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Pumping boiling liquid hydrogen without cavitation

• By **JOHN F. DiSTEFANO**, *Chief Engineer—Development, Pesco Products Division Borg-Warner Corporation, Cleveland, Ohio*

PESCO PRODUCTS DIVISION
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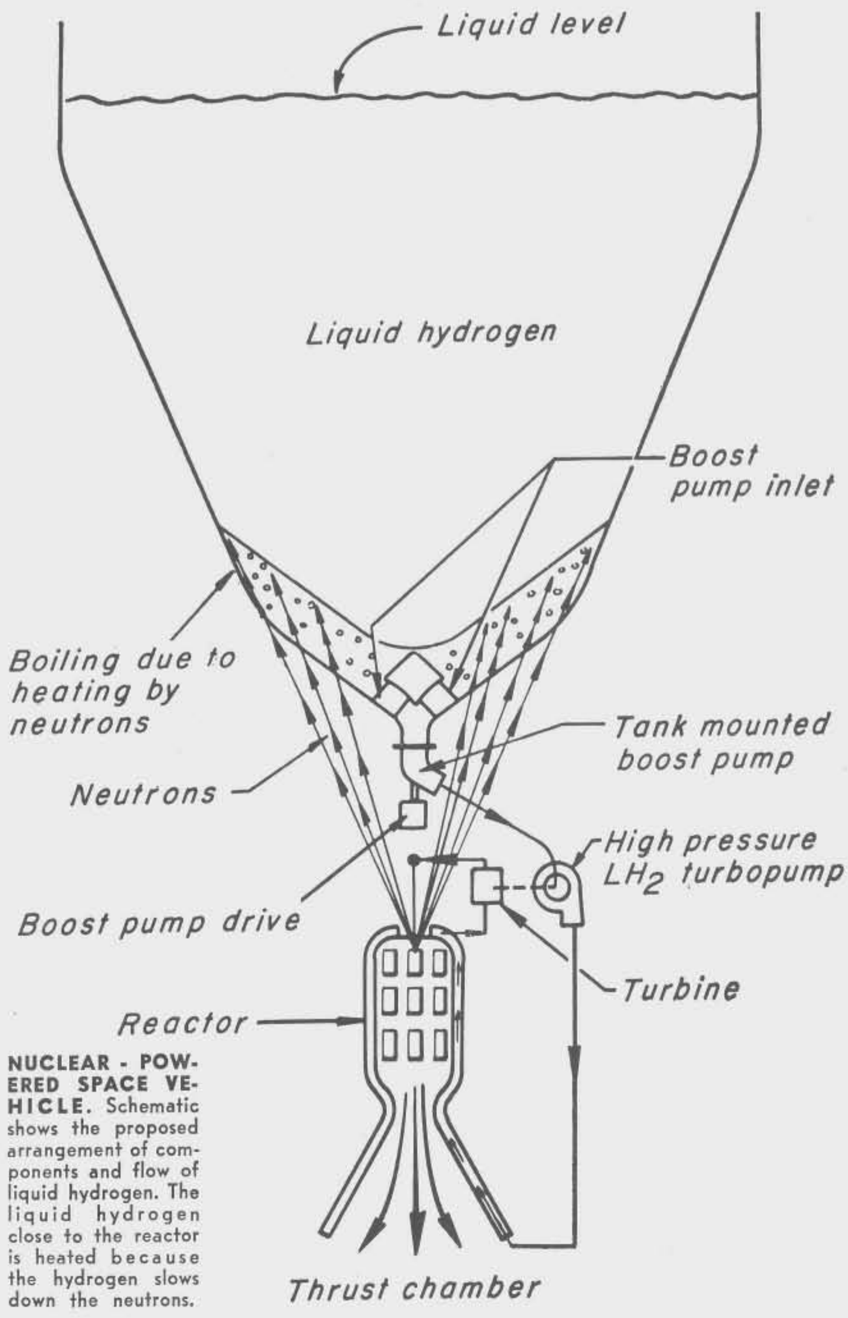
A booster pump submerged in liquid hydrogen at −420 F delivers boiling hydrogen with enough pressure to avoid cavitation in a downstream pump.



NUCLEAR - POWERED SPACE VEHICLE. Schematic shows the proposed arrangement of components and flow of liquid hydrogen. The liquid hydrogen close to the reactor is heated because the hydrogen slows down the neutrons.

LIQUID HYDROGEN, the propellant in a reactor-powered space vehicle, is heated by the slowdown of gamma rays and neutrons absorbed from the nearby reactor. Depending on the temperature of the LH_2 when the reactor starts, the neutron slowdown may heat the fluid to the saturation point, or may even superheat and cause vigorous boiling to occur at the bottom of the tank. Heat input to the bottom of the tank is estimated at 1.0 watts/sq cm, which equals 53 Btu/min/sq ft. This boiling, gas-liquid combination causes the turbopump feeding the LH_2 to the reactor and thrust chamber to cavitate.

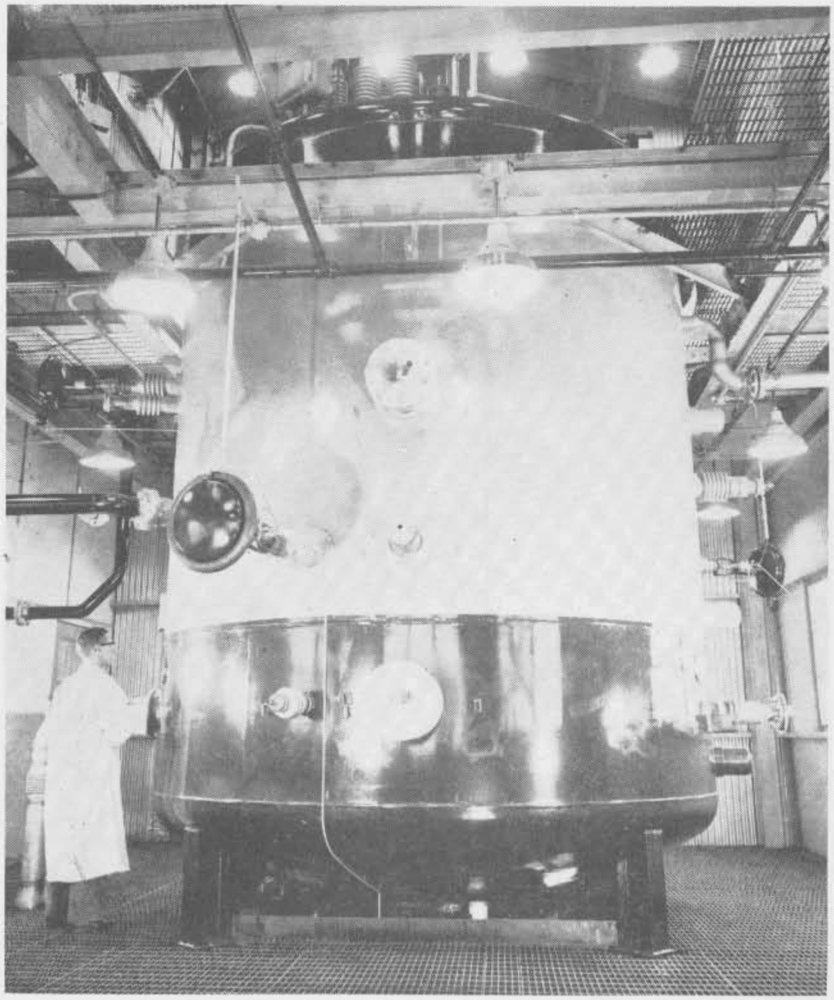
Pesco Products Division undertook a test program to show that a tank-mounted booster pump can deliver adequate net positive suction head (NPSH) to the inlet of a turbo-pump in a reactor-powered vehicle. This program proved that an all-inducer (no impeller stage), booster pump mounted inside the tank will deliver boiling LH_2 to the inlet of the high-speed, high-pressure turbopump with enough NPSH to prevent cavitation. Net positive suction head is the physical head of liquid above the vapor pressure of the liquid available to suppress cavitation.

In addition, this experimental program revealed some interesting sidelights. It was found that tank-mounted, high-speed, all-inducer booster pumps produce a great improvement in the commonly accepted cavitation parameters. This is due to pump design features and to thermal properties of LH_2. These improvements also result from certain physical phenomena associated with tank-mounted, inducer-type pumps:

- A properly designed inducer pump has high vapor-handling capability. The inducer collapses the vapor of the two-phase fluid, delivering pure liquid.
- To prevent the formation and aid the coalescence of vapor which chokes the inlet, the inducer pump should have a properly designed inlet bell.

• **Hydraulic and Thermal Similarity**—Cavitation of a pump depends not only upon the net positive suction head and the state of the liquid entering the pump, but also upon the ratio of vapor and liquid and their distribution in the flowing stream. Thus, a pump feasibility program must demonstrate hydraulic and thermal similarity between the prototype (the reactor installation in the space vehicle) and the model (the Pesco test unit). The booster pump in the space vehicle will be larger than the pump model used in the Pesco program.

Hydraulic similarity of non-cavitation and cavitation performance had to be established for the inducer pumps in the smaller test unit and the larger prototype unit. The first step was to determine the flow rate of the prototype pump as well as its inlet and outlet pressures. Systems manufac-



DEWAR OF 7000-GALLON CAPACITY occupies the center of the huge liquid hydrogen test cell at Pesco's Cryogenic Laboratory at Perry, Ohio. Valve actuators are at left center and far right. Vacuum-insulated connectors for an external flow loop are in the center. A single building at the Laboratory contains the central instrumentation and control for all test buildings.

INDUCER-BOOSTER PUMP DEFINITIONS

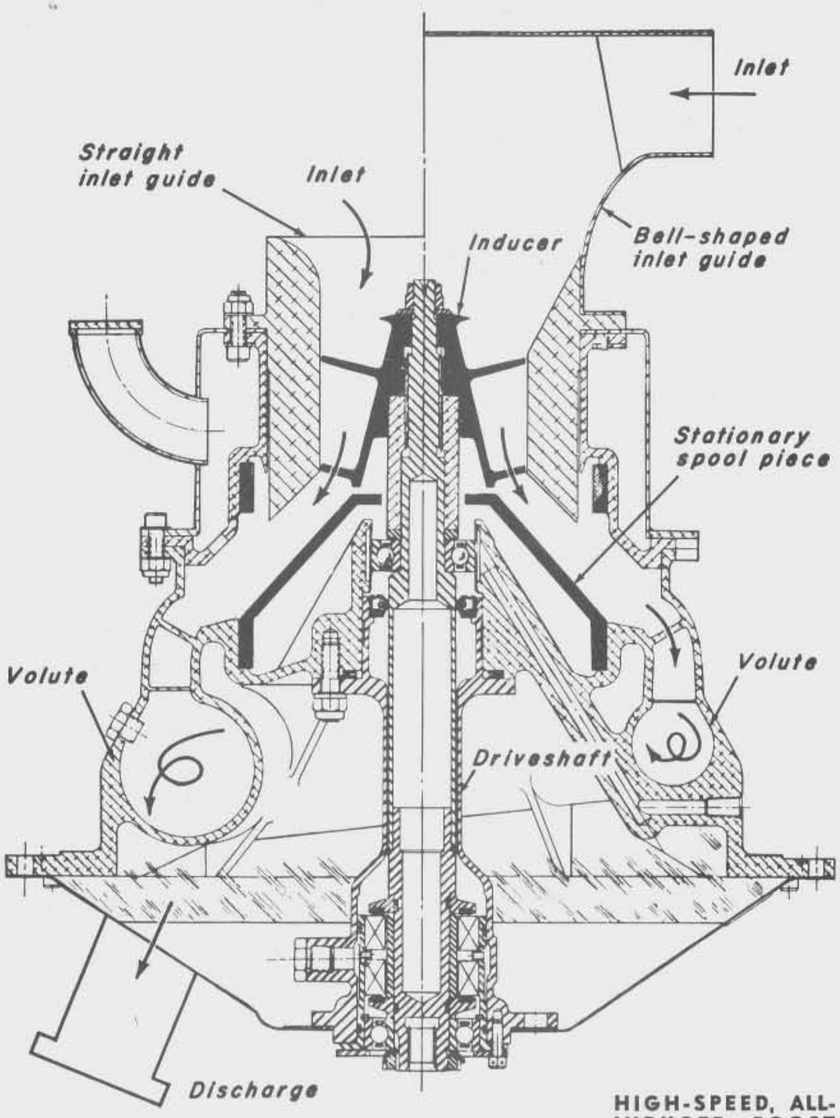
Cavitation occurs in a flowing stream of fluid when the absolute pressure of the fluid approaches the vapor pressure of the fluid. The resulting vapor disturbs flow, produces vibration and noise, and adversely affects pumps and other equipment in the circuit.

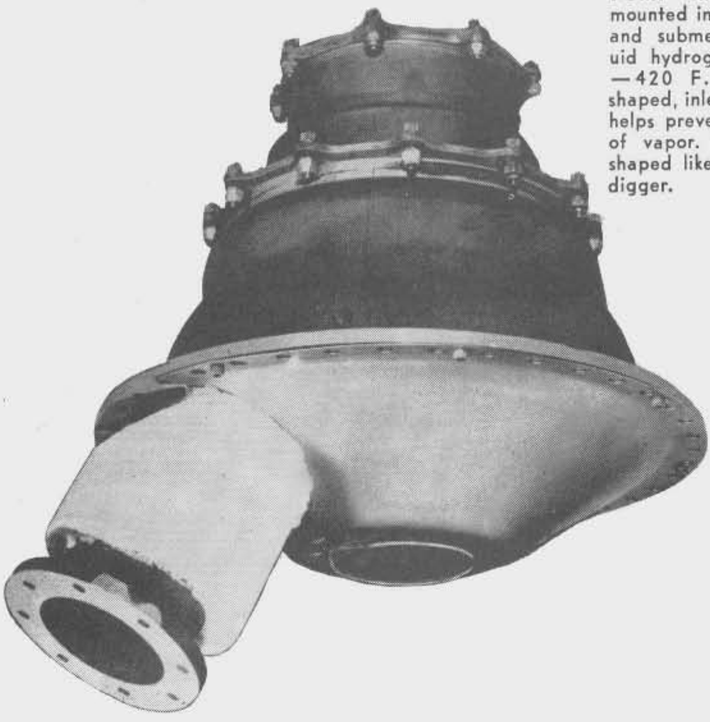
A booster pump increases the pressure in a closed stream of fluid sufficiently to maintain it as a liquid with adequate NPSH. This prevents cavitation in downstream pumps and equipment. The booster pump may be tank-mounted or line-mounted.

An inducer is a type of helical pumping element with the inherent ability to pump liquid under cavitation conditions.

An inducer-impeller pump is a multi-stage, centrifugal pump consisting of an inducer as the first stage, and a vane-type impeller as the second stage. The inducer helps resist cavitation by collapsing vapor pockets in the pumped fluid, and the impeller generates fluid pressure.

An all-inducer pump is a centrifugal pump having only an inducer as the rotating pressurizing element. As demonstrated by the Pesco research study, a properly designed all-inducer pump can efficiently handle a fluid having a high vapor content. By compressing the fluid, the inducer collapses the vapor and delivers only liquid.





HIGH-SPEED, ALL-INDUCER BOOST PUMP and drive are mounted inside the tank and submerged in liquid hydrogen at about −420 F. The bell-shaped, inlet guide vane helps prevent formation of vapor. Inducer is shaped like a post hole digger.

turers for reactor powered vehicles established reasonable values. These values were a flow rate of 8000 gpm (about 80 pps of liquid hydrogen), a tank pressure of 15 to 20 psia, and a pump head rise of 5 to 10 psi.

To demonstrate the hydraulic similarity between the model and the prototype, first the inlet pressure and outlet head values during operation must be the same for both the prototype and model. Then hydraulic similarity under both cavitation and non-cavitation performance is maintained by keeping the ratio of the model and prototype speeds inversely proportional to the square root of the model and prototype flows. Thus, to achieve hydraulic similarity, constant specific speed and constant suction specific speed must be maintained under non-cavitation and cavitation operation. This results in the model operating at a speed inversely proportional to the ratio of the square root of the flows.

• **Non-Cavitation Hydraulic Similarity**—The criterion for establishing non-cavitation hydraulic similarity is specific speed N_s, defined as:

$$N_s = \frac{N \sqrt{gpm}}{(H)^{3/4}} \qquad (1)$$

where: N = pump speed, rpm.
gpm = pump flow, gpm.
H = pump head, feet.

Inducers operate in the specific speed range of 5000 to 9000 rpm. Assuming an N_s of 7000 and a head rise of 300 feet (almost 10 psi), the operating speed of the prototype may be calculated as:

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

As stated previously, two pumps developing the same head will have hydraulic similarity if the ratio of pump speeds is inversely proportional to the square root of the flows. Capital letters refer to the prototype (larger) pump.

$$n = N \sqrt{\frac{Q}{q}} \qquad (2)$$

For $N = 5450$ and $q = 1000$:

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

• **Cavitation Hydraulic Similarity**—When comparing two similar tank-mounted or line-mounted pumps, pumping similar fluids, the criterion is the suction specific speed S, defined as:

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

where: N = pump speed, rpm.
gpm = pump delivered flow, gpm.
H_{sv} = net positive suction head, feet.

To demonstrate the same capability of emptying a tank of boiling liquid (the ability to pump to the same H_{sv} value), the model (smaller) pump speed is:

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

$$= 15{,}300 \text{ rpm} \qquad (4)$$

Thus, the speed is the same for both cavitation and non-cavitating operation.

• **Thermal Similarity**—Heat leak rate and thermal similarity were established by measuring liquid hydrogen boil-off. This rate was determined by noting the change of the liquid level in the tank per unit of time. Knowing the latent heat of vaporization of liquid hydrogen, the exposed area of the tank, and tank pressure, it was possible to determine the heat leak per unit area.

These calculations are somewhat conservative because most of the heat leakage takes place at the pump mounting surface, which is in itself a heat short. Heat leak rates of over 80 Btu/min/sq ft were calculated. This is 50% greater than the estimated rate expected in a nuclear reactor-powered vehicle.

• **Test Apparatus**—An inducer-impeller pump, driven by a hydraulic motor, was especially modified for the test program. The second-stage pump impeller was replaced with a stationary spool piece which effectively guided the liquid flow into the volute. A straight inlet adapter was provided over the modified inducer.

The pump and drive assembly were mounted on the sump of a 7000-gallon dewar, and were foam-insulated at the mounting base. Sufficient heat leakage (over 80 Btu/min/sq ft) was allowed through this area to simulate the radiation heat leak described previously.

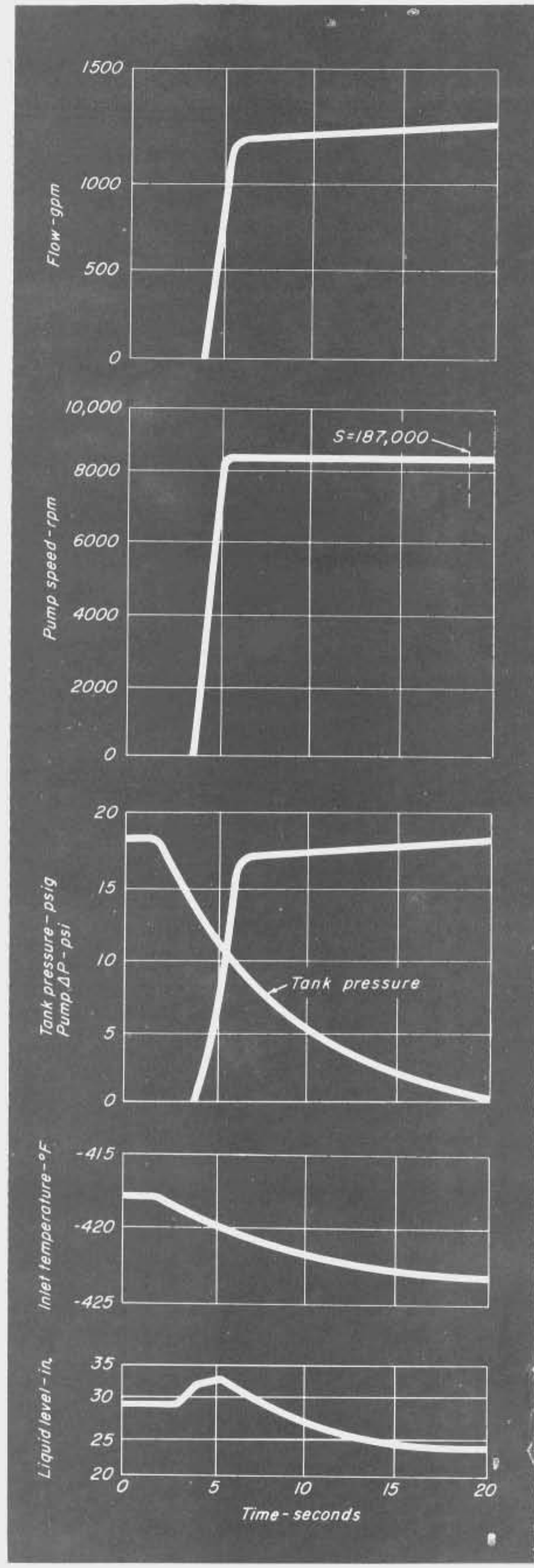
The boiling of the liquid hydrogen at the pump inlet was filmed with a motion picture camera mounted atop the dewar on a modified cover plate. The camera was operated with the tank pressurized to 5 psig, and while the tank was being depressurized at 1 psi per second. Of particular interest was the active, deep-foaming to which the boiling hydrogen flared during depressurization.

• **Test Data Confirmed Calculations**—The measured test data confirmed earlier calculations with remarkable accuracy. As previously indicated, the computed model pump speeds under non-cavitation and cavitation conditions were identical (15,300 rpm). Also the pump was to deliver 1000 gpm with a head rise of 300 ft.

The model pump in the simulated test vehicle used in the 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 specific speed number of 9000.

During the tests, tank-mounted booster pumps handling liquid hydrogen consistently achieved suction specific speeds of over 200,000. An optimum tank-mounted installation using a well-designed, inlet bell achieved S-numbers of over 400,000.

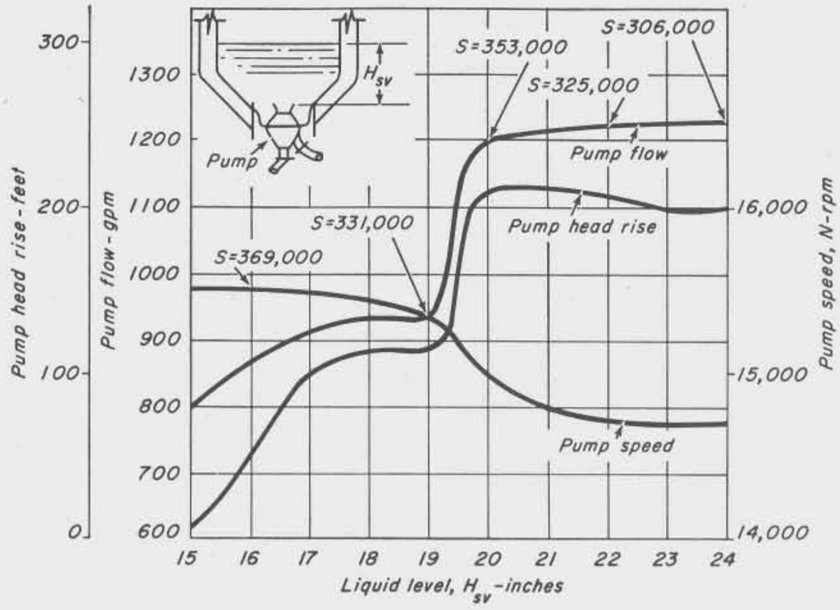
The plot of *static* boiling performance graphically illustrates the test data obtained from the test vehicle without an inlet bell. Static boiling occurs when the liquid hydrogen is saturated. Notice that at the intermediate liquid level (from 20 to 17½ inches) there is a sharp fall-off in flow and pressure. This is fol-



TEST DATA OF PUMPING DYNAMIC BOILING LIQUID HYDROGEN. During the 20-second test the initially saturated (static boiling) liquid hydrogen is depressurized from about 18 psi to zero, producing violent boiling and foaming. The booster pump was able to produce high enough net positive suction head to prevent cavitation in the downstream pump.

lowed by a gradual deterioration in performance as the liquid level decreases. Before any significant fall-off in performance, the test vehicle obtained suction specific speeds of over 350,000. This is remarkably good cavitation performance.

The performance of the test vehicle was also plotted for *dynamic* boiling conditions. This occurs when tank pressure is rapidly decreased from saturation conditions. The plot shows that the pump was started after tank depressurization began. Even under these extreme boiling conditions, the test pump delivered liquid only (single phase) with adequate net positive suction head to prevent cavitation in a downstream pump. ▼▼▼



TEST DATA OF PUMPING STATIC BOILING LIQUID HYDROGEN. The suction specific speed number S (defined in Equation 3) shows remarkably good cavitation performance.

MOTION PICTURE OF LIQUID HYDROGEN TEST AVAILABLE

A 12-minute, black and white print (16 mm, silent) of the motion picture made inside the dewar during the Pesco pumping test is available on loan. Write on your company letterhead stating the reason for your interest. Send your request to R. H. Montgomery, Pesco Products Division, Borg-Warner Corp., 24700 N. Miles Rd., Bedford, Ohio.

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