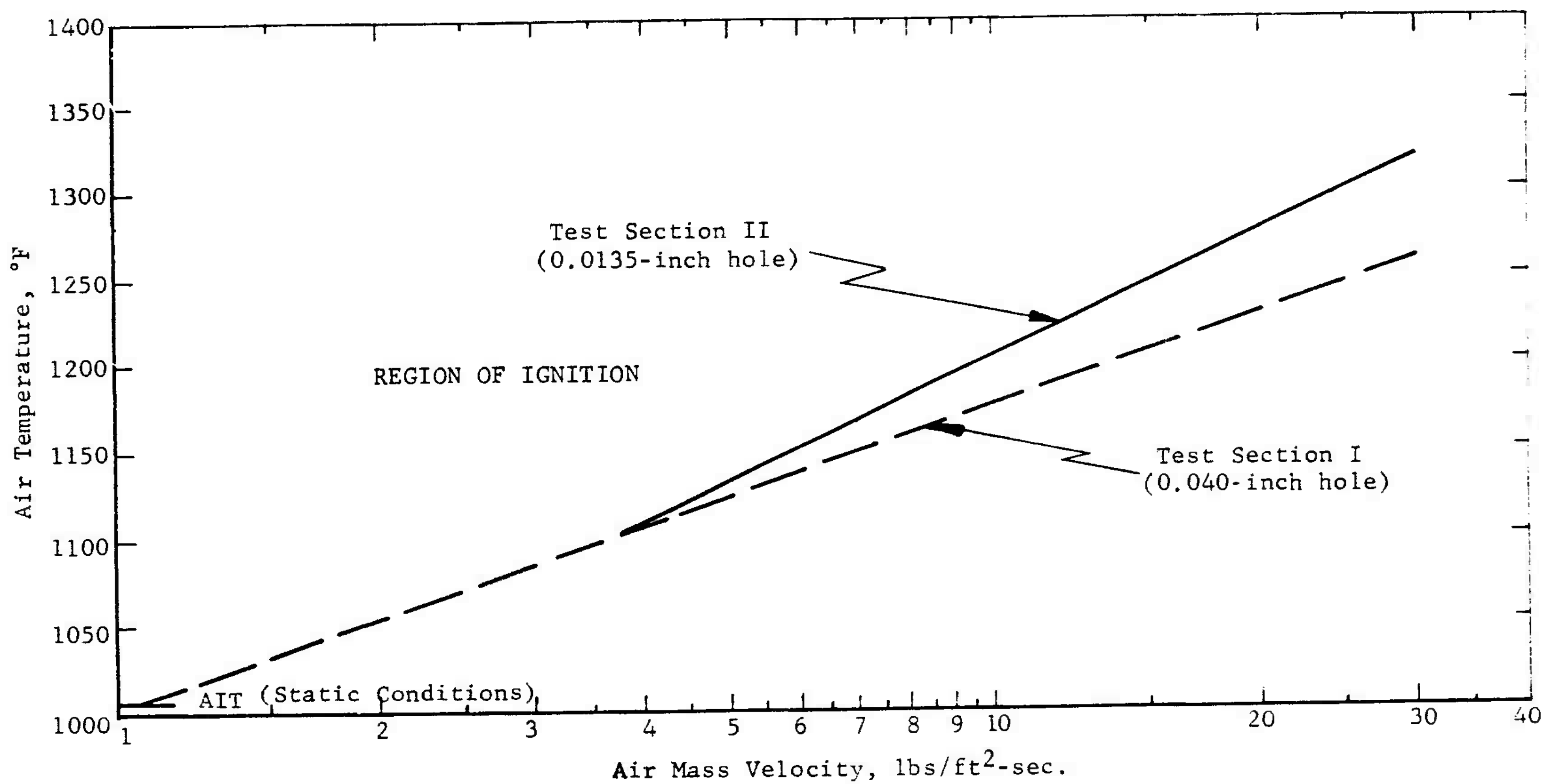

Figure 7. Air temperature required to ignite unheated hydrogen gas injected into a moving air stream through a single hole in a 1/8-inch tube mounted diametrically in a 2-inch pipe.

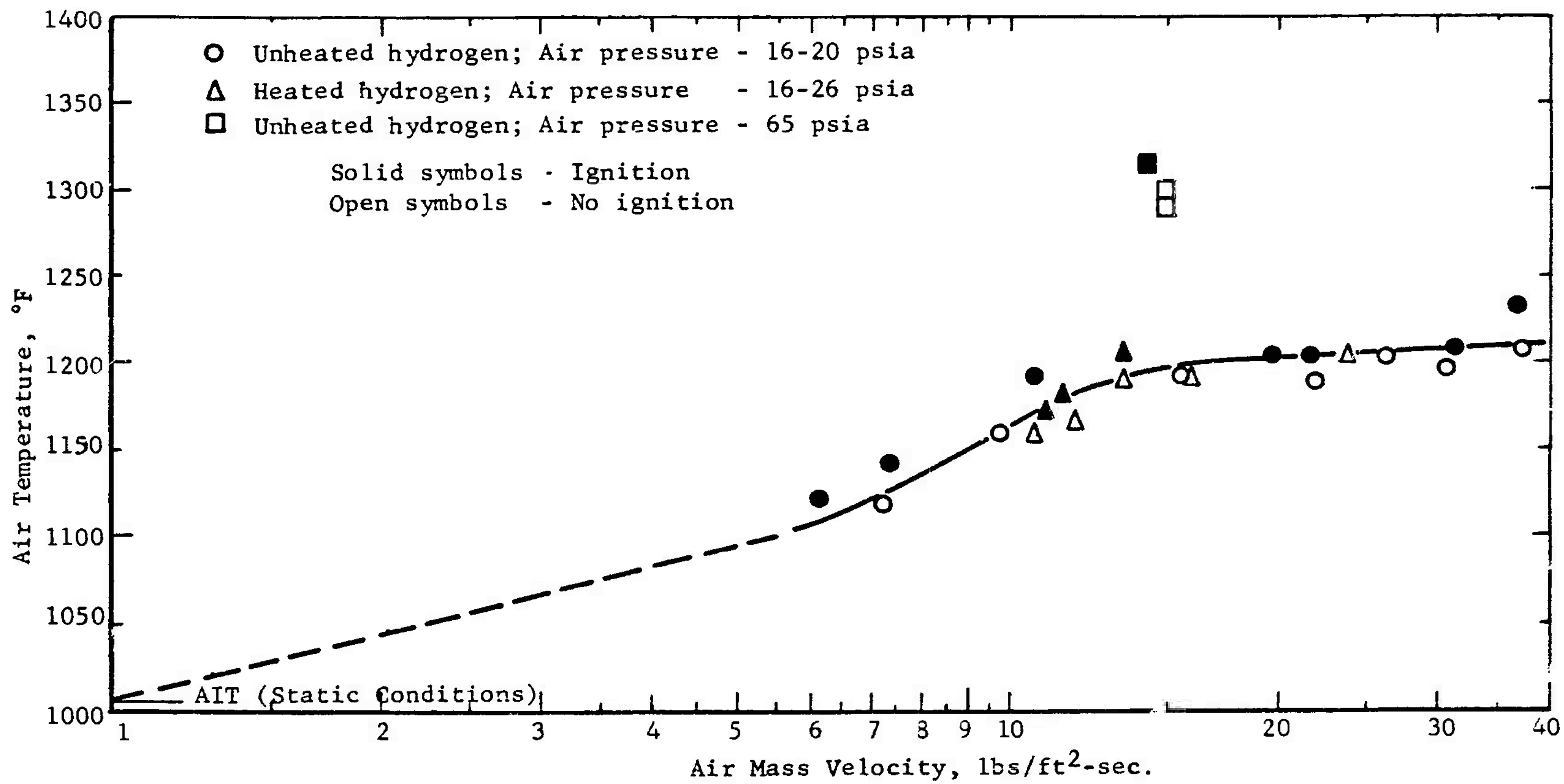

Figure 8. Air temperature required to ignite heated and unheated hydrogen gas injected into a moving air stream through a single hole in multiple tube section V.

APPENDIX

The pebble-bed flow facility consists basically of (1) air supply and storage units, (2) a pebble-bed heater, (3) a gas-fired air-cooled burner system, and (4) controls and instrumentation. A schematic diagram of the entire flow system is given in Figure 9 and a detailed drawing of the pebble-bed heater is shown in Figure 10.

The bed of the heater consists of 1-inch alumina spheres which are heated by direct firing from the top of the heater. The burner system consists of an air blower, a ratio controller to maintain correct gas-air mixtures, and a spark plug as an ignition source at the burner nozzle. The system is instrumented with standard commercial safety controls which include pressure switches in the combustion air line, gas feed line, and mixture feed line. In addition, an ultra-violet flame detector monitors the burner operation.

Briefly, these controls permit the burner to be started only at its lowest firing rate (210,000 BTU/hr) and, in the event of flameout or power failure, the system automatically closes down. The positions of the valves for the heating cycle are as follows: process air valve V-7 closed, vent valve V-8 open, burner cooling air valve V-9 closed, and burner valve V-10 open. The outlet of the heater is blanked off and a valve in the drain port at the bottom of the heater is partially opened, permitting water formed by combustion to be expelled; here the temperature of the bottom portion of the bed governs condensation of the water. Three thermocouples are located in the pebble bed (bottom, middle, and one-foot from top), and another thermocouple is located in the vent line to determine the exhaust gas temperature.

At completion of the heating cycle, the burner is shut down by shutting off the gas supply with the safety shut-off manual reset valve. With flameout the flame detector automatically denergizes the ignition source. An alternate method of shutting down is to turn off the power supply for the flame detector which in turn closes the safety shut-off manual reset valve in the gas line. The burner valve V-10, vent valve V-8, and drain valve are then all closed. The test section is mounted at the outlet of the heater and burner-cooling air valve V-9 is adjusted to permit cooling air to flow through the burner. This is necessary when the top of the bed is at very high temperature (>2000° F) to prevent overheating of burner nozzle by radiation from the pebble bed.

During a blow-down or test cycle, air is supplied from four storage tanks (total capacity 2000 cubic feet) which can be pumped to 250 psig before each series of runs is made. The air flow is controlled by the manual control for regulating valve V-5. The flow rate is metered by an appropriate orifice; read-out of the differential pressure across the orifice and the pressure at the upstream orifice tap is made on the air flow recorder. The temperature of the air entering the test section can be varied by mixing unheated air with the heated air through the by-pass valve V-6. This valve can be operated manually or, if desired, automatically to maintain a set temperature by feed-back from the exit air thermocouple to the exit air temperature recorder-controller.

A measure of the performance of the pebble-bed heater is indicated by the following example. The bed temperatures and exhaust temperatures prior to blow-down were:

Bed temperature, bottom	-	650° F
Bed temperature, middle	-	1680° F
Bed temperature, top	-	2030° F
Exhaust gas	-	555° F

Air at 64° F was passed through the heater at the rate of about 73 SCFM for one hour. Air temperature reached a maximum of 1610° F in 12 minutes; one hour later the air temperature was 1420° F and the bed temperatures were as follows:

Bed temperature, bottom	-	115° F
Bed temperature, middle	-	1200° F
Bed temperature, top	-	1570° F

Utilizing 0.0808 lbs/cu.ft. as the density of air and 0.241 BTU/lb-°F as the heat capacity of air, the total heat abstracted from the bed was approximately 124,000 BTU.

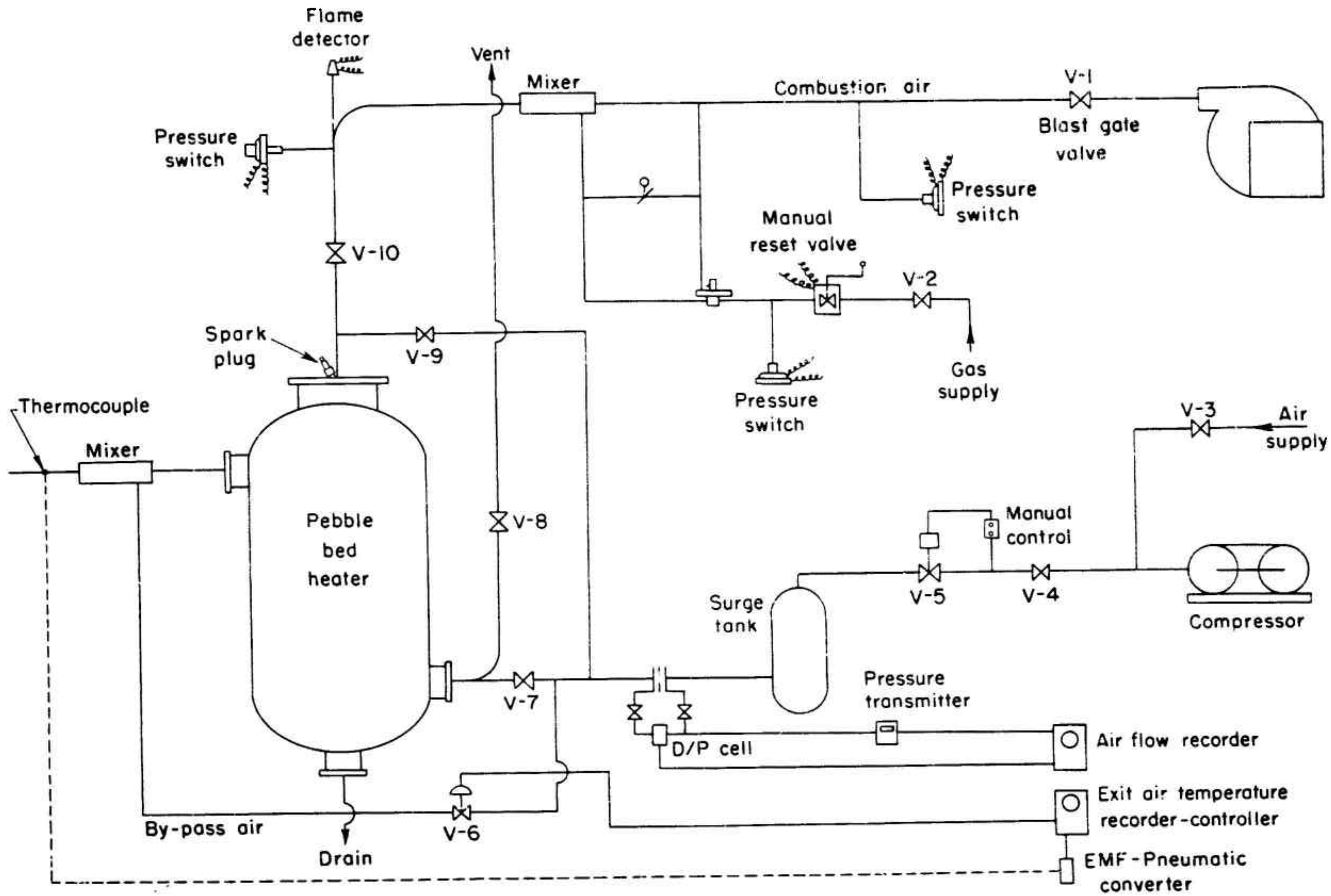

Figure 9. Schematic of pebble bed heater and flow facility.

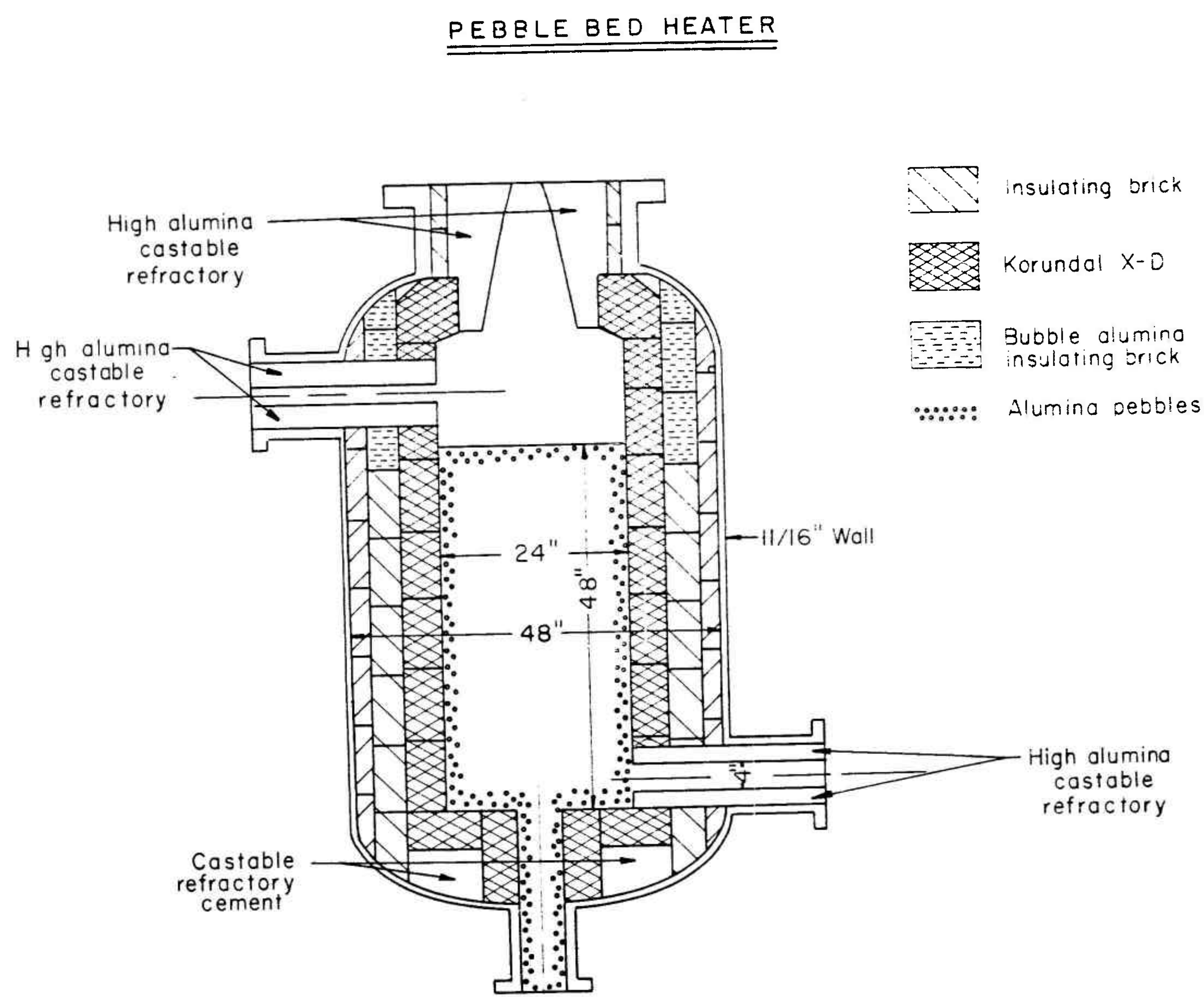

Figure 10. Vertical cross-section of pebble bed heater.

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