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SUMMARY

A hot wire-stillwell liquid level sensor system was developed for general use as a liquid level sensor for cryogenic fluids. Results of an analytical and experimental study showed that the device possesses a fast time response and is sufficiently accurate, rugged, and electronically simple for both filling and outflow applications. It is not subject to the cool-down problem of most level sensors. Information and recommendations are provided herein for the design of hot wire rakes and stillwells for cryogenic applications.

INTRODUCTION

A problem associated with the use of liquids as rocket propellants is the determination of the mass of the liquid in the propellant tank. Liquid content of propellant tanks is required during filling and topping operations to assure the proper amount of propellant to complete a specific mission. Liquid content is also needed during stage operation to assure optimum propellant utilization. In addition, the liquid content of storage and transport tanks is required for various applications.

Various techniques and methods for gaging liquid content of tanks have been employed with relatively good success for conventional propellants including liquid oxygen. Some techniques and methods that have been commonly employed are: weighing, pressure head, buoyant force, mass-flow measurements, capacitance measurements, and various liquid-vapor interface detectors, such as float switches, temperature elements, sonic devices, and hot wires. Other techniques and methods such as nuclear radiation absorption have been proposed but have not, as yet, been developed to the hardware stage.

Factors that influence, to varying degrees, the performance of various techniques are: interface disturbances, liquid adhering to sensors, splashing or dripping of liquid onto sensors, time lags, variations in the mass of gas and liquid, and cool-down times of the sensor.

With the use of liquid hydrogen as a rocket propellant, the task of gaging the amount of liquid in a tank has become more difficult because of some of the unique properties of that liquid. Hydrogen properties, such as low boiling temperatures and low density, markedly influence the performance of commonly used liquid content gages.

In order to evaluate various liquid content gages for liquid-hydrogen use, the NASA Lewis Research Center is conducting a comprehensive analytical and experimental program in this area. As part of this program the hot wire technique has been investigated analytically and experimentally to determine if it could be successfully employed for gaging the content of liquid hydrogen in a tank. The hot wire principle has been used in anemometry for several years (refs. 1 to 4) and has also been used in some liquid level gaging applications.

The ability of a hot wire to measure velocity or detect liquid-vapor interfaces is produced by changes in heat transfer coefficients, which in turn produce a change in the resistance of the wire, which can be detected and measured. Since the hot wire is a point sensor, its accuracy in determining the location of the interface or liquid level is greatly affected by interface disturbances and clinging or splashing of droplets on the sensing element or wire. Interfacial disturbances and splashing produced during filling operations with cryogenic liquids can be very severe. Therefore, the use of the point sensing hot wire gaging is not very satisfactory unless some means of suppressing these disturbances is employed.

Stillwells which are generally cylindrical containers, hydraulically connected to the tank fluid by some restriction near its bottom, have been successfully used to suppress interfacial disturbances. However, their use introduces two new problems. With conventional liquids the stillwell causes a level lag inside the stillwell during changes of liquid level outside. With cryogenic liquids, especially during filling with liquid hydrogen, boiling occurs inside the stillwell as the stillwell cools down.

This report describes the design and performance of an integrated hot wire-stillwell liquid level gage for general liquid hydrogen use. An analysis along with experimental verification, where practical, of the hot wire-stillwell system performance is presented. Such items as cool-down time, stillwell disturbance suppression and level lag, effect of tank conditions, accuracy, and electrical problems are considered.

ANALYSIS OF PROBLEMS

General Discussion

The hot wire is able to locate a liquid-vapor interface because of the large difference in the heat transfer coefficient at the wire surface for the two phases. The difference in heat transfer causes the temperature of the wire to change, which results in a change in its electrical resistance.

To determine the liquid content in a tank accurately, a hot wire point sensor-stillwell system must accurately indicate the mean liquid head when the interface passes it. To do this task, a number of possible error sources in content measurement must be made small by this system. The important error sources are:

(1) Thermal time lag of the hot wire

(2) Level errors resulting from tank pressure and/or fluid temperature affecting sensor operation

(3) Waves and other liquid disturbances

(4) Level lag of a stillwell

(5) Thermal time lag of a stillwell during filling

(6) Thermal time lag of the system superstructure during filling

(7) Unknown liquid density

(8) Repeatability and accuracy of the hot wire in locating a fixed placid interface

Experience indicates that a reasonable goal in level detection accuracy is of the order of 0.1 inch (ref. 4). In the following sections these problems will be discussed in detail. The discussion will lead to an integrated hot wire-stillwell system design, which was ultimately built and tested.

Hot Wire Analysis

Consider a long thin cylindrical wire through which a current flows and generates heat. Four situations that closely agree with the physical situation will be considered. They are:

(1) The heated wire is surrounded by gas at T_g (symbols are defined in appendix A), transferring heat at steady state.

(2) The heated wire is surrounded by liquid at T_l, transferring heat at steady state.

(3) The heated wire is quenched by moving it from the gas to the liquid very rapidly.

(4) The heated wire is withdrawn from the liquid to the gas very rapidly.

<u>Steady state</u>. - Consider a heated cylindrical wire (of radius R and length L) dissipating heat to a surrounding fluid whose temperature is T_∞. A steady-state heat balance on an element of this wire results in

$$P\begin{pmatrix}\text{Joulean}\\ \text{heat generated}\end{pmatrix} - q_{\text{convected away}} + q_{\text{conducted in}} - q_{\text{conducted out}} = 0 \qquad (1)$$

The temperature gradients along the wire can be neglected since $L \gg R$ (ref. 5). Thus, the steady-state energy equation becomes

$$\mathcal{H}A(T_W - T_\infty) - P = 0 \tag{2}$$

or

$$T_W = T_\infty + \frac{P}{\mathcal{H}A} \tag{3}$$

When the wire is in the gas, $\mathcal{H} = \mathcal{H}_g$, $T_\infty = T_g$, $P = P_g$, and $T_W = T_{W,g}$. The equation describing heat dissipation to the gas is

$$T_{W,g} = T_g + \frac{P_g}{\mathcal{H}_g A} \tag{4}$$

For the wire in the liquid, $\mathcal{H} = \mathcal{H}_l$, $T_\infty = T_l$, $P = P_l$, and $T_W = T_{W,l}$, which results in

$$T_{W,l} = T_l + \frac{P_l}{\mathcal{H}_l A} \tag{5}$$

These two equations, then, describe the steady-state wire temperature when it is surrounded by a gas at T_g dissipating heat according to $\mathcal{H}_g$ or when the wire is immersed in a liquid at T_l dissipating heat according to $\mathcal{H}_l$.

The difference in the wire temperature in each phase results in a difference in wire resistance. The equation that relates wire temperature to wire resistance is

$$\Omega_W \cong KT_W + \Omega_c \tag{6}$$

where K and Ω_c are constants for a given wire. Substituting equations (4) and (5) into equation (6) gives

$$\Omega_g \cong K\left(T_g + \frac{P_g}{\mathcal{H}_g A}\right) + \Omega_c \tag{7}$$

and

$$\Omega_l \cong K\left(T_l + \frac{P_l}{\mathcal{H}_l A}\right) + \Omega_c \tag{8}$$

All point sensors are on-off devices that locate the interface by sensing a large change in some property across it. In the case of the hot wire this property difference is $\Omega_g - \Omega_l = \Delta\Omega$. Subtracting equation (7) from equation (8) reresults in

$$\Delta\Omega \cong (\Omega_g - \Omega_l) = K\left[(T_g - T_l) + \frac{1}{A}\left(\frac{P_g}{\mathcal{H}_g} - \frac{P_l}{\mathcal{H}_l}\right)\right] \tag{9}$$

At the interface ($T_g = T_l$) and for constant power ($P_l = P_g = P$), the equation becomes

$$\Delta\Omega \cong \frac{KP}{A}\left(\frac{1}{\mathcal{H}_g} - \frac{1}{\mathcal{H}_l}\right) \tag{10}$$

A large value of $\Delta\Omega$ is desirable to assure reliable phase indication. The term P/A can be made large, however, and, as will be pointed out, increases of these variables are limited. Clearly a large value of K and a large difference in surface coefficients of heat transfer are necessary. This can be done in practice by choosing the proper wire material and by adjusting the electrical power to the wire so that the heat dissipation from the wire, when in liquid ($\mathcal{H}_l$), is by nucleate boiling (then $(1/\mathcal{H}_l) \ll (1/\mathcal{H}_g)$).

To take maximum advantage of the resistance difference $\Omega_g - \Omega_l$, the hot wire is used as one leg of a resistance bridge. The bridge electronics are such that its potential output is a positive function of the wire resistance Ω_W. The circuit is so adjusted that it will switch its fluid phase indication as the wire resistance Ω_W passes some critical switching value Ω_{SW} (fig. 1). Equations (7) and (8) and figure 1, then, relate the electronic indication of phase to the fluid temperature, Joulean heat, and surface coefficient of heat transfer.

Time response. - The thermal transient response of the wire can be examined to estimate its time response.

Cool-down time response: The cool-down time response is the time required for the hot wire to indicate liquid after it is rapidly immersed. The hot wire cools during this time period essentially by film boiling.

The energy equation in differential form is

$$c_m \rho_m V \frac{dT_W}{d\tau} + \mathcal{H}A(T_W - T_\infty) - P = 0 \tag{11}$$

Integration of equation (11) to determine the thermal time constant is difficult because $\mathcal{H}$ and c_m change greatly during cool down. An order-of-magnitude estimate of the time constant for a given wire can be obtained by assuming $\mathcal{H}$, c_m, T_∞, and P to be constant. Equation (11) then describes a simple first-order system whose time constant is given by

$$\Delta\tau \sim \frac{\bar{\rho}_m \bar{c}_m R}{2\bar{\mathcal{H}}} \qquad \text{(63.3 percent cool down)} \tag{12}$$

By using reasonable values ($\bar{\rho}_m$ = 500 lb mass/cu ft, $\bar{c}_m$ = 0.04 Btu/(lb mass)($^{\circ}$R), $\bar{\mathcal{H}}$ = 100 Btu/(sq ft)(hr)($^{\circ}$R)) in equation (12), the estimated time constant, for a 1-mil-diameter wire, would be of the order of 15 milliseconds. This will result in a level error of the order of 0.1 inch at a fill rate corresponding to an interface velocity of 3 inches per second. Thus, a 1-mil wire is a reasonable choice. The time response must be verified by experiment because of the uncertainties involved in the estimate (see RESULTS AND DISCUSSION).

Warmup response time: Evaluation of the warmup time, or the time required for the hot wire sensor to indicate gas after being suddenly removed from the liquid, is difficult because liquid will cling to the wire upon removal. This liquid film must vaporize before the wire can warm up and indicate the gas phase. Determination of the mass of the liquid film is difficult. Because of the difficulties apparent in an analytical approach, especially from the liquid film that clings when the wire is withdrawn to the gas, experimental data must be cited (see RESULTS AND DISCUSSION).

Factors affecting wire resistance. - Many variables could affect the wire temperature, or wire resistance: pressure, fluid contamination, environment temperature, Joulean heat, fluid used, and so forth. The electronics can be adjusted to switch its phase indication at a critical value of wire resistance Ω_{sw} (fig. 1). If the wire resistance exceeds this critical value (i.e., $\Omega_w > \Omega_{sw}$), the electronics would indicate gas, whereas a liquid indication would occur if Ω_{sw} was not exceeded ($\Omega_w < \Omega_{sw}$). Clearly then, it is desirable to pick an Ω_{sw} so that a change in tank conditions, excepting a change in phase, will not cause Ω_{sw} to be passed in either direction during operation.

Wire in liquid: When the wire is immersed in the liquid,

$$\Omega_l \cong K\left(T_l + \frac{P_l}{\mathcal{H}_l A}\right) + \Omega_c \tag{8}$$

The hot wire is adjusted to dissipate heat in the liquid by nucleate boiling. Because of the very large value of the surface coefficient of heat transfer that occurs with nucleate boiling, equation (8) simplifies to

$$\Omega_l = KT_l + \Omega_c$$

because

$$\frac{P_l}{\mathcal{H}_l A} \ll T_l$$

This result shows that the wire resistance in the liquid is not directly dependent on the surface coefficient of heat transfer or electrical power. Therefore, changes in fluid velocity, fluid contamination, and wire contamination that affect $\mathcal{H}_l$ should not affect Ω_l. Temperature profiles, which vary with time, form in the vertical direction. They are caused by less dense liquid, warmed by heat leak at elevated pressure, which "floats" to the surface and forms a "layer" of warm liquid there. Liquid at the interface is saturated and is the warmest. With increased depth, the liquid temperature decreases until it reaches a uniform temperature a short distance below the interface (liquid bulk) (refs. 6 and 7). The temperature of this liquid bulk increases very slowly with time, whereas the liquid nearer the interface warms much more rapidly. Increased pressure may cause Ω_l to exceed Ω_{sw}, thus erroneously indicating gas, when the hot wire is immersed in liquid near the interface. The near constancy of the wire resistance in the liquid bulk (fig. 1) can be used to simplify the phase-indicating technique. This simplification, as previously described, involved nulling the bridge ($E_o = 0$ when the wire is in the bulk liquid dissipating heat by nucleate boiling). Nucleate boiling was chosen over film boiling as the heat dissipation means in the liquid because the former has less practical problems and results in greater sensitivity $((1/\mathcal{H}_g) - (1/\mathcal{H}_l))$.

Wire in gas: When the wire is in the gas,

$$\Omega_g \cong K\left(T_g + \frac{P_g}{\mathcal{H}_g A}\right) + \Omega_c \tag{7}$$

Numerically $P_g/\mathcal{H}_g A$ and T_g are about the same order of magnitude; thus, the equation cannot be simplified further. At constant heat generation or constant electrical power, an increase in gas temperature alone will increase the first term and cause a small decrease in the second term through $\mathcal{H}_g$, which results in an overall increase in the wire resistance. This will not cause any difficulty since Ω_g will not drop below Ω_{sw} and falsely indicate liquid.

As the tank pressure increases such that the thermodynamic critical point of the fluid is approached, the quantity $(1/\mathcal{H}_g) - (1/\mathcal{H}_l)$ will approach zero at the interface, since the distinction between the phases disappears there. Therefore, accurate interface location at high pressure becomes difficult because of the decreased sensitivity. This does not mean that the device will be totally unable to distinguish fluid phases. In well-insulated tanks, temperature gradients through the fluid exist in practice; these gradients could allow the device to locate an effective interface at high pressure.

Structural Rigidity and Thermal Stresses

It was previously shown that the hot wire must be very thin. Unfortunately, such a wire is very weak and must be physically isolated from shock and loads. The wire can be physically isolated by "stretching" the wire between two spikes, which are part of a very rigid superstructure. To assure that no thermal stress problems exist the designer would only have to be certain that the wire is mounted such that there is adequate slack to make up for differences in the relative contraction of the rake and wire.

Stillwell Discussion

The hot wire is a point sampling sensor and is therefore very sensitive to sampling error sources such as waves, bubbles, and splashed droplets. A stillwell can be employed to isolate the point sensor from these error sources. The point sensor is placed inside this stillwell. A stillwell is a container, usually cylindrical, that is hydraulically connected to the fluid in the tank by some restriction near the bottom of the stillwell (fig. 2). This restriction might be essentially zero, as in the case of an open pipe, or large, as in the case of small orifices with a closed bottom. A shielded bottom and top (fig. 2) must be used so that bubbles and splashed droplets cannot enter inside the stillwell and affect the phase indication of the wire.

The inertia of the column of liquid in the stillwell and/or energy dissipation by small orifices are used to dampen waves. Generally, the hydraulic connection of the stillwell should be as deep as possible for maximum disturbance suppression. Further discussion of the wave suppression ability of a stillwell and tank sloshing can be found in reference 8. If a long stillwell is not possible, then small orifices can be used for suppression. The use of small orifices in stillwells to suppress disturbances can produce a level lag error that could be quite large, depending upon the size of the orifices and the rate of change of the liquid level.

Level lag of stillwell. - As a stillwell is immersed or withdrawn from the liquid, there will be a difference (Δh) between the level inside and outside the stillwell. This level lag error Δh (fig. 3) will depend upon the sum of the frictional pressure drops in the stillwell vent, pipe, and inlet. For steady flow, if the vent pressure drop is neglected, the level lag can be predicted by

$$\Delta h = \frac{1}{12}\left[\underbrace{\frac{1}{C^2}\left(\frac{D^2}{nd^2}\right)^2}_{\mathrm{I}} + \underbrace{f\left(\frac{h_s}{D}\right)}_{\mathrm{II}}\right]\frac{v^2}{2g} \tag{14}$$

Numerically, term I of equation (14) is very large compared with term II in most practical cases where suppression orifices are used. Should the stillwell be a pipe with no orifices, then term I would become an entrance pressure drop. The lag resulting from each term is plotted in figure 4.

Stillwell cool down. - The cool-down problem with the superstructure can be sidestepped by placing most of the superstructure outside the stillwell volume.

A rough estimate of the cool-down time lag of a stillwell suddenly plunged in a cold environment can be made from the following equation (derived in appendix C):

$$\Delta\tau \cong \left(\frac{M\bar{c}_m}{A_s\bar{H}}\right)\ln\left(\frac{T_i - T_\infty}{T_b - T_\infty}\right) \tag{15}$$

where T_b is the stillwell temperature when film boiling ceases. This equation is plotted in figure 5.

For filling applications the stillwell should be made to possess low heat storage per degree per unit surface area $\bar{c}_m M/A_s$ so that it will cool down rapidly enough before and/or upon contact with the liquid to eliminate the film-boiling problem. By using reasonable values for $\bar{\rho}_m$ and $\bar{c}_m$ it can be shown that a 1-mil-Mylar stillwell will cool from room temperature to that of liquid hydrogen in about 1/2 second in gas ($\bar{H} \approx 10$ Btu/(sq ft)(hr)($^{\circ}$R)). Therefore, this stillwell should be cooled enough to prevent film boiling before the liquid reaches it. A commonly used 0.01-inch-thick metal stillwell could be undesirable, since the lag would be about 50 times longer.

Effective liquid density within the stillwell. - Any determination of liquid mass requires knowledge of the effective liquid density. The interface of a boiling liquid will be somewhat higher than that of a nonboiling liquid of the same mass because of the volume of the bubbles. A bubble-shielded, tank-length, stillwell that runs to the tank bottom should not contain bubbles within the stillwell during most operations, excepting bulk boiling situations (e.g., a saturated liquid experiencing a pressure drop) where bubbles are created in the liquid. This type of arrangement is essentially a manometer with the boiling liquid of the tank as one leg and the one phase liquid (density can be found in thermodynamic tables) of the stillwell as the other leg. A level location, therefore, leads directly to a mass determination.

Dripping and drop clinging. - Drops cling to the wires, and liquid can run down or drip off the superstructure onto the wires below when the hot wire sensor is withdrawn from the liquid. The latter problem can be handled by placing most of the superstructure outside the stillwell and sloping the wire supports inside the stillwell down away from the wire. The effect of clinging drops is best studied by experiment.

APPARATUS AND PROCEDURE

A number of different integrated hot wire-stillwell configurations were designed, fabricated, and tested based on the foregoing principles. The final configurations will be described along with the facility in which they were tested.

Description of Sensors

The hot wire material is a commercially available alloy of 72 percent nickel and 28 percent iron in the form of a wire 1 mil in diameter and 3/8 inch long. This wire was chosen for its high resistance, high resistivity (i.e., small diameter), and high temperature coefficient. The hot wire-stillwell configurations (figs. 6 and 7) have several of these 3/8-inch wires mounted horizontally across rigidly supported, electrically insulated spikes. The supporting superstructure of the wires is placed outside the stillwell volume with the spikes pierced through the stillwell wall. The enclosing stillwells were made of 1-mil Mylar. This material was either stretched between supports or formed as a cylinder. At the top of the stillwell an arrangement similar to a "screened porch" is used as a vent. The bottom is closed by an overhanging cone that shields the orifices that are cut in the side walls of the stillwell, so that bubbles cannot enter. The supporting structure for the stillwell is connected to the stillwell by long thin thermally isolating Mylar tabs. The spikes holding the hot wires are sloped so that liquid runs down away from the wires.

Description of Electronics

The hot wire is used in one arm of a standard alternating-current bridge circuit similar to the simplified version shown in figure 8. The output potential of the bridge E_o is a function of the sum of the hot wire resistance and the lead resistance. This output is amplified and fed to a phase-indicating device (lights, relays, etc.) that will "switch" phase indication at Ω_{sw}. The bridge is balanced when the wire is in liquid and dissipating heat by nucleate boiling. The bridge was designed to keep the power P to the hot wires nearly constant.

Test Facility

The test facility is shown in figure 9 and can be described briefly as a tank inside a vacuum-jacketed tank. The inside tank assembly and associated hardware maintain a fixed placid liquid level by the judicious use of weirs. Conditions in the tank can be visually observed. The sensor to be tested is fixed to a micrometer-like movable probe that can immerse the sensor a known amount, referenced visually to the liquid level by a sharp spike (fig. 9). The level locating accuracy of the rig is

Level locating accuracy of spike and micrometer, etc. . . . . 0.005 in.
Hot wire referenced to spike within . . . . 0.005 in.

Thus, the overall accuracy is approximately 0.01 inch.

Level locating repeatability . . . . 0.001 in.

Procedure

The tests were designed to determine the performance of the integrated hot wire-stillwell systems in liquids nitrogen and hydrogen. The thermal time response of the hot wire was determined independently as described in appendix B.

Liquid nitrogen tests. - A stillwell test, in part, consisted of the rapid immersion of a warm stillwell system into liquid nitrogen, contained in an open Dewar, while noting how quiet the interface remained inside the stillwell during the plunge. This dunking also acted as a severe thermal shock to the system. The level locating ability of the hot wire was initially tested in nitrogen.

Liquid hydrogen tests. - The steady-state wire resistance was measured when the wire was in each fluid phase (see appendix B). The probe's level locating accuracy and repeatability at lower pressure and the effect of elevated pressure (maximum pressure = 40 lb/sq in. gage) upon its operation were determined. Various interface conditions (placid, boiling, and splashing) were simulated, and the interface condition inside the stillwell was observed. Also, the hot wire itself was closely observed as to its tightness, type of heat emission (i.e., boiling, etc.), drop clinging, and so forth.

RESULTS AND DISCUSSION

Hot Wire Structural Considerations

Rapid immersion of the rake in liquid nitrogen and hydrogen caused no apparent structural damage to the Mylar stillwell, superstructure, or hot wires. Apparently there are no noticeable thermal stress problems. The structure, in practice, has proved to be sufficiently rugged for general use.

Hot Wire

Hot wire resistance. - The resistance of the hot wire in liquid and gaseous hydrogen at 36.7° R was measured at various power levels as described in appendix B. The results are plotted in figure 10. As the analysis indicated, the resistance of the wire in liquid, dissipating heat by nucleate boiling, is independent of electrical power; while the resistance in gas depends on the power. According to figure 10, the resistance change ($\Delta\Omega/\Omega_l$) of the device (at 0.15 watt) is 37 percent at the boiling point. A finer wire than that used in this study may be necessary in some applications to reduce boiloff (0.003 lb/(hr)(wire)).

Effect of tank conditions. - The hot wire was able to locate the interface at pressures up to 40 pounds per square inch gage (the limit of the test facility). The effect of elevated pressure upon accuracy was not determined. As the analysis predicted, the wire resistance in gas was observed to increase with increased gas temperature. The surface coefficient of heat transfer from the wire in the gas was calculated from data in figure 10 to be about 500 Btu/(sq ft)(°R)(hr). This figure is three times higher than one calculated from the best available correlation (ref. 9).

Electronics. - Performance tests indicated that, while the system tested performed satisfactorily, there are a number of electrical changes that are recommended to improve performance:

(1) The hot wire should operate at constant current instead of constant power (fig. 10) for greater sensitivity.

(2) A double bridge could be used so that lead resistance and variations in wire resistance would have no effect on sensitivity. A less complicated scheme would be to place the electronics as close to the hot wires as possible. Separate nulling might still be necessary for this latter scheme.

(3) Adjustable relays, or the equivalent, should be used to eliminate the difficulties experienced with the directly driven lamps.

Time lag. - The thermal time constant of the 0.001-inch-diameter hot wire, rapidly immersed and withdrawn from liquid hydrogen, was measured as described in appendix B. Order-of-magnitude values for the time constant are:

Immersed: 20 ms cool-down time lag

Withdrawn: 30 ms warm-up time lag

The time lag on immersion bears out the analytical estimate made previously. The level errors that would result from these measured time lags are plotted in figure 4.

Stillwell

Thermal isolation. - The stillwell volume proved to be thermally isolated from the supporting structure. No apparent boiling occurred inside the stillwell volume when the rake, initially at room temperature, was rapidly immersed into liquid nitrogen. This result is very important for it shows that hot wires can be used in a filling operation when the stillwell is able to isolate the wire environment from the excessive film boiling that would normally occur. The early versions of the triangular Mylar stillwell (fig. 6) proved ineffective because of insufficient thermal isolation (i.e., the connecting tabs were too short).

Hydrodynamic disturbance isolation. - Because of space limitations, most of the hot wire-stillwell configurations tested used small orifices ($D^2/nd^2 \cong 10$) as their primary means of disturbance suppression. Disturbances that occurred during the filling of a warm Dewar (the waves were 4 in. in amplitude, and liquid splashed throughout the ullage volume) were adequately damped. The stillwell volume remained quiet and shielded the wires from bubbles and droplets. Of course, the use of small orifices means that an appreciable level lag can result. Further stillwell experiments confirmed the theory that a long stillwell with very large orifices shielded from bubbles by an overhanging dish (figs. 6 and 7) is usually desirable.

In general, this type of stillwell was able to maintain a bubble-free, well-damped liquid environment for the point sensing hot wire it enclosed. This was true for most operations except where bulk boiling would occur within the stillwell.

Dripping and droplet clinging. - Sloped wire supports and the placement of the superstructure outside the stillwell volume prevent difficulty from fluid running or dripping down from above. One minute drop would many times cling to a wire when it was withdrawn from the liquid but was apparently too small to affect performance.

Structural considerations. - There is a negligible pressure difference across the stillwell, and so long as very strong flow does not directly impinge upon the Mylar stillwell there should not be any structural failure of the stillwell. No noticeable movement of the pliable stillwell walls was observed in hydrogen due to waves. This may, however, be a problem in some applications of very large waves and/or high liquid denisty. The triangular-shaped stillwell has stretched panels for walls (fig. 6) and would, therefore, be more effective in such applications.

Accuracy

The hot wire was found to be repeatable to 0.001 inch for a fixed placid level. Placid-level accuracy was limited by the liquid interface adhering to the wire when it was withdrawn from the liquid and also by wire slack. The adhering interface would break off about 0.01 inch above the level. The slack error was also about 0.01 inch. These error sources had no apparent effect on repeatability.

CONCLUDING REMARKS

A number of items have been mentioned that must be considered in the design of an integrated hot wire-stillwell level detector. For the hot wire they are:

1. For a rapid time response and high wire resistance, a small-diameter hot wire is required.

2. The fragile hot wire requires a rigid superstructure for mechanical loads. Thermal stressing of the wire due to the relative contraction of the hot wire and the superstructure can be avoided by mounting the wire with some slack.

Items to be considered in the design of a stillwell are:

1. The stillwell should "completely" enclose the hot wires to prevent the entrance of bubbles and splashed droplets.

2. The stillwell should have a minimum heat storage per unit surface area for fast cool down during filling.

3. The supporting superstructure should be placed thermally outside the stillwell volume to minimize heat storage within the stillwell.

4. The stillwell should be as long as possible for maximum wave suppression. If a stillwell must be short, small orifices should be used for suppression; however, when there is a change in level, a level lag can result inside the stillwell.

5. The design must include means of preventing fluid from running or dripping down upon the hot wires from above as the level drops.

It appears possible to design a hot wire-stillwell sensor that could locate the level during filling and outflow within 0.1 inch, provided the stillwell wave suppression is adequate. Furthermore, a level location of the nonboiling liquid within the above stillwell leads directly to a mass determination of boiling liquid under most conditions.

The major application of this device will be for tank filling because of its ability to be dunked warm into a cryogenic liquid and still accurately indicate the level. It can be used to gage the level in a pressurized tank during outflow.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, August 7, 1963

APPENDIX A

SYMBOLS

A surface area of wire, sq ft

A_s surface area of stillwell, sq ft

C orifice coefficient

c_m specific heat of material, Btu/(lb mass)($^{\circ}$R)

D effective stillwell diameter, in.

d effective diameter of disturbance suppressing holes, in.

E_o output potential of standard bridge circuit, v

f friction factor

g acceleration due to gravity, 32.2 ft/sec^2

$\mathcal{H}$ surface coefficient of heat transfer, Btu/(sq ft)($^{\circ}$R)(hr)

h liquid height, ft

Δh level lag, in.

h_s liquid level in stillwell, in.

K constant, ohm/$^{\circ}$R

L wire length, in.

M mass of material, lb mass

n number of suppression orifices

P electrical power to heat wire, Btu/hr

q heat transfer rate, Btu/hr

R hot wire radius, ft

T temperature, $^{\circ}$R

T_b wire temperature at which film boiling switches to nucleate boiling in hydrogen, $^{\circ}$R

T_i wire temperature before cool down, $^{\circ}$R

T_w wire temperature, $^{\circ}R$

V wire volume, cu ft

v interface velocity, in./sec

ρ_m mass density of material, lb mass/cu ft

τ time, hr

$\Delta\tau$ cool-down time before change in phase indication, hr

Ω, Ω_w hot wire resistance, ohm

$\Delta\Omega$ wire resistance difference at interface, ohm

Ω_c constant, ohm

Ω_{sw} switching resistance, ohm

Subscripts:

g gas

l liquid

max maximum

∞ ambient

Superscript:

$(\bar{\ })$ average value

APPENDIX B

MEASUREMENT OF TIME RESPONSE AND RESISTANCE

OF HOT WIRE

Time Response

To determine the hot wire response time in hydrogen, an alternating-current bridge circuit was used, with the bridge output fed into a recording oscillograph. Tracings of these records are shown in figure 11. The frequency of the signal is 60 cycles per second, which is too low for any more than an estimate of the time constant. The hot wire was rapidly moved between phases at a constant environmental temperature of 36.7° R to obtain these data.

Wire Resistance

To determine the resistance of the hot wire in hydrogen, potential leads were connected across a hot wire, and a small precision resistor, with potential leads across it, was connected in series with the hot wire. The hot wire was connected to the alternating-current bridge shown in figure 8. With the wire immersed in the liquid (T_l = 36.7° R), the power was varied, and the wire current and potential were measured. This procedure was repeated with the wire in the gas at the same temperature (T_g = 36.7° R, 1/8 to 1/4 in. above interface). The results of this test are plotted in figure 10.

APPENDIX C

STILLWELL COOL DOWN

Consider a solid material of mass M and surface area A_s, initially at T_i, that is plunged into an environment at T_∞, $(T_i >> T_\infty)$. The object is to determine the time required to cool this material to a temperature T_b at which film boiling ceases. For no internal temperature gradients or heat sources, the differential equation describing the material's cool down is

$$c_m M \frac{dT}{d\tau} = -\mathcal{H} A_s (T - T_\infty)$$

By assuming average values of $\mathcal{H}$ and c_m, the equation can be integrated between the limits T_i and T_b to estimate the time required for the stillwell to cool to T_b in gas or liquid. The result is

$$\Delta\tau = \left(\frac{M}{A_s}\right)\left(\frac{c_m}{\overline{\mathcal{H}}}\right) \ln\left(\frac{T_i - T_\infty}{T_b - T_\infty}\right) \tag{C1}$$

The temperature at which film boiling ceases (T_b) should not vary much for a given fluid at the same conditions. From hydrogen boiling data its range is

$$2^\circ < (T_b - T_\infty) < 100^\circ \text{ R} \tag{C2}$$

If $300^\circ < T_i < 1000^\circ$ R, then

$$1 < \ln\left(\frac{T_i - T_\infty}{T_b - T_\infty}\right) < 6$$

Figure 5 follows directly from equation (C1) and these practical limits (eq. (C2)).

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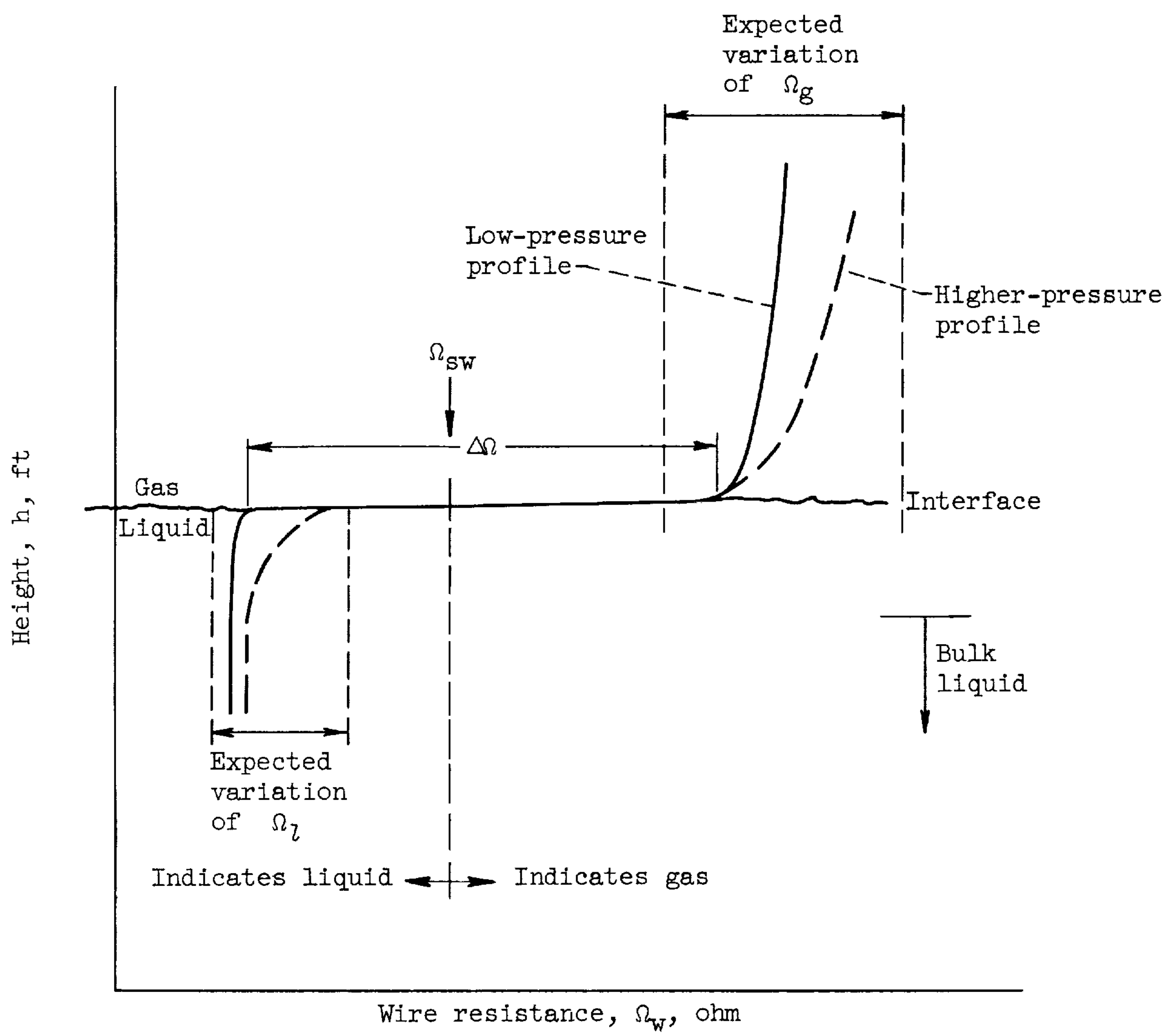


Figure 1. - Typical wire resistance profile across interface at low and high pressures.

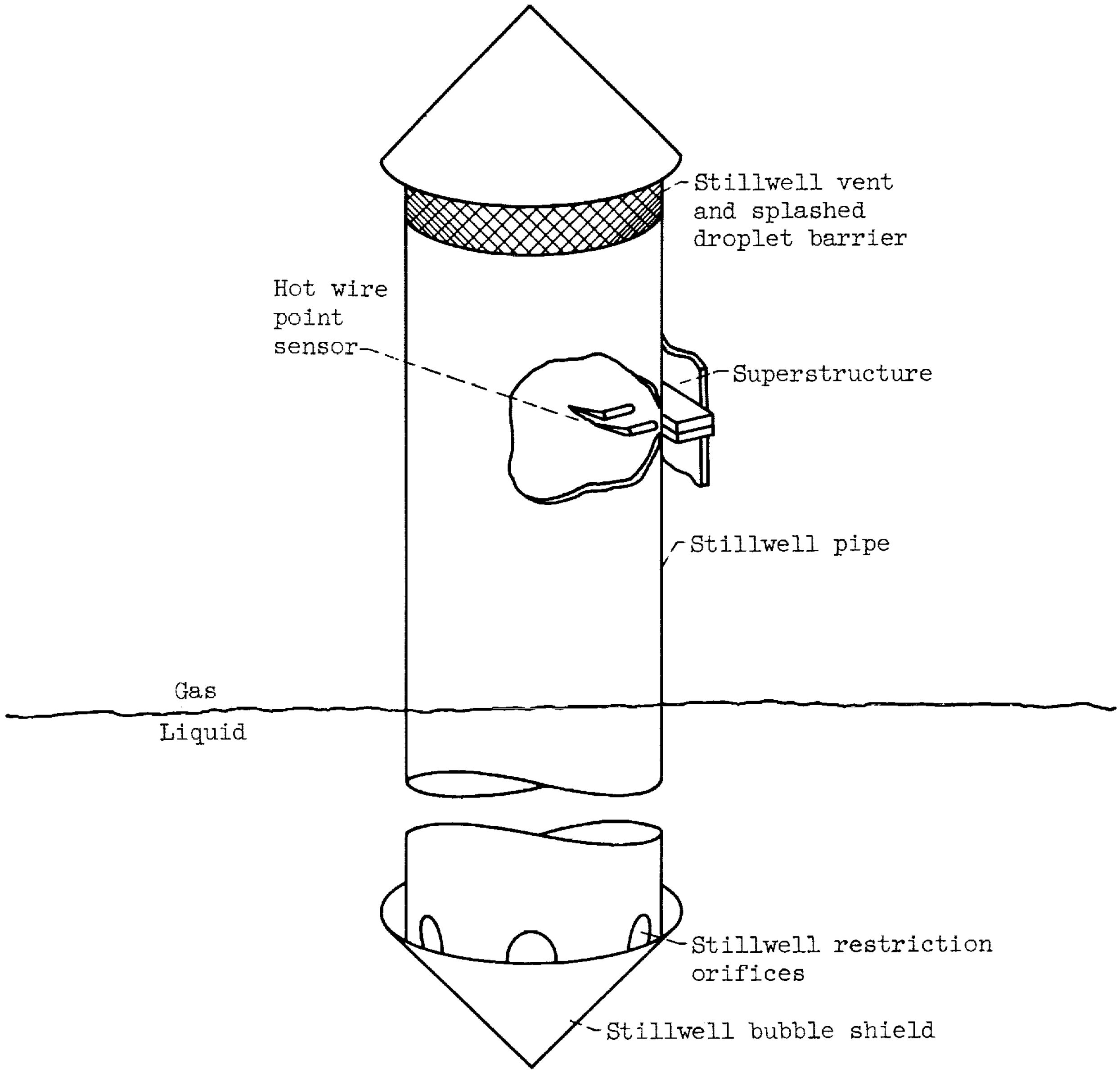


Figure 2. - Schematic of stillwell, with shielded bottom and orifices, for hot wire point sensors.

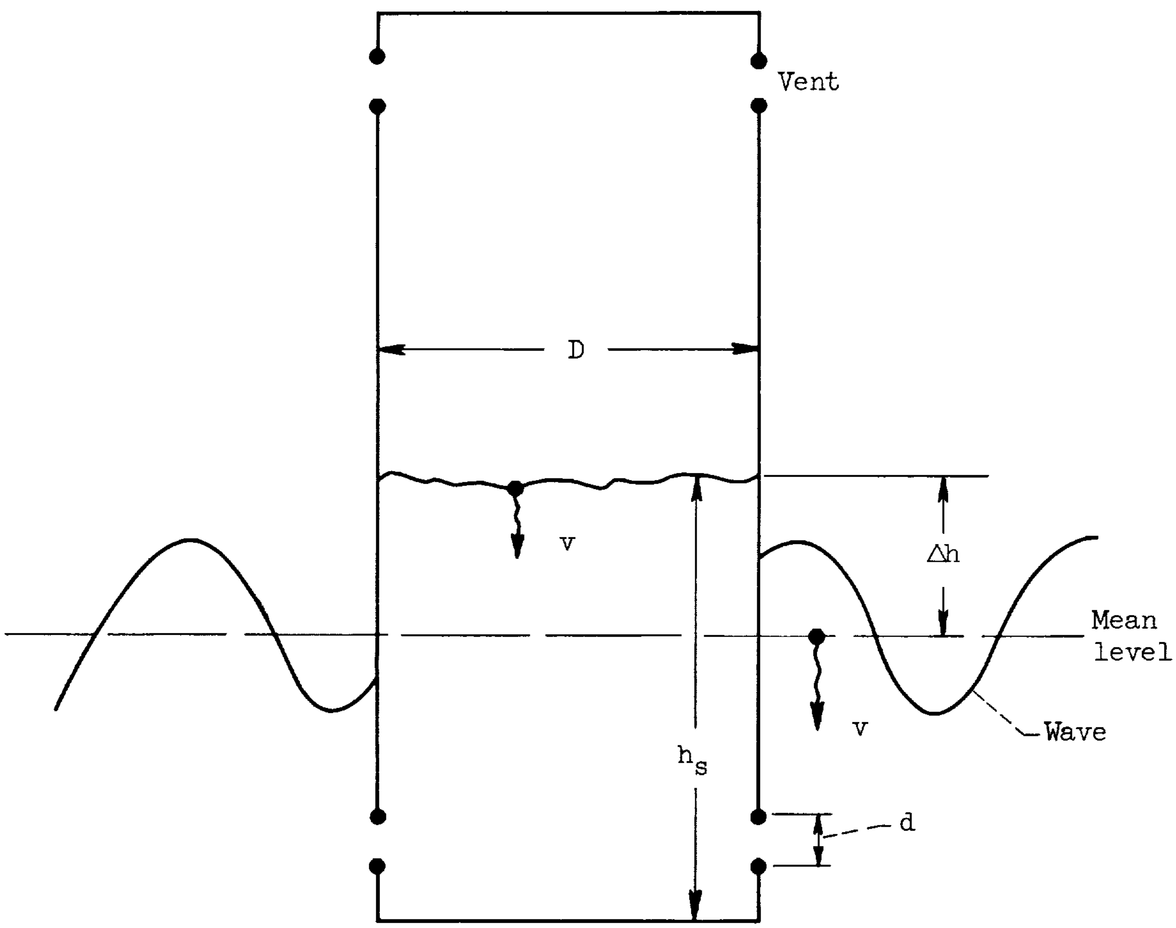


Figure 3. - Stillwell schematic showing level lag as level drops.

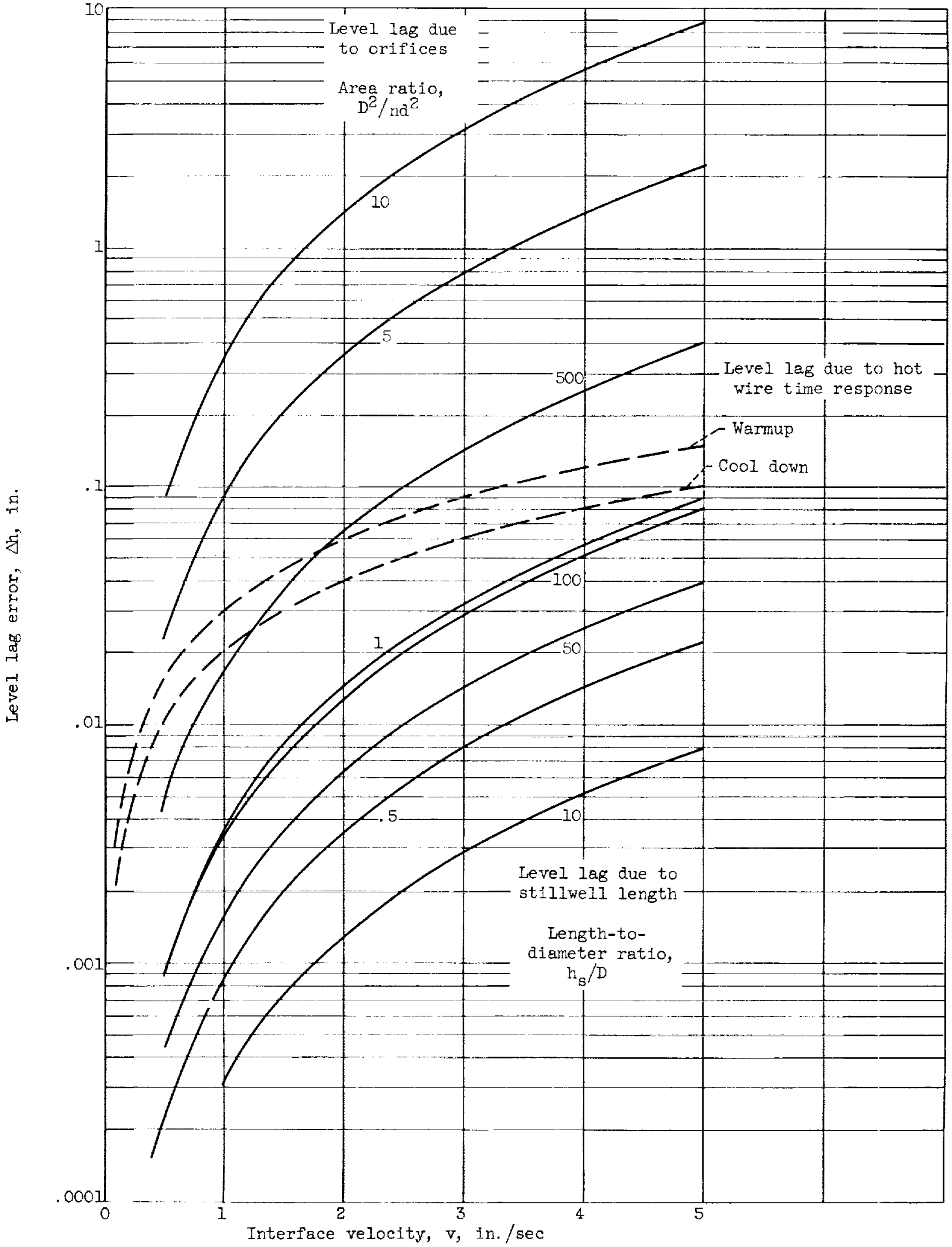


Figure 4. - Level lag errors for orifice coefficient of 0.61 and friction factor of 0.025 (smooth pipe).

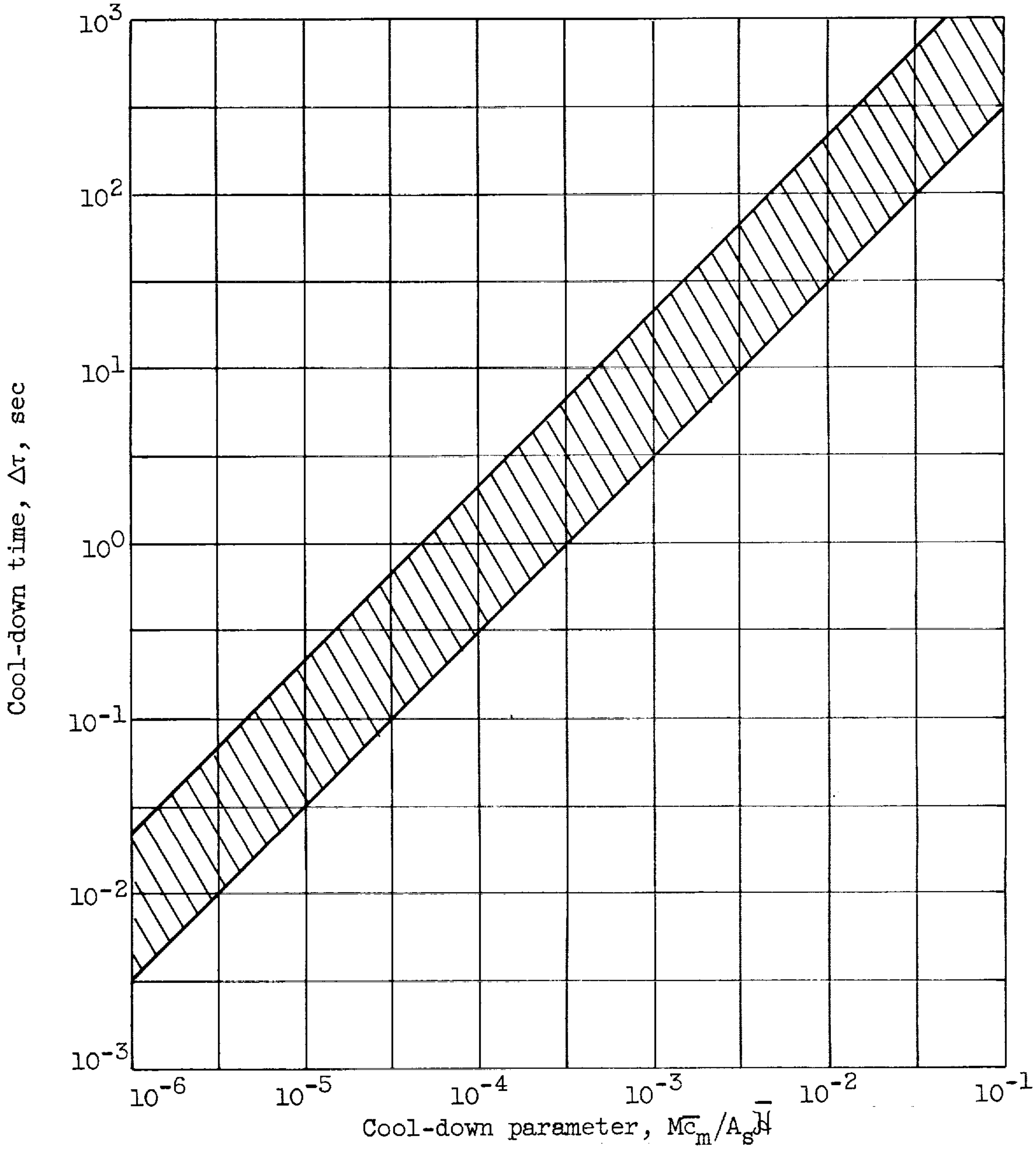


Figure 5. - Stillwell cool-down time.

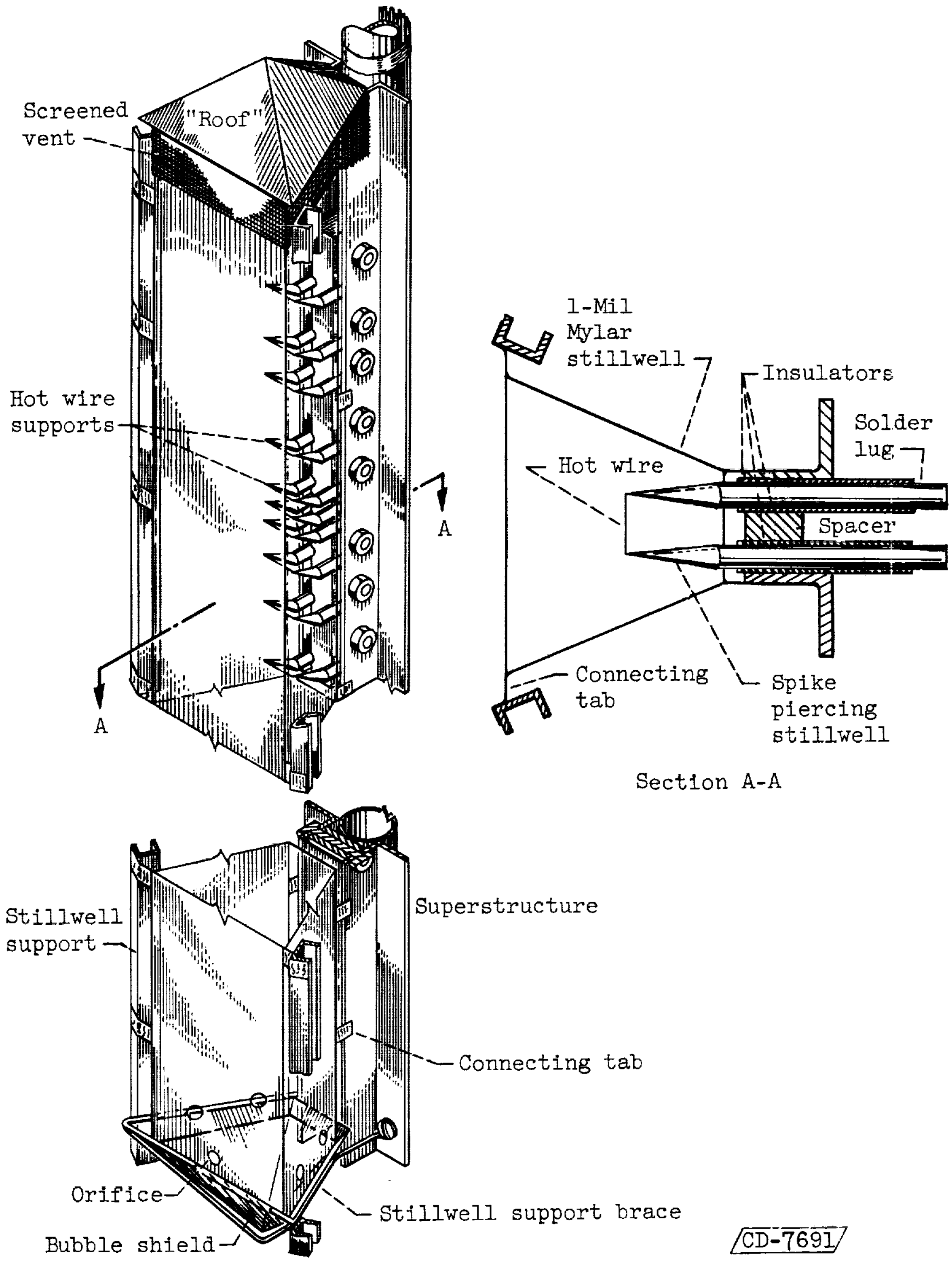


Figure 6. - Schematic of rake with triangular stillwell.

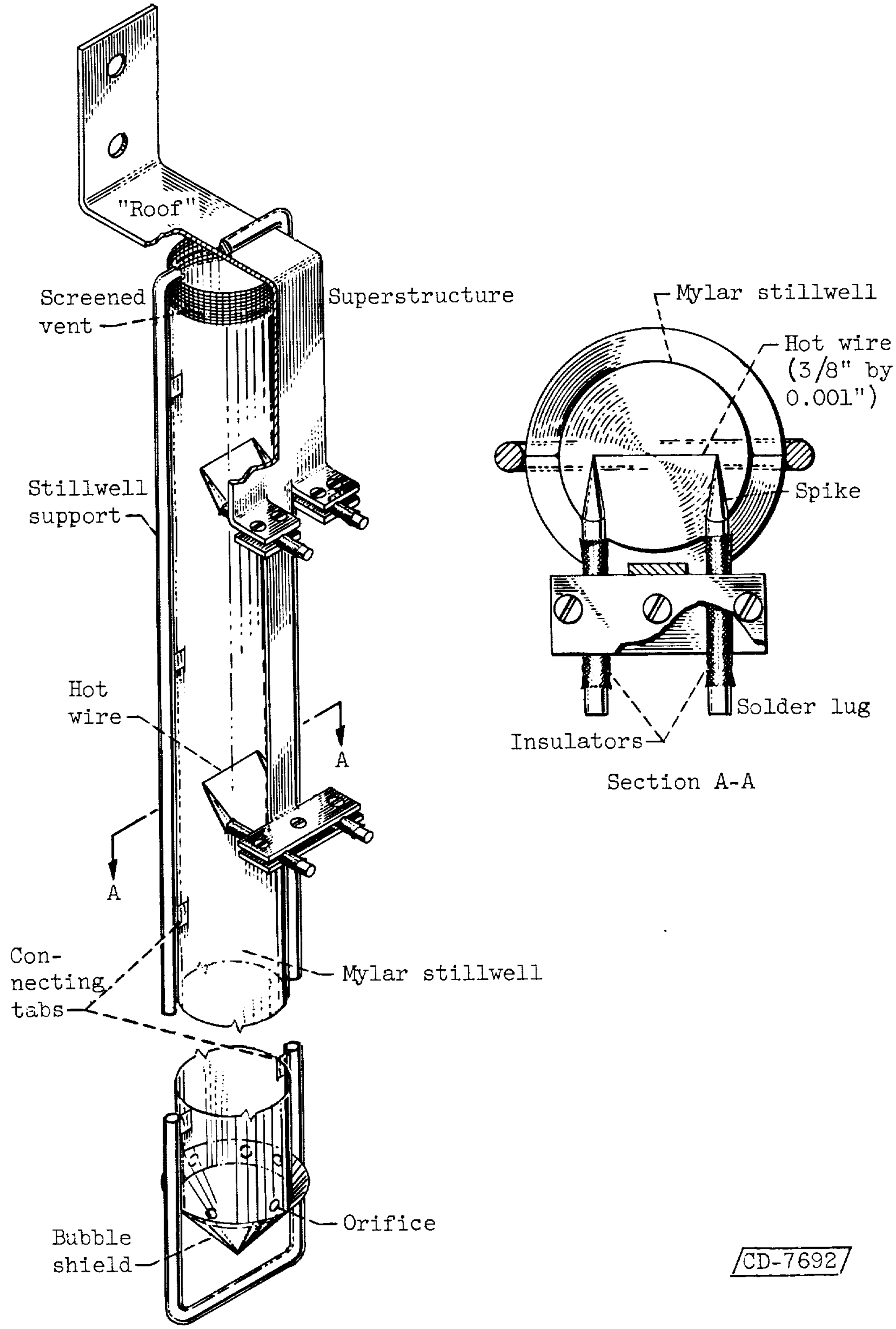


Figure 7. - Schematic of rake with cylindrical stillwell.

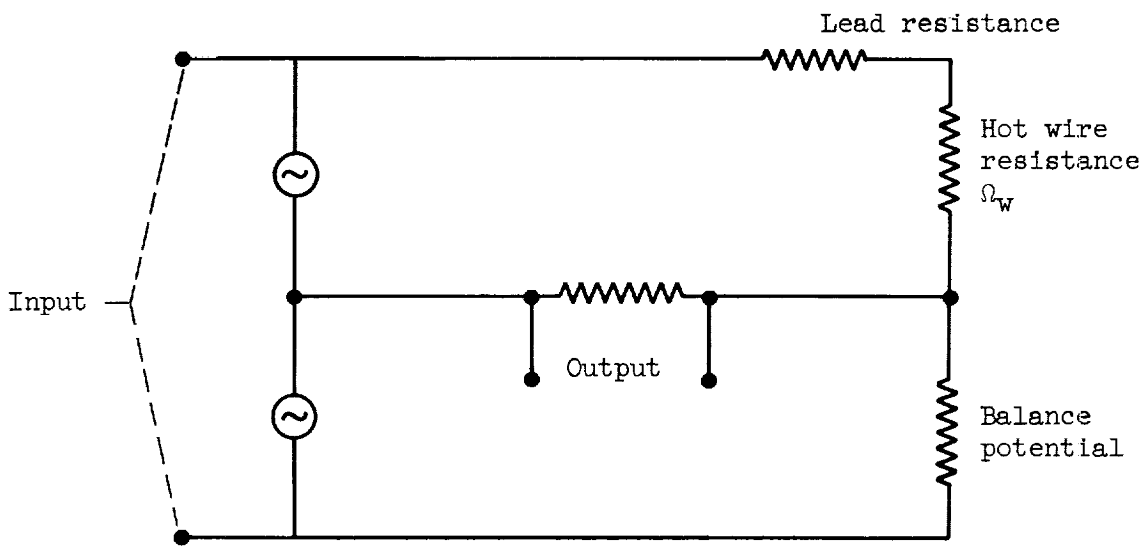


Figure 8. - Schematic of bridge circuit.

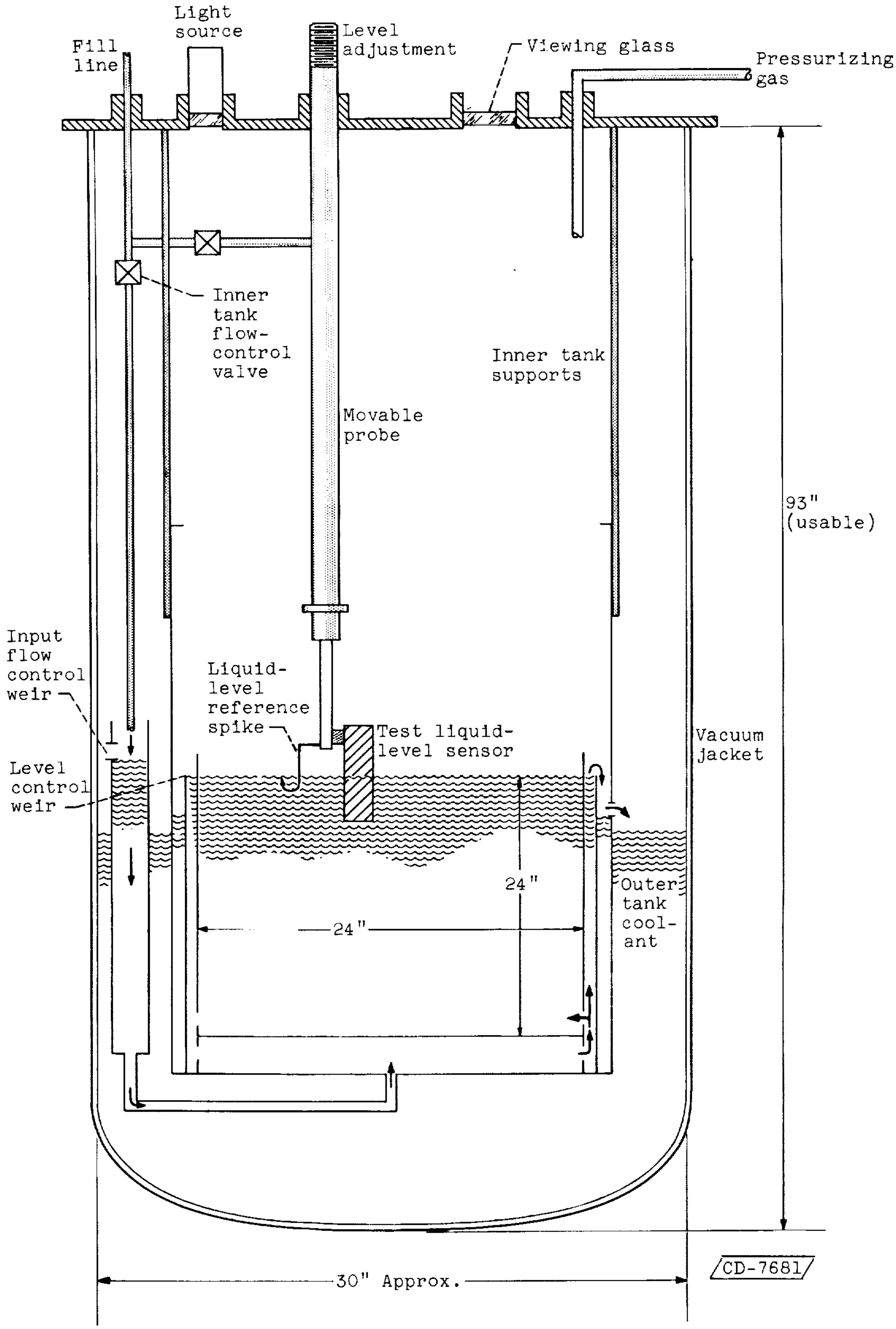


Figure 9. - Schematic of large liquid-level rig.

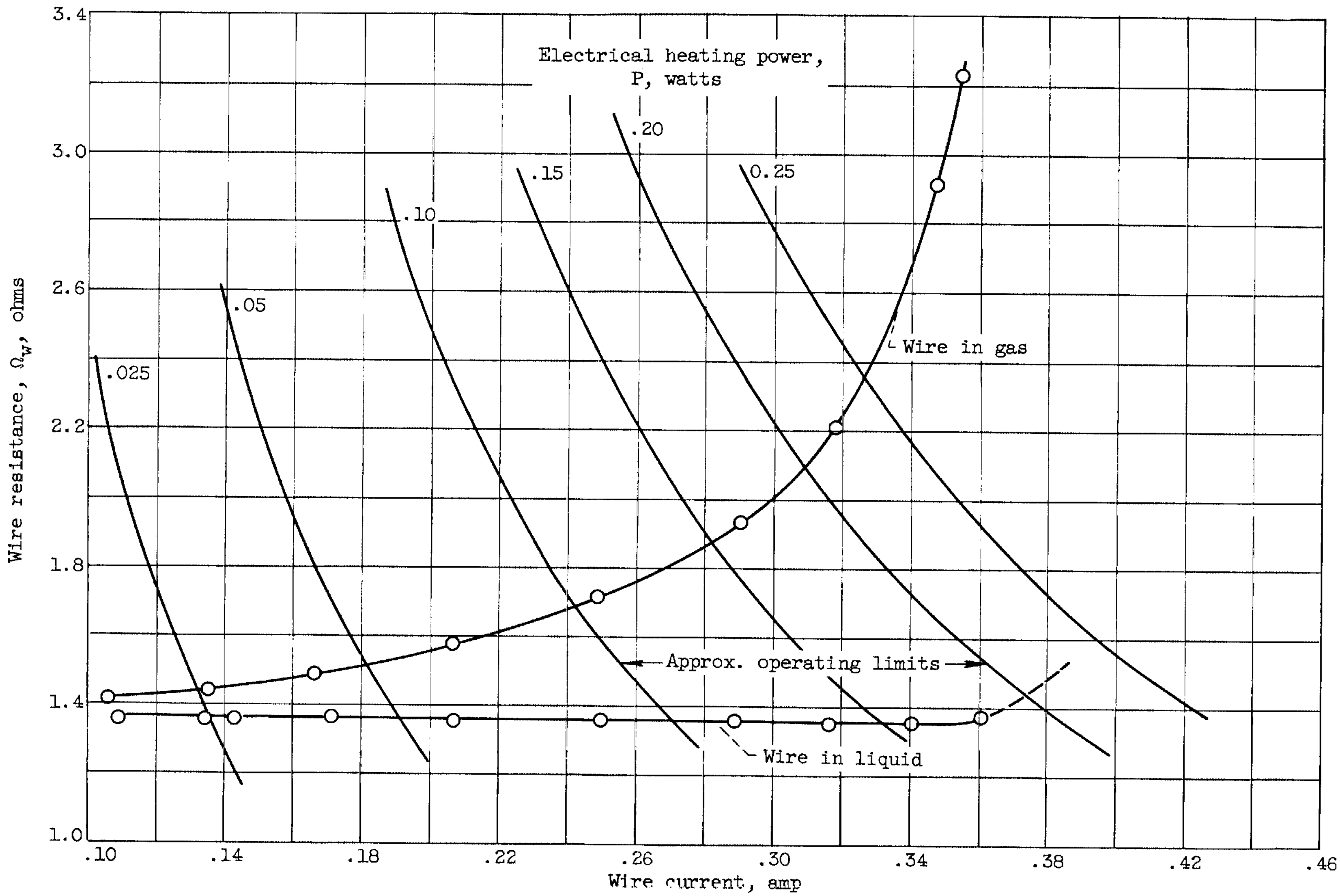
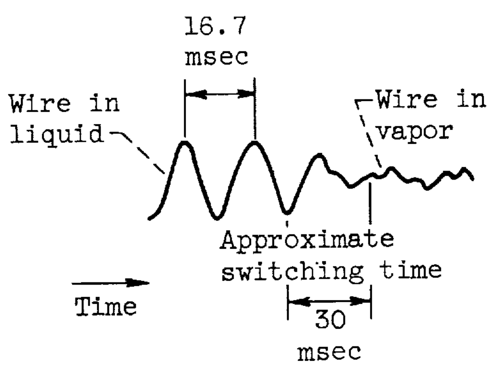
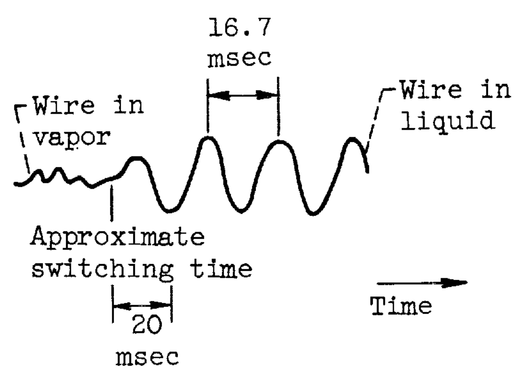


Figure 10. - Measured hot wire resistance in liquid and gaseous hydrogen at $T_g = T_l = 36.7^{\circ}$ R for 3/8-inch-long by 0.001-inch-diameter wire.



Withdrawal from liquid



Immersion into liquid

Figure 11. - Response time of hot wire in hydrogen.