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Use of tank mounted booster pumps for providing NPSH to turbopumps operating in a radiation environment

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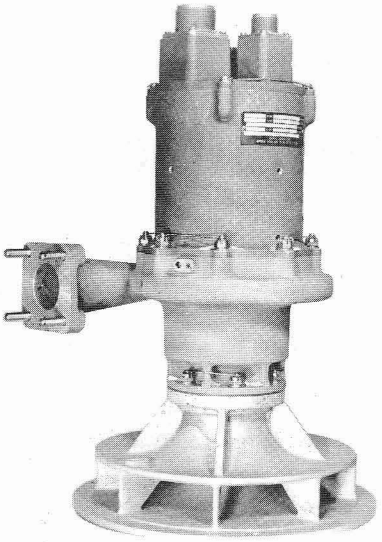
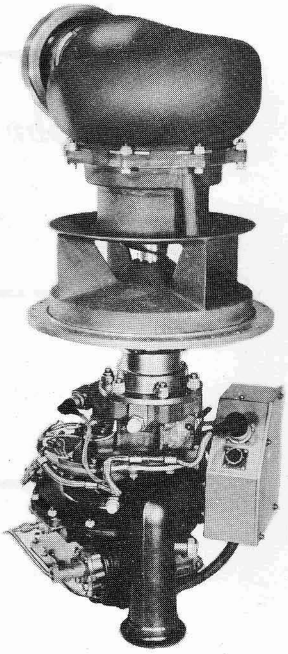
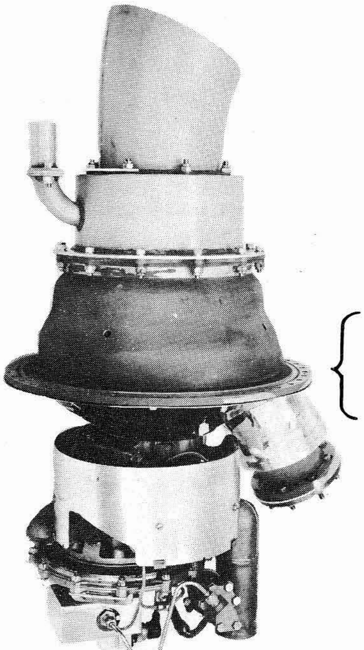
TYPICAL PESCO CRYOGENIC PRODUCTS



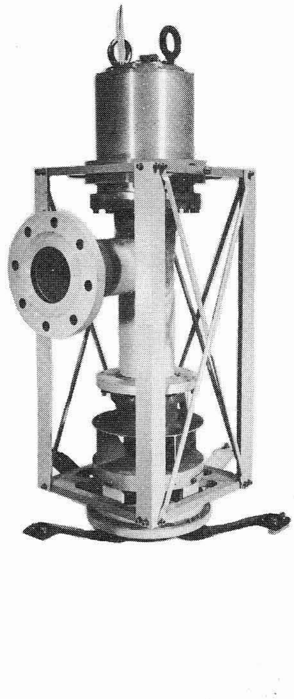
This submerged mounted liquid hydrogen pump produces 160 gpm at 80 psi rise. It is direct driven at 24000 rpm by a 10 hp cryogenic induction motor. This unit was used by The Bureau of Standards in a program to obtain high magnetic field strength by cooling electro magnetic coils in liquid hydrogen. The program was sponsored by the Atomic Energy Commission.



Pesco's liquid oxygen boost pump with attached hot gas turbine drive and variable speed control for space application. This light-weight, high speed pump is flange-mounted within and at the bottom of the liquid oxygen tank.



This high speed, light weight turbine-driven liquid hydrogen boost pump was designed for tank mounting and space application.



Pesco's gimble mounted electric dynamometer is designed for submerged operation in liquid hydrogen. The electric motor drive measures only 5.75 inches in diameter and develops 50 hp at 24000 rpm. The pump delivers 1400 gpm at 20-40 psi rise.

SUMMARY

This paper outlines the results of a test program which was planned to demonstrate the feasibility of using a tank mounted, all-inducer, high speed liquid hydrogen booster pump to provide NPSH for the turbo pump in a reactor-powered vehicle. The cavitation problem associated with pumping liquid hydrogen, when used as a propellant, is further aggravated by localized heating caused by radiation from the reactor.

This heating occurs from gamma ray and neutron flux absorption in the bottom two or three feet of the liquid hydrogen tank. Depending upon the amount of sub-cooling available in the liquid hydrogen when the reactor is started, it is possible for the neutron slowdown to heat the hydrogen to the saturation point, or even superheat some localized regions. Estimates of the heating near the bottom of the tank have indicated that it can be equivalent to a power level of 1.0 watt/cm^2, which is equal to a heat flux of 53 BTU/sq. ft.-min. Figure 1 indicates how this heating takes place.

The question that the test program was planned to answer is this:

Can a tank mounted booster pump deliver saturated or violently boiling liquid hydrogen to the inlet of a downstream pump, with sufficient NPSH to suppress any incident of cavitation?

INTRODUCTION

A test program to prove the feasibility of using a tank mounted booster pump to provide maximum NPSH for the turbo-pump in a reactor powered vehicle must demonstrate hydraulic and thermal similarity.

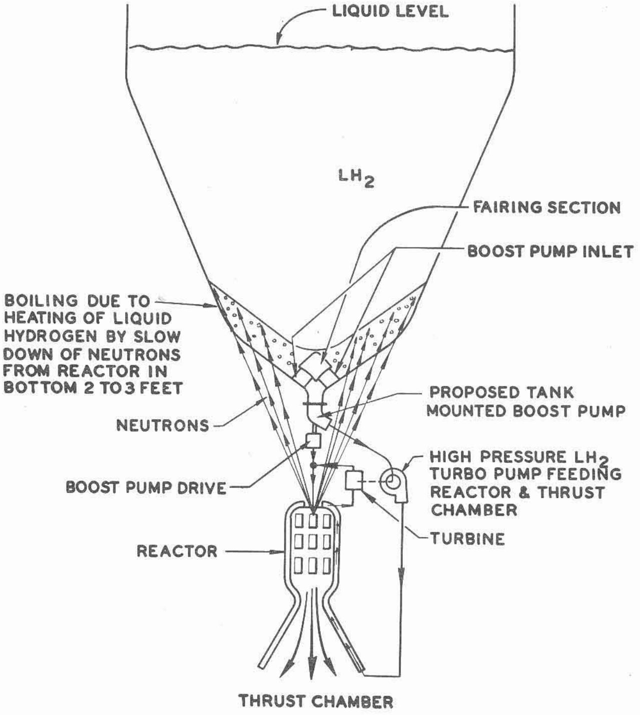


Figure 1. Schematic showing boiling at tank bottom in reactor powered vehicle.

Hydraulic Similarity

Hydraulic similarity must be established from a non-cavitation and cavitation performance standpoint. Before any hydraulic similarity between prototype (reactor installation) and model (test vehicle) can be established, the prototype flow rate must be determined. For a first generation reactor powered vehicle, a flow rate of 8000 gpm (approximately 80 pps of liquid hydrogen) was assumed. To establish hydraulic similarity, it is also necessary to determine pump inlet and outlet pressures. For purposes of this program, tank pressure of 15 to 20 psia with a pump head rise of five to 10 psi were assumed. It is believed that these are valid numbers for a first attempt at solving the problem.

Non-Cavitation Similarity

Here the criterion is the parameter, Specific Speed, N_S, is defined as:

$$N_S = \frac{N\sqrt{gpm}}{(H)^{3/4}}$$

Where:

N = pump speed

gpm = pump flow

H = pump head in feet

Inducers operate in the specific speed range of 5000 to 9000 rpm. Assuming an N_S = 7000 and a head rise of 300 feet (almost 10 psi), one calculates a prototype operation speed of:

$$N = \frac{7000\,(300)^{3/4}}{\sqrt{8000}} = 5450 \text{ rpm}$$

Hydraulic similarity will be obtained in a pump developing the same head, if the ratio of pump speed is inversely proportional to the square root of the flow, thus:

Where:

$$n = N\sqrt{\frac{Q}{q}};$$ where caps refer to prototype or larger pump

For N = 5450

and q = 1000

$$n = 5450\sqrt{\frac{8000}{1000}} = 15,300 \text{ rpm}$$

The test vehicle used in this program delivered 1000 gpm with a head rise of 330 feet (10 psi) at its best efficiency points, while operating at 14,800 rpm. Test data obtained at 20,000 rpm demonstrated inlet hydraulic similarity to a 9000 specific speed number.

Cavitation Similarity

When comparing similar installations (tank or line mounted pumps) pumping similar fluids, the parameter suction specific speed can be used to compare and predict the cavitation performance of centrifugal pumps. Suction specific speed, S, is defined as follows:

$$S = \frac{N\sqrt{gpm}}{(H_{SV})^{3/4}}$$

Where:

N = pump speed, rpm

gpm = pump delivered flow in gallons per minute.

H_{SV} = Net positive suction head, which is the physical head of liquid above the pump inlet when pumping a boiling liquid.

Pesco tank mounted liquid hydrogen pumps have demonstrated the capability of consistently achieving suction specific speeds of over 200,000. An optimum tank-bottom installation utilizing a good inlet bell, has achieved S numbers of over 400,000.

To demonstrate the same capability of emptying a tank of boiling liquid; i.e., the ability to pump to the same

H_{SV} value, the model pump speed calculates as follows:

$$n = N\sqrt{\frac{Q}{q}} = 5450\sqrt{\frac{8000}{1000}}$$

$$= 15,300 \text{ rpm}$$

Thermal Similarity

Heat leak conditions and thermal similarity were established by measuring liquid hydrogen boil-off. The boil-off rate was determined by noting the change of liquid level in the tank per unit of time. Knowing latent heat for vaporization of liquid hydrogen, the exposed area of the tank and the tank pressure, it was possible to determine the heat leak per unit area. These calculations are somewhat conservative, since most of the heat leakage takes place at the pump mounting surface, which is in itself a heat short. Heat leak rates in excess of 80 BTU/min.-ft.^{2} were calculated greater by 50 per cent than the estimated rates expected in a nuclear reactor powered vehicle.

Pump Description

The inducer test pump, which was driven by a hydraulic motor is illustrated in Figure 2. An inducer-impeller pump was modified for this program. The modifications were:

A. The second stage pump impeller was removed and replaced with a stationary spool piece, which effectively guided the liquid flow into the volute.

B. The outside diameter of the inducer was reduced to 3.83 inches with an inlet angle of 10.7° and a discharge angle of 21.2°.

C. A straight inlet adapter was provided over the modified inducer.

TEST PROGRAM

1. Normal Speed Movie Observation

The boiling activity of liquid hydrogen at the inlet of a tank mounted booster pump was filmed with a Bolex camera at a speed of 18 frames per second. This was done in two stages; first, with the tank pressurized to 5 psig, and second, with the tank depressurized. The boiling was filmed while the tank was under constant pressure, and also while it was being depressurized.

2. High Speed Still Photography Observation

The above procedure was repeated and photographed with a Nikon F camera and an Edgerton microflash unit in order to observe the actual vapor formation around and within the inducer.

APPARATUS

Description of Test Installation No. 1 (See Figure 3.)

For the moving picture test set-up, the pump and drive assembly were mounted to the 7000 gallon dewar sump, and were foam insulated at the mounting base. Sufficient heat leak (over 80 BTU/min.-ft.^{2}) was allowed through this area to simulate the radiation heat leak condition in the space.

Three banks of lights and reflectors were installed inside the dewar, one set being submerged in the liquid hy-

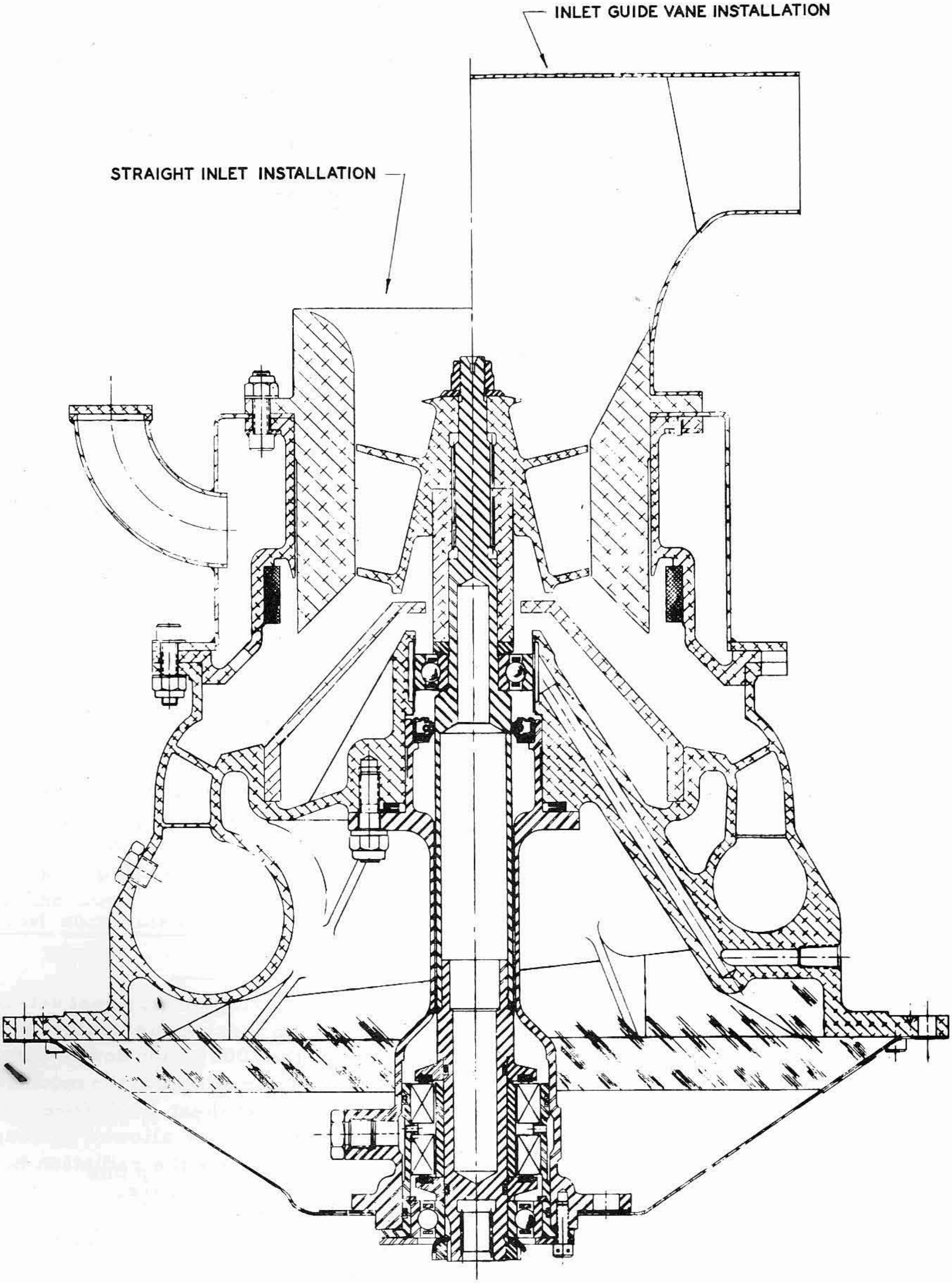


Figure 2. Cross section of high speed inducer test pump.

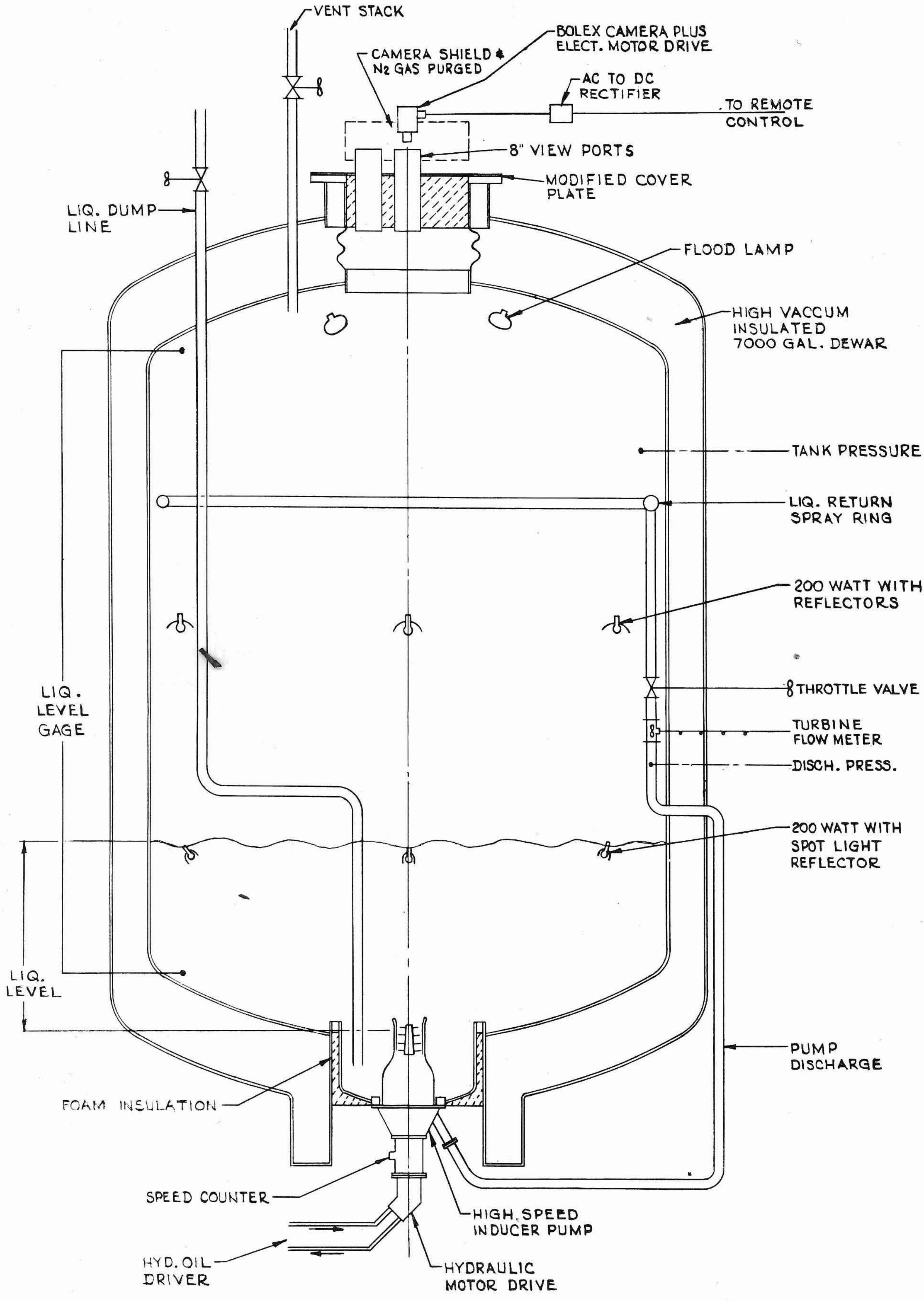


Figure 3. Schematic of test installation No. 1.

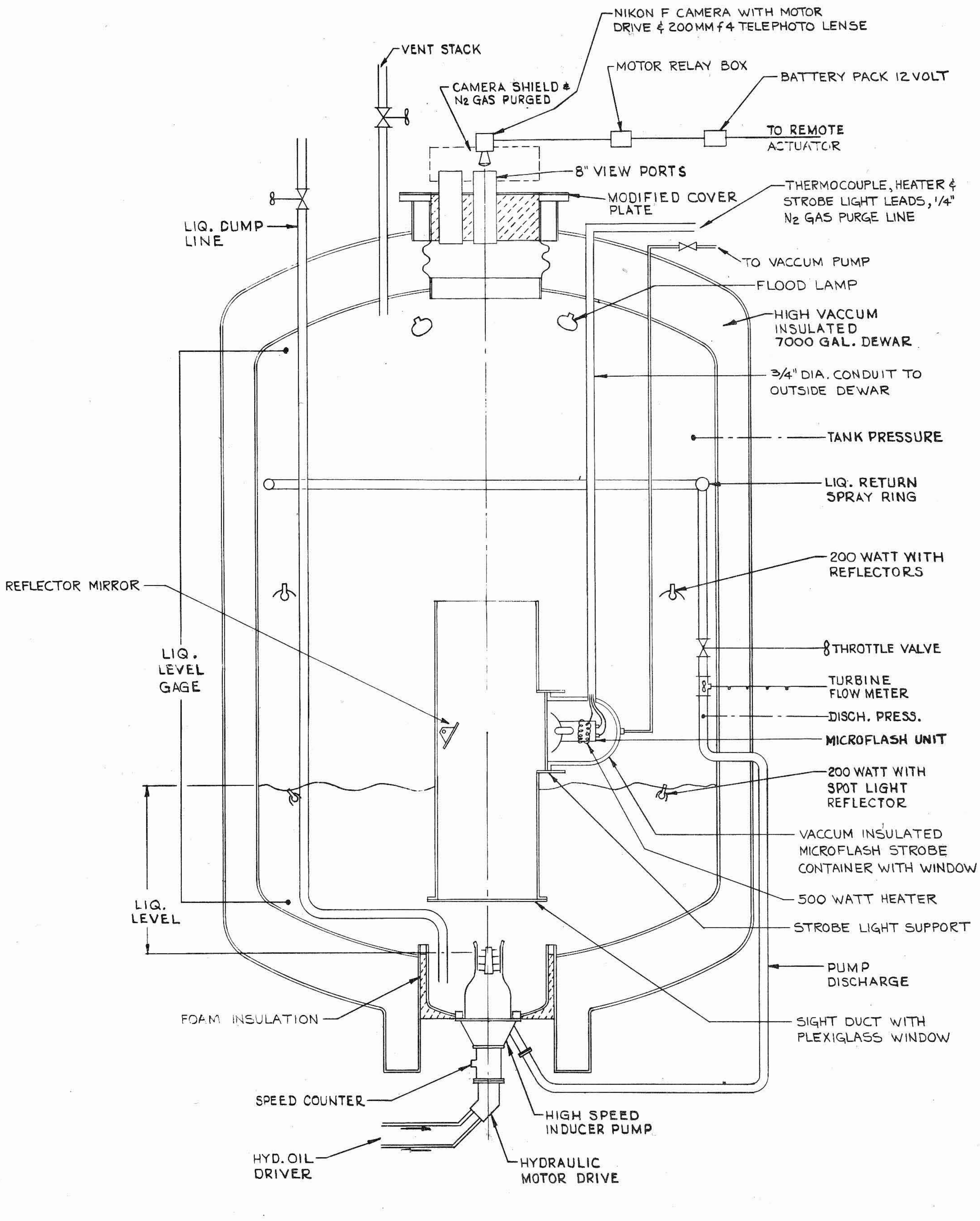


Figure 4. Schematic of test installation No. 2.

drogen. All lamps were lighted at a reduced voltage to protect their filament. The liquid hydrogen flow patterns were photographed through an eight inch diameter vacuum insulated view port located on top of the dewar cover. The pictures were taken with a Bolex movie camera equipped with an electric motor drive. The camera was set at f2.8 lense opening and operated at a speed of 18 frames per second.

Description of Test Installation No. 2 (See Figure 4.)

For the high speed still photographic test set-up, the pump installation was the same as for test installation No. 1. The light source, however, was obtained by using an electronic flash unit manufactured by Edgerton, Germeshausen, and Grier Inc. The microflash unit, Model No. 549 was housed inside a vacuum insulated container which was attached to a sight duct. The entire unit was lowered into the liquid hydrogen test dewar. The unit was so arranged that when a stroboscope was triggered, a mirror attached to the duct, reflected light onto the inducer inlet area. The flash duration from this unit was 0.5 microseconds with peak light intensity of 50 x 10^6 beam candle power. A still image of rotating elements was photographed by a motor driven, remotely operated Nikon F camera equipped with a 200 mm f4 telephoto lense which was set at an opening of approximately f8. Kodak Tri X film was used.

RESULTS AND DISCUSSION

Normal Speed Photography

A seven minute film clip showing the boiling activity of liquid hydrogen in the vicinity of the pump inlet, under various test conditions, was shown at the oral presentation of this paper. Of particular interest is the active, deep foaming condition to which the boiling liquid flared during the depressurization testing.

High Speed Photography

Figures 5 and 6 are typical photographs of the liquid hydrogen surface

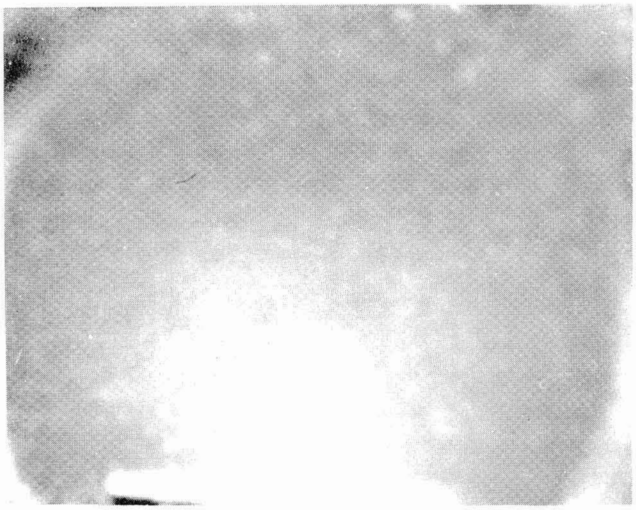


Figure 5. Surface of liquid hydrogen during saturation with pump speed of 9000 rpm.

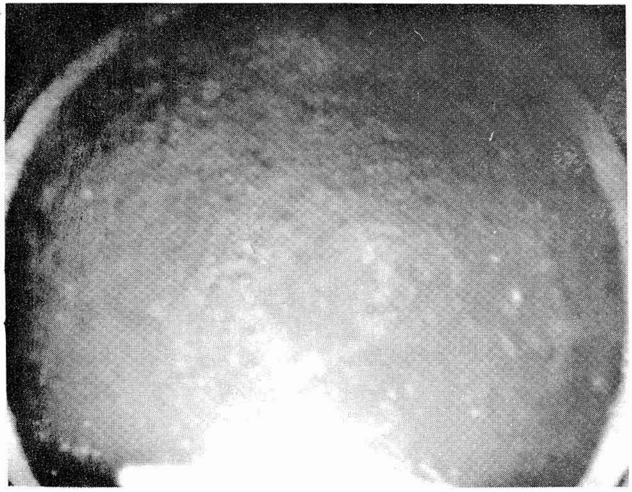


Figure 6. Surface of liquid hydrogen during saturation with pump speed of 15,000 rpm.

during saturation. Photographic technique has not progressed to a point where photographs can be taken of liquid and vapor entering the pump inlet and indirect passages below the surface of the liquid. A program to obtain this photographic data will be conducted during this coming year.

Test Data

Figure 7 is a plot of "static" boiling test data obtained with the test vehicle without an inlet bell. Note the fall-off in flow and pressure and an intermediate liquid level, from 20 to 17-1/2 inches. This is followed by a gradual deterioration in performance with decreasing liquid level. Suction specific speeds in excess of 350,000, before any appreciable fall-off in performance, were obtained with the test vehicle. This represents exceptionally good cavitation performance.

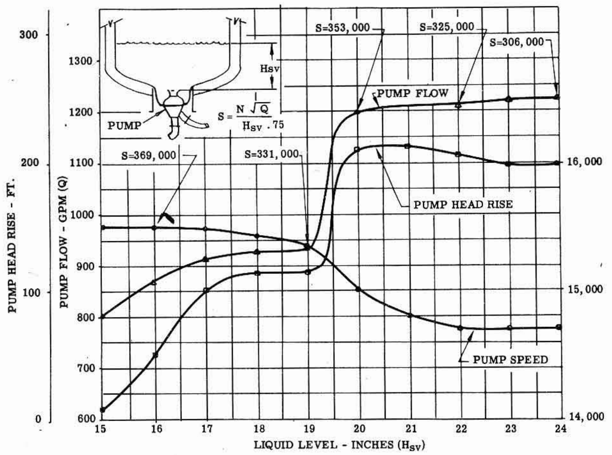


Figure 7. Pump down performance in boiling liquid hydrogen.

Figure 8 is a plot of "dynamic" boiling tests run in this program.

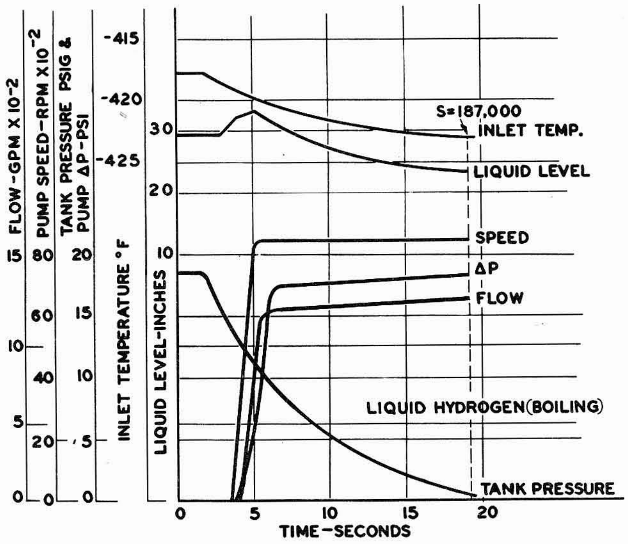


Figure 8. Plot of dynamic boiling test.

"Dynamic" boiling tests differ from "static" boiling as follows:

Static boiling is the condition existing when the liquid hydrogen is at saturation. Dynamic boiling conditions occur when tank pressure is rapidly decreased from saturation conditions. Depressurization rates of 1 psi per second were used for this program. Note that the test data in Figure 8, shows that the pump was started after tank depressurization was initiated. Even under these extreme boiling conditions, the test vehicle delivered single phase liquid with adequate net positive suction head.

CONCLUSIONS

The test program reported on herein, demonstrates that a tank mounted booster pump can be used to deliver boiling liquid hydrogen to the turbo pump of a reactor-powered vehicle with adequate NPSH to prevent cavitation. It further demonstrates that tank-mounted, high speed, all inducer type booster pumps exhibit extreme improvements in the commonly accepted cavitation parameters. These improvements are attributed to special design features, thermal properties of liquid hydrogen, and certain physical phenomena associated with tank-mounted pumps.

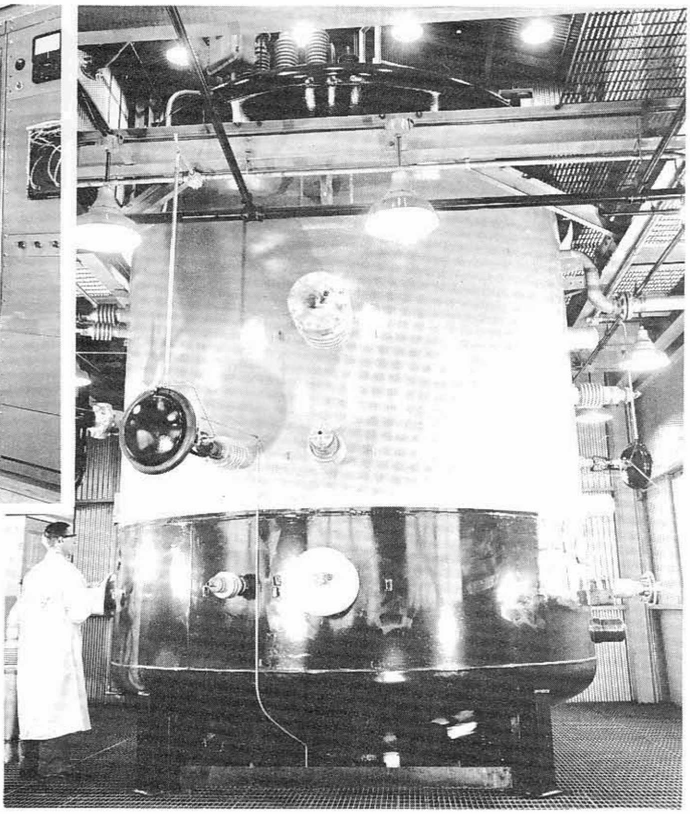
The phenomena are:

High vapor-handling capability of a properly designed inducer pump.

A tank installation having an inlet bell to the pump will prevent the formation and coalescence of vapor from choking the inlet to the pumping mechanism.

The cavitation performance of a pump depends not only upon the net positive suction head or state of the liquid entering the pump, but also on the ratio of vapor and liquid in the flowing stream and the distribution of vapor and liquid therein.

Central instrumentation and control for all test buildings at Pesco's Cryogenic Laboratory at Perry, Ohio. Control console with test monitoring instruments at left; recorders, center; oscillograph, calibrating controls and program boards at right.



View from second floor of test cell, showing center section of 7000 gallon dewar with valve actuators at left center and far right. Vacuum insulated connectors for external flow loop are shown in center.