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DEVELOPMENT OF THE SATURN S-IV AND S-IVB LIQUID HYDROGEN TANK INTERNAL INSULATION

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SPACE SYSTEMS CENTER – HUNTINGTON BEACH, CALIFORNIA

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DEVELOPMENT OF THE SATURN S-IV AND S-IVB LIQUID HYDROGEN TANK INTERNAL INSULATION

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INTRODUCTION

In April of 1960 the Douglas Aircraft Company was awarded a contract to develop the second and uppermost stage for the Saturn I space booster. In order to realize the high specific impulse available, this stage, called the S-IV, was to utilize liquid hydrogen and liquid oxygen as the propellants. After burn-out of the first stage, the S-IV Stage was to ignite its engines at an altitude of approximately 200,000 feet, burn for approximately 8 minutes, and inject a 20,000 lb spacecraft into a low earth orbit. This program represented Douglas's first major endeavor with liquid hydrogen. It was necessary to develop an insulation for the S-IV Stage that was capable of withstanding the thermal shock associated with loading, could provide adequate insulative properties to limit the flow of heat into the hydrogen, and was of minimum weight. This latter fact cannot be over emphasized because every extra pound of insulation is one less pound of available payload weight.

The development program described in this paper was long and arduous. Engineers and technicians spent many hours evolving the ideas and concepts that are so briefly described. New testing techniques and apparatuses had to be designed to provide representative test conditions. Virtually no analytical techniques were available. Materials had to be tested on a "see if it works" basis. Program schedules were ever present. In order to check out the propulsion system the insulation had to be developed before the flight stage so it could be installed in a heavy-walled, static ground test vehicle. All objectives of the development program were successfully met, and, on January 29, 1964, the first S-IV Stage was orbited.

A program aimed at improving the insulation was well along by that time. This improvement program was for the S-IVB Stage, a new stage which was to have a requirement for orbiting about the earth for up to 4.5 hours with sufficient hydrogen and oxygen remaining for a second burn to achieve escape velocity. One of the basic philosophies of the S-IVB program was to use as much of the S-IV technology as possible. This meant that the hydrogen tank insulation that had been designed for strictly a boost mission of 10 minutes total now had to function throughout the 4.5 hour orbit. Analysis showed that the hydrogen tank could be sized to carry the expected boiloff losses so that a new insulation development was not required.

In 1960 it was more conventional to consider insulations external to a hydrogen tank. However, it was decided to develop an insulation to be bonded internally for the following reasons:

1. The difficulties in maintaining an adequate bond of the insulation external to a surface at $-423^{\circ}F$ were much greater than for an insulation bonded internally to a surface which is above $-100^{\circ}F$.
2. Cryopumping of air with attendant liquefaction and increased heat transfer is avoided.
3. Unavoidable damage due to handling or shipping is minimized.

4. There is no exposure to salt spray, fungus, sand, rain, etc.
5. LH_2 boiloff during loading and tank contraction due to chilling is minimized.

Composite Concept

The composite concept was evolved because no single material was found which could adequately satisfy all the design requirements. The results of test programs discussed on subsequent pages led to the noted materials. The components of the composite insulation system are:

(a) A core which has a sufficient structural integrity while serving as the primary thermal barrier. Polyurethane foam, reinforced in all three planes with fiberglas threads, was developed for the S-IV and retained for the S-IVB.

(b) A liner that physically ties together the individual segments of foam, that prevents the formation of surface cracks in the core, and that acts as a base for a seal coat. A #181 fiberglas cloth impregnated with an epoxy adhesive was selected for the S-IV. This was changed to a lighter #116 fiberglas cloth impregnated with a newer polyurethane resin for S-IVB as a weight reduction measure.

(c) A sealer that acts as a barrier to retard the permeation of hydrogen and inhibits any moisture penetration. Six spray coats of polyurethane resin were selected for S-IV. These were changed to a lighter wiped-on coating of a polyurethane resin used to bond the cloth to the foam.

TEST PROGRAM

The natural direction of the testing program, after the series of component and screening tests had been performed, was the composite testing. There was a chronological overlapping between these testing areas because of the complexity of the problem. The primary modes of testing were directed toward structural integrity, thermal performance, and developmental proof testing whereas the component tests resulted in basic property data (tensile strength, lap shear, etc.).

Thermal/Structural Plate Testing

The primary purpose of this type of test was to verify the structural integrity of the insulation configurations. A secondary objective was to obtain approximate thermal performance data.

The basic apparatus used in plate testing is shown in Fig. 1.

The upper half of the sphere contains liquid hydrogen in direct contact with the insulation mounted on a plate between the two hemispheres. The bottom hemisphere was maintained in a helium purged atmosphere. The quartz lamp array mounted in the lower hemisphere simulated an external environment. Instrumentation was provided to measure the plate temperature at three locations. The power levels required to hold the plate at various temperatures were also recorded. A deflection potentiometer was used on some of the plate tests to measure deflections at the center of the plate. The pressure in each hemisphere was controlled to simulate the maximum flight conditions.

SCHEMATIC OF THREE-FOOT DOME TEST APPARATUS

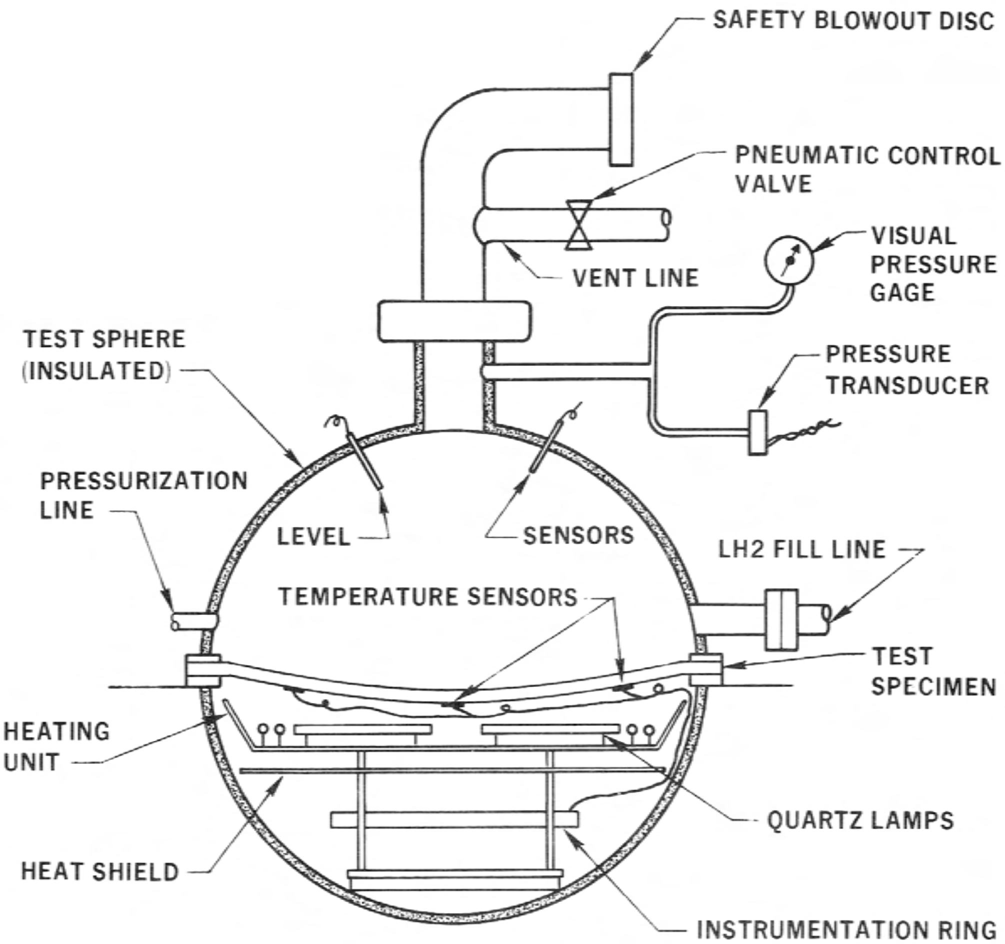

FIGURE 1

The results of these tests were a simple "acceptable" or "failed" statement. Most acceptable plates were tested several times to insure that failure did not occur. The thermal data were used more for observing trends rather than for obtaining absolute values.

Thermal Conductivity Testing

The acquisition of thermal conductivity data was one of the most pertinent phases of this program. The basic element of this testing apparatus is the guarded hot plate. The temperature of the guard ring is balanced against the temperature of the control plate to assure no lateral heat flow. Thermocouple instrumentation provides the temperature differential data. The heat input to the control plate is measured. From this information the thermal conductivity can be calculated. The problem of determining thermal conductivity at cryogenic temperatures is a difficult task, particularly for an internal insulation. Recognizing that permeation of hydrogen into the materials will, in some cases, materially affect the thermal conductivity, it was deemed advisable not only to test at cryogenic temperatures but also to have direct exposure of the test surfaces to liquid hydrogen. Figures 2 and 3 shows the apparatus used for achieving this direct exposure. The ring of the "banjo" is machine-milled out of a single piece of aluminum so that no edge leaks to air would be possible. Each hydrogen container is capable of being pressurized so that tank pressure conditions can be simulated. Initial testing showed that the thermal conductivity would increase with exposure time, depending on the effectiveness of the sealer. This necessitated testing continuously for time periods approaching 50 hours so that all possible accumulation effects could be noted. Figure 4 shows typical results with the S-IVB reinforced foam configuration for a single hot face temperature which represents the maximum ground hold conditions.

SCHEMATIC OF "BANJO" TEST APPARATUS

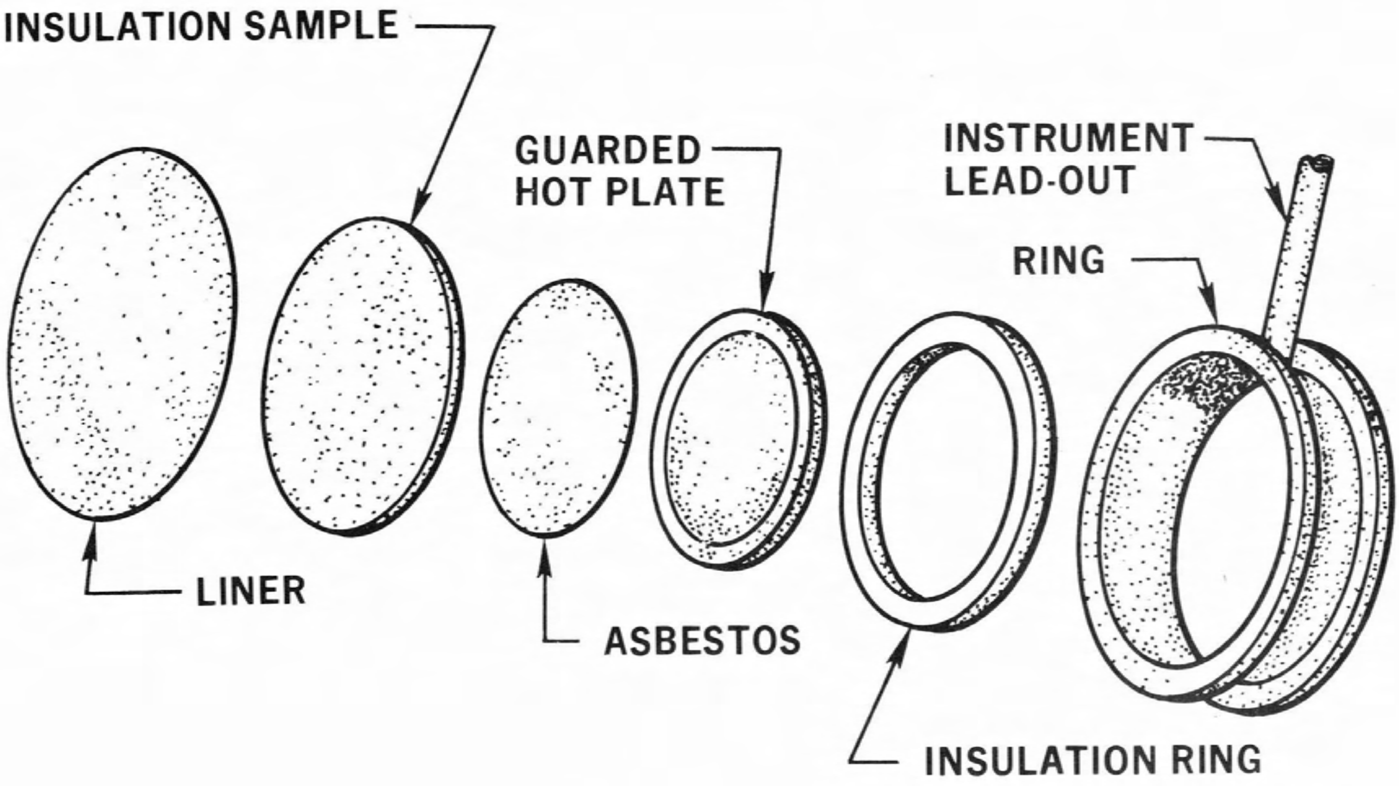

FIGURE 2

THERMAL CONDUCTIVITY TEST APPARATUS

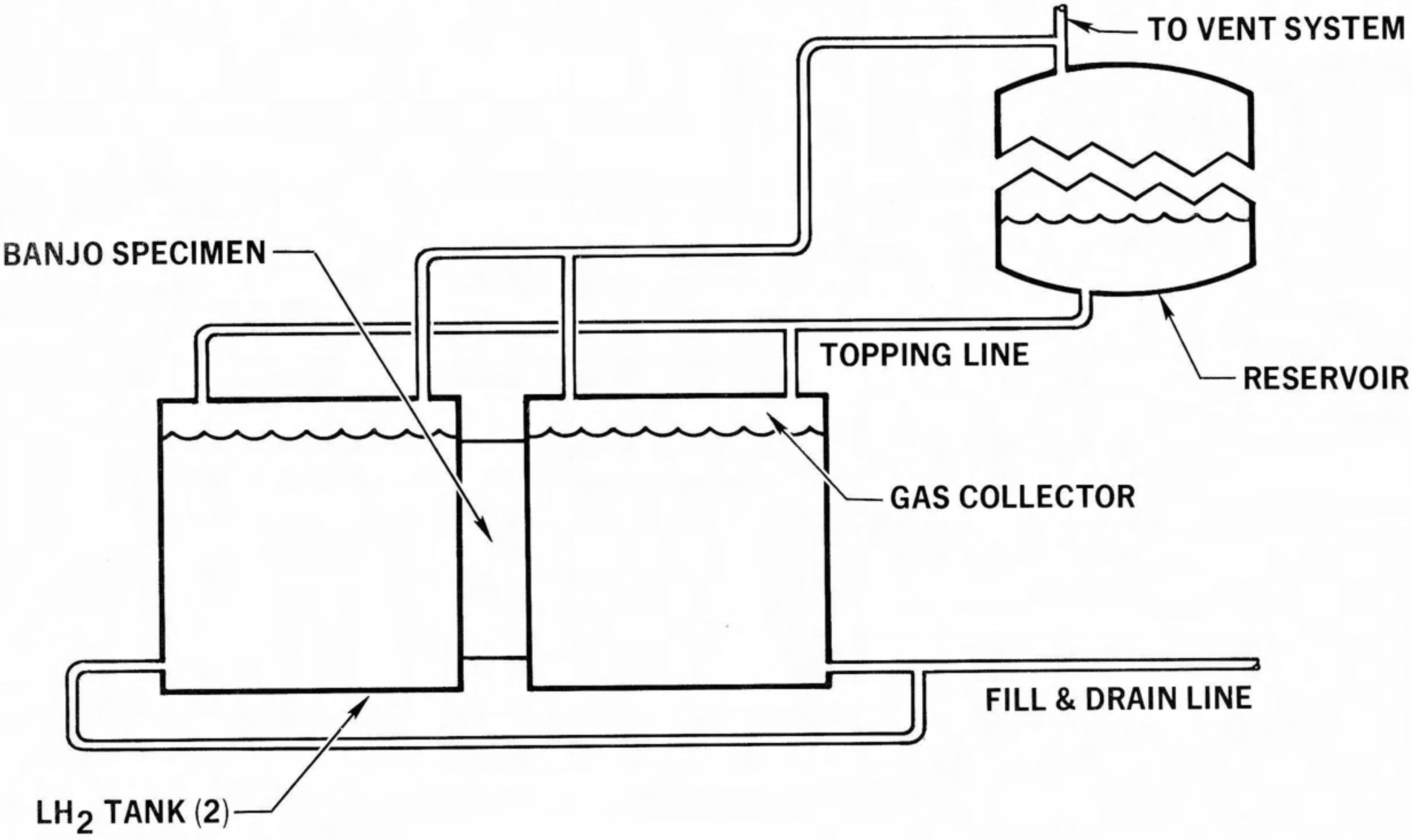

FIGURE 3

SATURN S-IVB LH2 TANK INTERNAL INSULATION THERMAL CONDUCTIVITY HISTORY

MEAN TEMPERATURE = -185°F

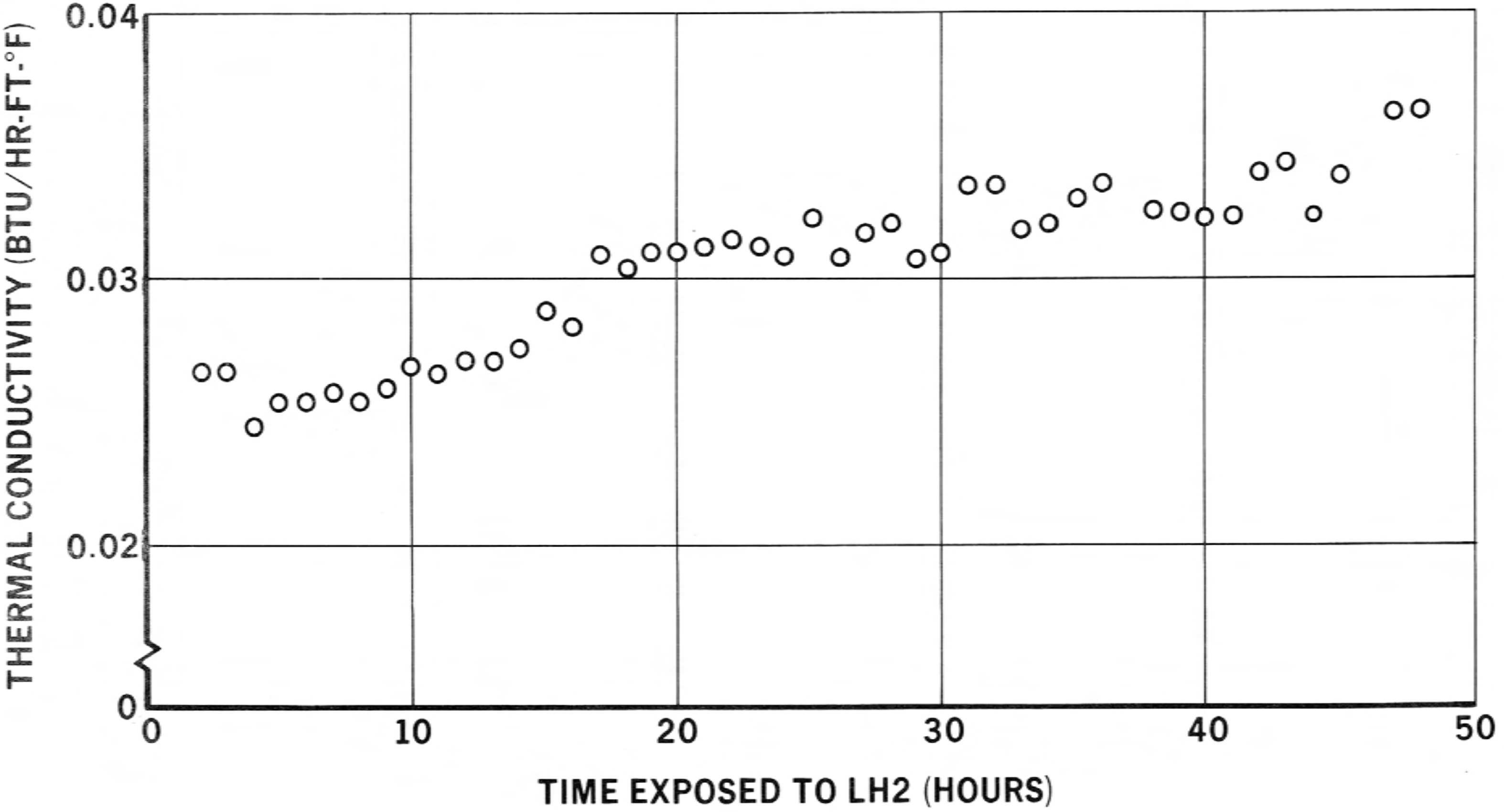

FIGURE 4

Scale Tank Test Program

The purpose of the scale tank test program was to subject the final insulation configuration, installed in a representative scale tank in a manner similar to production techniques, to repeated conditions of hydrogen loading, pressurization, extend holds, and draining. Data were obtained on boiloff rates and tank wall temperatures that allowed for the calculation of an effective thermal conductivity. Similar tests were conducted for both S-IV and S-IVB insulation configurations. Only the S-IVB data are presented. Figures 5 and 6 show a schematic and photograph, respectively, of the test tank.

The following test procedure was used:

1. Following an initial purge, the tank was filled with liquid hydrogen to a level of 8.5 feet.
2. The level was maintained until thermal equilibrium was obtained (approximately 2 hours).
3. The pressure was allowed to increase to 42 psia and held for 15 minutes. A relief valve setting was used to automatically maintain the pressure.
4. The tank pressure was relieved to ambient and the hydrogen level topped off to the 8.5 foot level.
5. The hydrogen was allowed to boil off.
6. The tank was drained after the liquid level sensor at 4.0 feet indicated gas at that level.

The insulation was inspected both visually and with ultrasonic equipment after initial insulation installation and after each test. The visual observations were used primarily inside the tank to determine any noticeable effects on the liner. The pulse echo ultrasonic method (utilizing a water couplant adapter) was used for detecting any areas of debonding of the foam from the aluminum tank wall and domes.

EIGHT FOOT DIAMETER TEST TANK

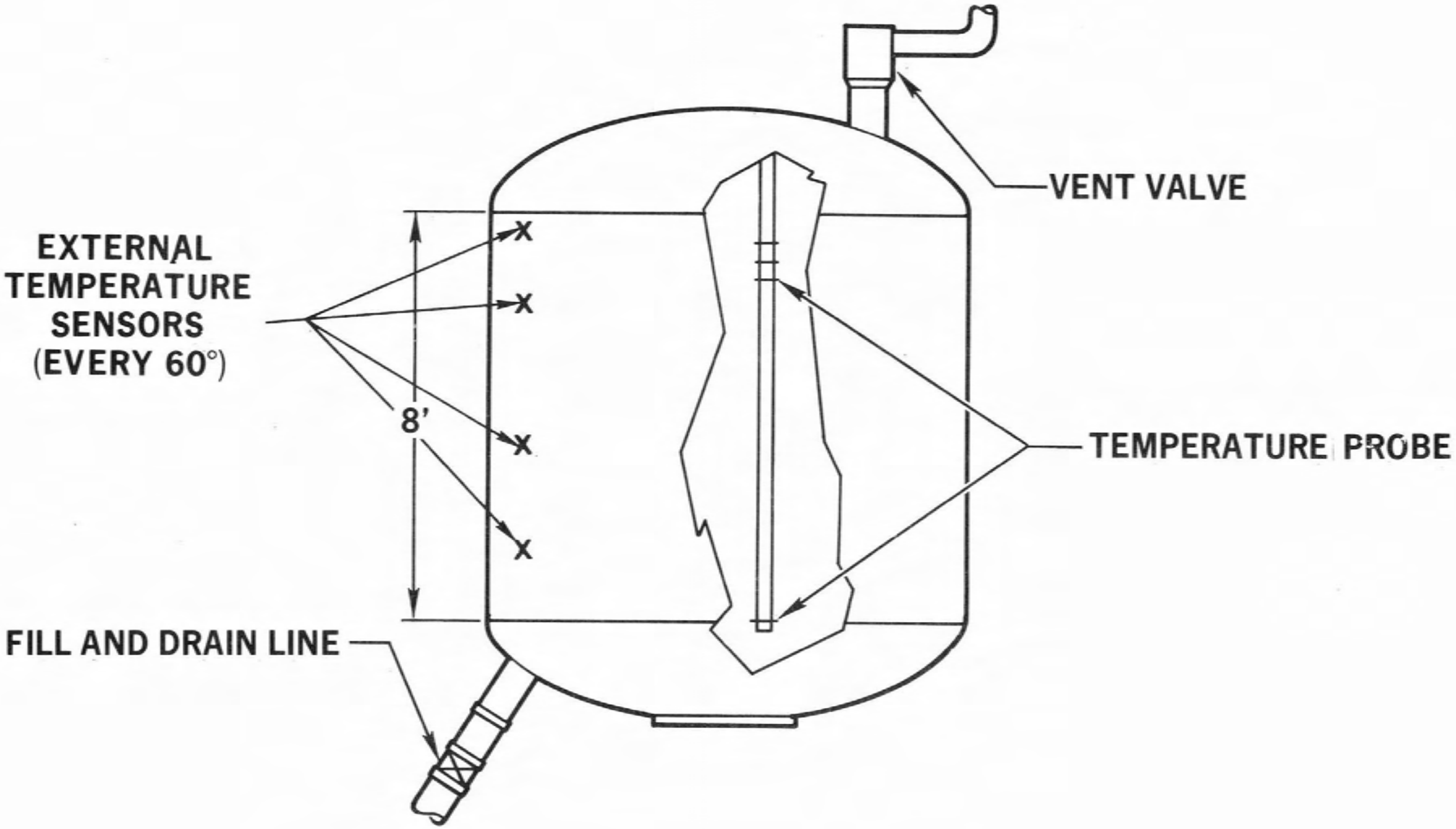

FIGURE 5

EIGHT-FOOT TANK DURING TEST

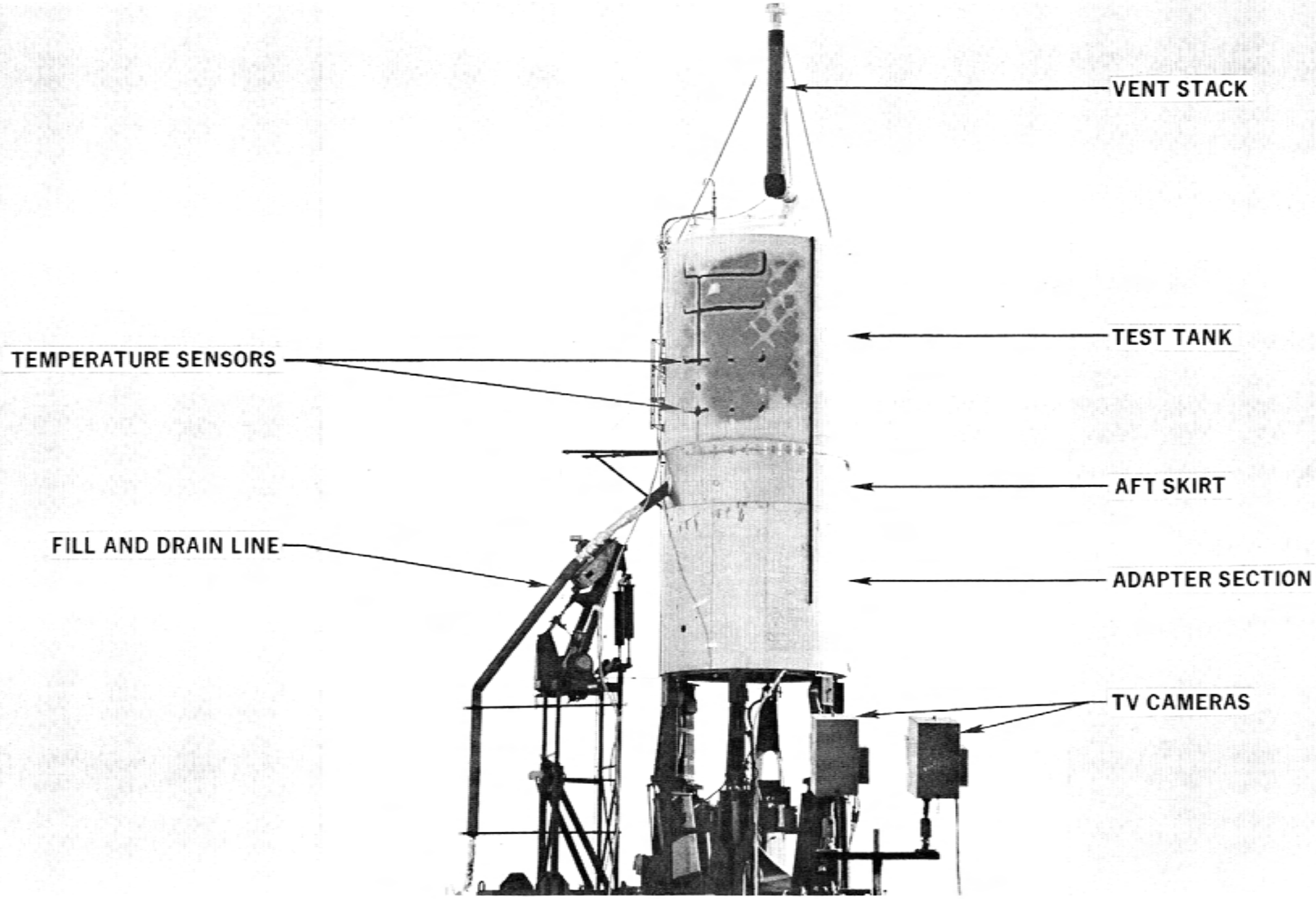

FIGURE 6

Of most significance was the thermal performance of the insulation (thermal conductivity). This parameter was calculated for steady state conditions by knowing the rate of heat transfer through the insulation ($\dot{q}_{net}$) and the temperature differential across the insulation. Boiloff data were recorded which was the total heat transfer rate to the hydrogen ($\dot{q}_{total}$). (Calculations showed that heat transfer from the unwetted wall and the ullage gas were negligible.) To obtain the desired net heating rate required calculating a heat leak value ($\dot{q}_{leak}$) to satisfy the following heat balance.

$$\dot{q}_{total} = \dot{q}_{net} + \dot{q}_{leak}$$

Heat transfer calculations were made to determine $\dot{q}_{leak}$ by utilizing Douglas's three-dimensional heat transfer program and measured temperature profiles near all major regions. Measuring the temperature gradients near the heat leaks substantially removed the uncertainty in this calculation that existed during a similar S-IV test program. Here, the uncertainty in heat leaks caused an inaccuracy in the thermal conductivity calculation of approximately 25 percent. By measuring the temperatures it is believed that the uncertainty in the thermal conductivity calculation was reduced to 5 to 10 percent since a few assumptions were still necessary.

Figure 7 shows the results compared to conductivity values measured by the guarded hot plate technique discussed earlier in the paper, including substantially more data. The additional data were obtained because of the lower insulation temperatures measured during the 8-foot tank tests and to try to establish repeatability in the data. It is apparent that the spread in data is quite large. (For information, conductivity values are shown for hydrogen gas and for an insulation sample that was sealed from hydrogen permeation. The implication is, of course, the better

SATURN S-IV INSULATION
THERMAL CONDUCTIVITY
8 FOOT TANK AND BANJO
DATA COMPARISON

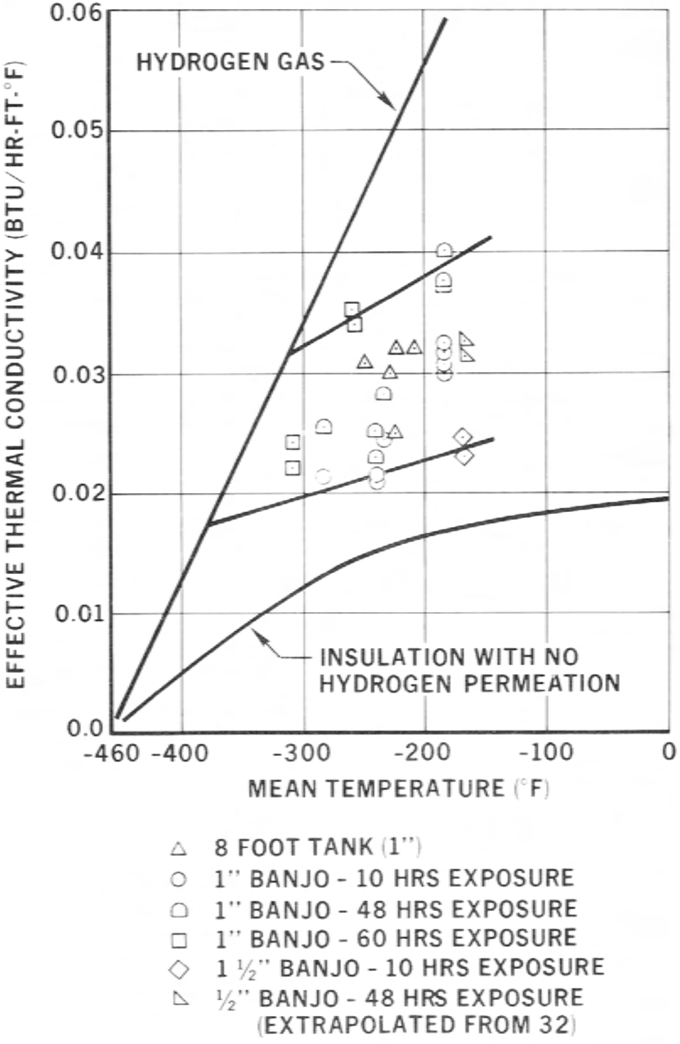

FIGURE 7

the sealer the closer the data should approach the lower curve. Conversely, the poorer the sealer, the closer the conductivity should approach that of hydrogen gas.) Since data exist over such a large range, it is impossible to select a single curve. Instead, the lines representing the maximum and minimum conductivity extremes are used, depending on the desired condition. It is believed that the degree of correlation between that 8-foot tank and the banjo tests is still good considering the complexity of the heat transfer process and some differences that existed between the 8-foot tank and banjo insulations.

S-IVB FLIGHT CONDITIONS

The S-IVB stage is in orbit for up to 4.5 hours. During this time the mean temperature of the insulation varies between -170°F and -350°F, depending on time and conductivity. It was believed that this variation could be used to advantage since conductivity is proportional to temperature. The predicted mean temperature of the insulation (averaged radially around the tank) is shown in Fig. 8. The conductivity data from Fig. 7 are also shown corresponding to the associated mean insulation temperature. It can be seen that for the majority of the orbital time period, the conductivity is less than 0.03 Btu/hr-ft-°F. This results in the ability to predict transient heating rates by iteration whereby the appropriate thermal conductivity value is used as the insulation temperature decreases. In practice, the insulation temperatures are not averaged radially since there are significant differences between the side facing the earth and the side away from the earth.

SATURN S-IVB LH2 TANK INSULATION TEMPERATURE AND THERMAL CONDUCTIVITY

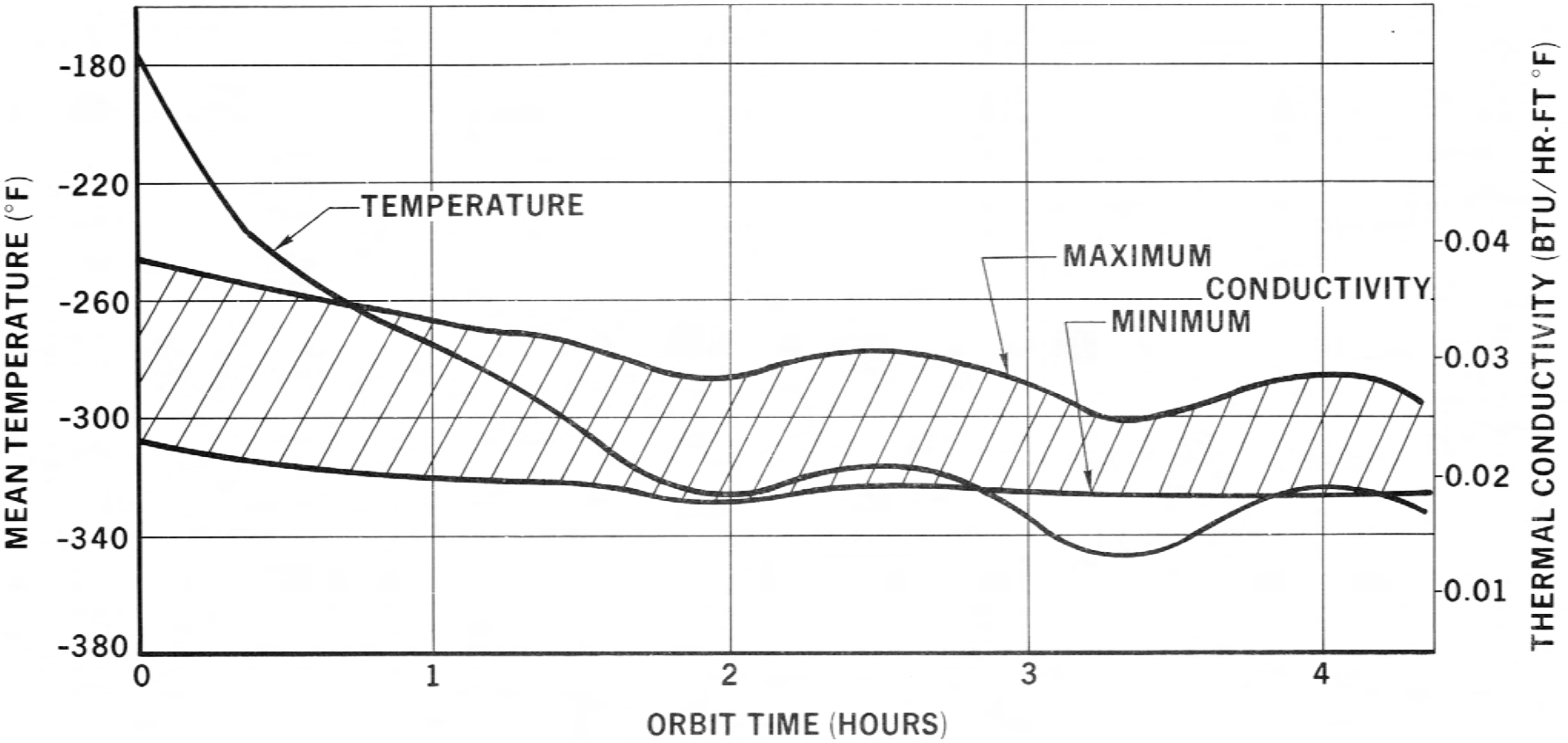

FIGURE 8

It was noted from Fig. 4 that conductivity is time dependent. The data in Fig. 7 includes this effect, for 60 hours exposure, but the time dependency has not been specifically used in Fig. 8. The two curves that encompass the data on Fig. 7 include the time effects on a gross basis. It was believed that a single curve of conductivity as a function of time (at a given temperature) should not be used since it is difficult to determine whether the time should be based on total accumulated exposure over many months or just the final exposure over a relatively short time period. Of course, the latter would be more desirable. The S-IV experience has tended to show that the effects are cumulative and not just the last exposure. These cumulative effects occur over approximately a one year time period. It will be necessary to wait until several S-IB Stages have been flown before this effect can be isolated.

SUMMARY

The S-IV insulation development program resulted in selecting a polyurethane foam reinforced with fiberglas threads. This same foam is in current use on the S-IVB, however, the liner and sealer have been changed to lighten the weight of the system. A number of test programs were required to obtain the necessary data which required developing new testing apparatuses to provide necessary simulation. Thermal conductivity measurements have been compared to values calculated from scale tank tests which illustrate the time dependence on the conductivity measurement. Additional measurements have been made simulating orbital temperature conditions to use the lower temperature effect.

ACKNOWLEDGEMENTS

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