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COLLEGE OF ENGINEERING
Department of Mechanical Engineering
Heat Transfer and Thermodynamics Laboratory

Progress Report No. 19

# PRESSURIZATION OF LIQUID OXYGEN CONTAINERS

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## ABSTRACT

Twenty-nine experimental runs have been made and the residual densities reduced and reported. For the twenty-nine runs the imposed heat flux was programmed at four levels, adiabatic, 1200, 2200, and 2800 Btu/hr-ft$^2$. For each level of heat flux the inlet-gas temperature was varied from -275° to 102°F. It is noted that the heat flux of 2800 Btu/hr-ft$^2$ reduced the residual density based on the adiabatic runs by 14%. Installation of a new heat exchanger for low inlet-gas temperatures was made.

Difficulties encountered in the correlation of theoretical analysis presented in Progress Report No. 18 with the experimental data are discussed. Methods for eliminating these difficulties are outlined.

A summary of the final report on the influence of acceleration on boiling is given including significant figures.

## I. EXPERIMENTAL PROGRAM

During the last period further experimental runs were made. These runs included programmed heat-flux conditions at four levels of heat flux. The nominal values of heat flux at the four levels were; adiabatic, 1200, 2200, 2800 Btu/hr-ft$^2$. It was previously stated that with the 220-volt heaters a heat flux of 5000 Btu/hr-ft$^2$ might be obtained, but due to the current limitations of the power supply, 3000 Btu/hr-ft$^2$ is the maximum flux that can be obtained. At each level of heat flux the inlet-gas temperature was varied from approximately 185°R (-275°F) to 562°R (+102°F). There were 29 runs made in the above categories.

The difficulty mentioned in Progress Report No. 18 of erratic behavior of the inlet-gas thermocouple has been eliminated on all the above runs. This was done by installing a new heat exchanger used for the low inlet-gas temperature runs.

The final mean density vs. inlet-gas temperature for these runs is plotted, along with the runs reported in Progress Report No. 18 in Fig. 1. It can be seen from these results that, in the range of inlet-gas temperatures used, a heat flux of 2800 Btu/hr-ft$^2$ will reduce the residual density by 14% based on the density obtained for the adiabatic runs.

The insulation for the inside of the container has been fitted and ready to install. The programmed runs with inside insulation will be made when the work of correlating the theory presented in Progress Report No. 18 is completed.

## II. ANALYSIS OF GAS- AND WALL-TEMPERATURE RESPONSE DURING THE DISCHARGE OF A CRYOGENIC LIQUID FROM A CONTAINER

Work on this phase has been directed toward the correlation of the experimental data to the theory presented in Progress Report No. 18. Thus far a good correlation has not been obtained. It is felt that the main difficulty in obtaining a good correlation is due to the uncertainty of the convection heat-transfer coefficient between wall and gas, and between wall and liquid. In the theory the convection coefficient was assumed constant to reduce the complexity of the analysis. It is now felt that the variation of the convection coefficient is too great to be ignored. The difficulty is especially pronounced in the heat flux case where the liquid-wall convection coefficient is known to be quite different from the gas-wall region convection coefficicent. An added, and large, variation in the convection coefficient exists in the region of wall just above the liquid interface where a known condensation and re-evaporation phenomena is taking place. Because of this phenomenon the convection coefficient is large in this region, and this causes the wall temperature to experience a very rapid transient at any location corresponding to this band of condensation-evaporation.

A further difficulty in the correlation arises from the gas-thermocouple arrangement presently installed in the tank. Under the present system the gas thermocouples are initially in the liquid, and as the run progresses they are successively exposed to the gas region. Because of this arrangement the thermocouple response is not representative of the gas temperature until the thermocouple is in equilibrium with the gas. This response period is further extended because the condensation-evaporation phenomenon discussed above takes place on the thermocouple wires as well as the wall. Because of these response difficulties, combined with a relatively short run (100 - 200 sec), the domain of correlation is small. In the hope of circumventing these response difficulties, a floating thermocouple column is now under consideration. This will keep the thermocouples in the gas region throughout the run and thus eliminate the response behavior due to the liquid-to-gas traverse of the thermocouples.

Methods of revising the analytical model are presently under consideration to help eliminate some of the above-mentioned differences between the model and the physical system.

## III. POOL BOILING IN AN ACCELERATING SYSTEM*

A study is made of the influence of system acceleration (1 to 21 g's) on pool boiling heat transfer in saturated distilled water at approximately atmospheric pressure. This is the first study made of heat transfer by boiling in the presence of a force field greater than that due to standard gravity.

A flat, electrically heated, chromium-plated copper disc served as the heat-transfer area, with a thin stainless-steel skirt attached to the periphery of the disc to provide a continuous surface. The water depth is maintained constant at 2-1/2 in., and a cooling coil on the underside of the cover condenses the vapor formed. Temperatures in the heating disc and water are measured with an uncertainty of ± 0.1°F by means of calibrated thermocouples. Figure 2 shows a cross section of the test vessel.

Acceleration is attained by use of the centrifuge principle. The test vessel is pivoted from the cross arm on a vertical shaft so that the accelera-

*The final report on this phase was published in November, 1959, as A Study of Pool Boiling in an Accelerating System, H. Merte, Jr., and J. A. Clark, UMRI Report 2646-3-T.

tion is always normal to the heating surface, as indicated in Fig. 3. Thermocouple emf's on the rotating member are measured through mercury slip-rings. Figure 4 is an over-all view of the test apparatus.

The magnitude of the acceleration is varied from that due to one standard gravity up to 21 times grativational acceleration. Heat-flux rate is varied from approximately 5,000 to 100,000 Btu/hr-ft$^2$.

Several tests were conducted with nonboiling convective heat transfer. The data agreed quite well with the correlation:

$$Nu = 0.14 \, (G_r \, P_r)^{1/3} \quad .$$

With boiling at heat-flux values up to 50,000 Btu/hr-ft$^2$, it was found that a small degree of subcooling significantly influenced the results with the system under acceleration. Data are presented showing the influence of subcooling for heat flux of 10,000 and 25,000 Btu/hr-ft$^2$ and for various accelerations. Figure 5 is a plot of the experimental data for boiling to saturated water in a standard gravity field. Figure 6 shows the influence of acceleration on $T_W - T_{sat}$ for the different levels of heat flux. The difference between the heating-surface temperature $T_W$ and the water-saturation temperature $T_{sat}$ at the heating surface decreases with an increase in acceleration at lower values of heat flux. As the heat-flux level increases, the decrease in $T_W - T_{sat}$ becomes smaller, and at the higher values of heat flux, $T_W - T_{sat}$ increases with an increase in acceleration. The decrease in $T_W - T_{sat}$ at low values of heat flux is attributed to the increased contribution of natural convection with acceleration. At higher values of heat flux, the effect of natural convection is relatively smaller. It is believed that the action of acceleration results in smaller bubble sizes at departure, with an attendent decrease in agitation. For a given total heat flux, more nucleating sites are required, which in turn require the observed higher wall temperatures.

Figure 7 is a plot of $T_W - T_5$ versus acceleration for the different levels of heat flux, where $T_5$ is the water temperature as measured 1/4 in. from the heating surface. The increase in $T_W - T_5$ with acceleration at higher levels of heat flux occurs because of the increased subcooling of the water near the heating surface. Figure 8 illustrates the relation between the measured water temperature and the local saturation temperature for several accelerations. It appears that the water temperature approaches saturation only in the upper half of the liquid. The large force field tends to maintain the water at a uniform temperature corresponding to the saturation temperature near the surface. As a means for obtaining a theoretical understanding of the process of boiling under the influence of high acceleration including the simultaneous effect of natural convection, a concept of the "Area of Influence" of the bubbles is defined and values calculated for the various accelerations and heat-flux rates. The convection and boiling contributions to the total heat flux are considered separable, and are weighed using a natural convection correlation based on experimental data for the nonboiling contribution, and a correlation for the peak heat flux for the boiling contribution. This is equivalent to taking the heat flux per unit bubble area projected on the heating surface equal to the peak heat flux.

The change in $T_W - T_{sat}$ with heat flux and acceleration is used to calculate the influence of heat flux on the number of active nucleating sites.

## IV. WORK DURING THE NEXT PERIOD

During the next period efforts will be directed toward establishing a value for the convection coefficient in the system and how it varies within the system. Attempts will also be made to establish a closer resemblance between the analytical model and the physical system. Design and construction of the floating thermocouple column will begin.

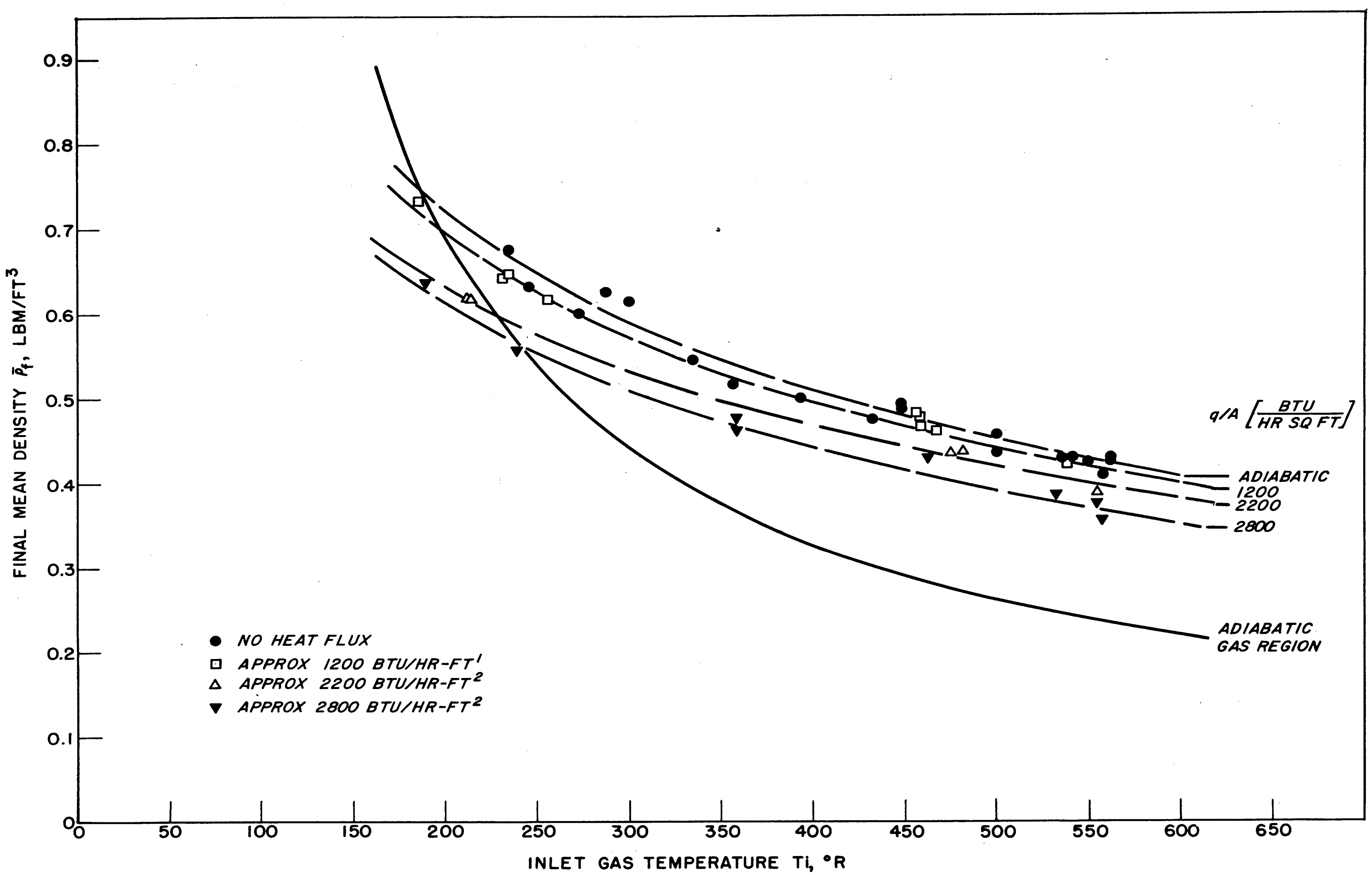


Fig. 1. Final mean density $\overline{\rho}_f$ of pressurizing gas as a function of inlet gas temperature $T_i$.

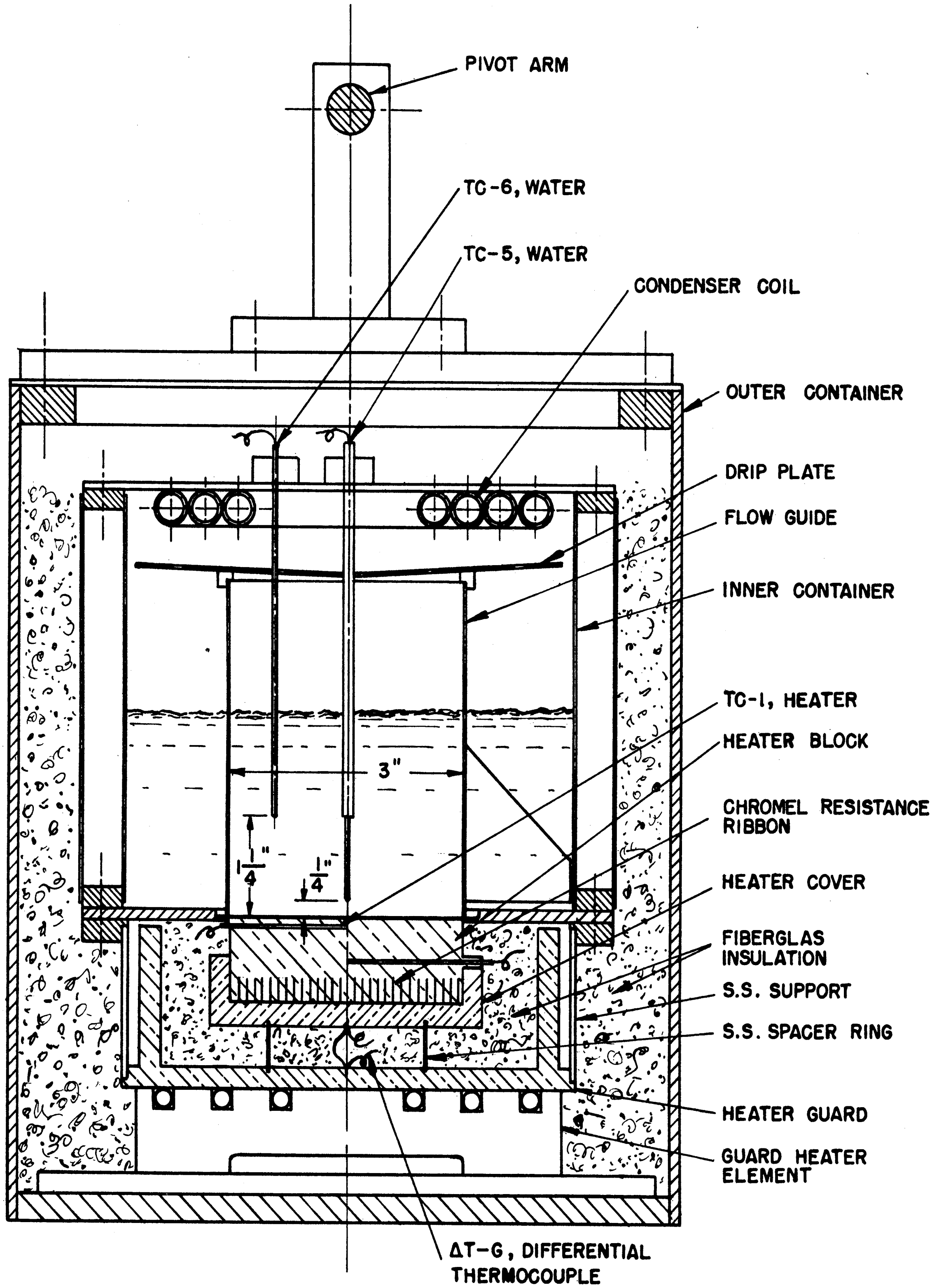


Figure 2. Test Vessel.

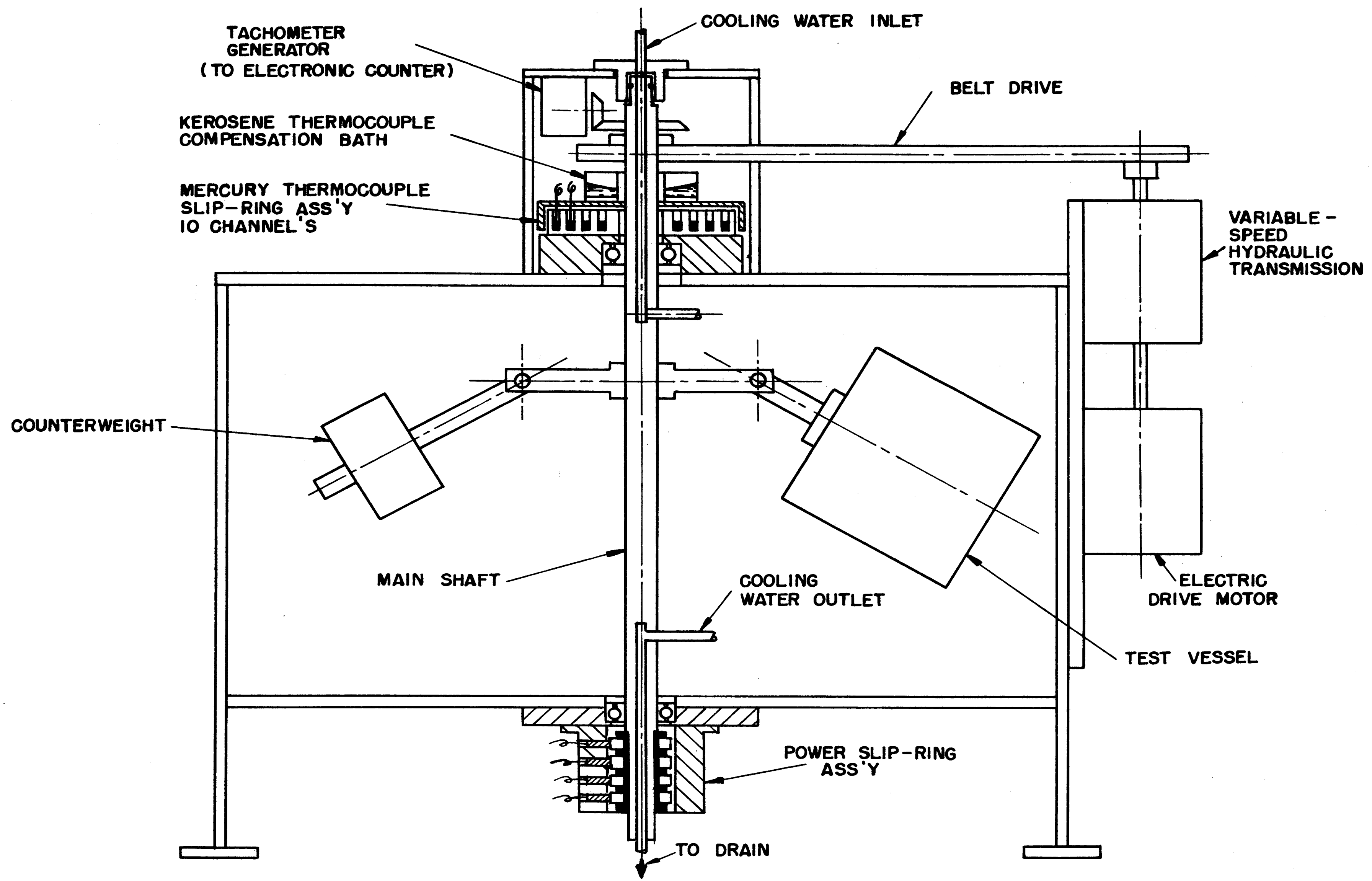


Figure 3. Centrifuge Assembly.

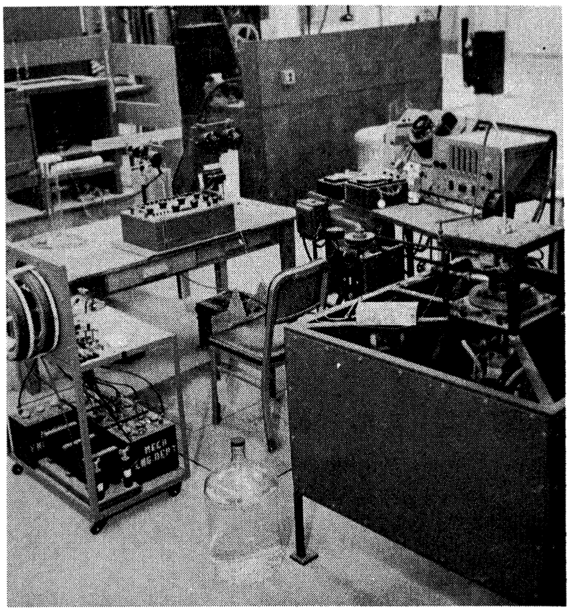

Figure 4. Overall View of Test Apparatus.

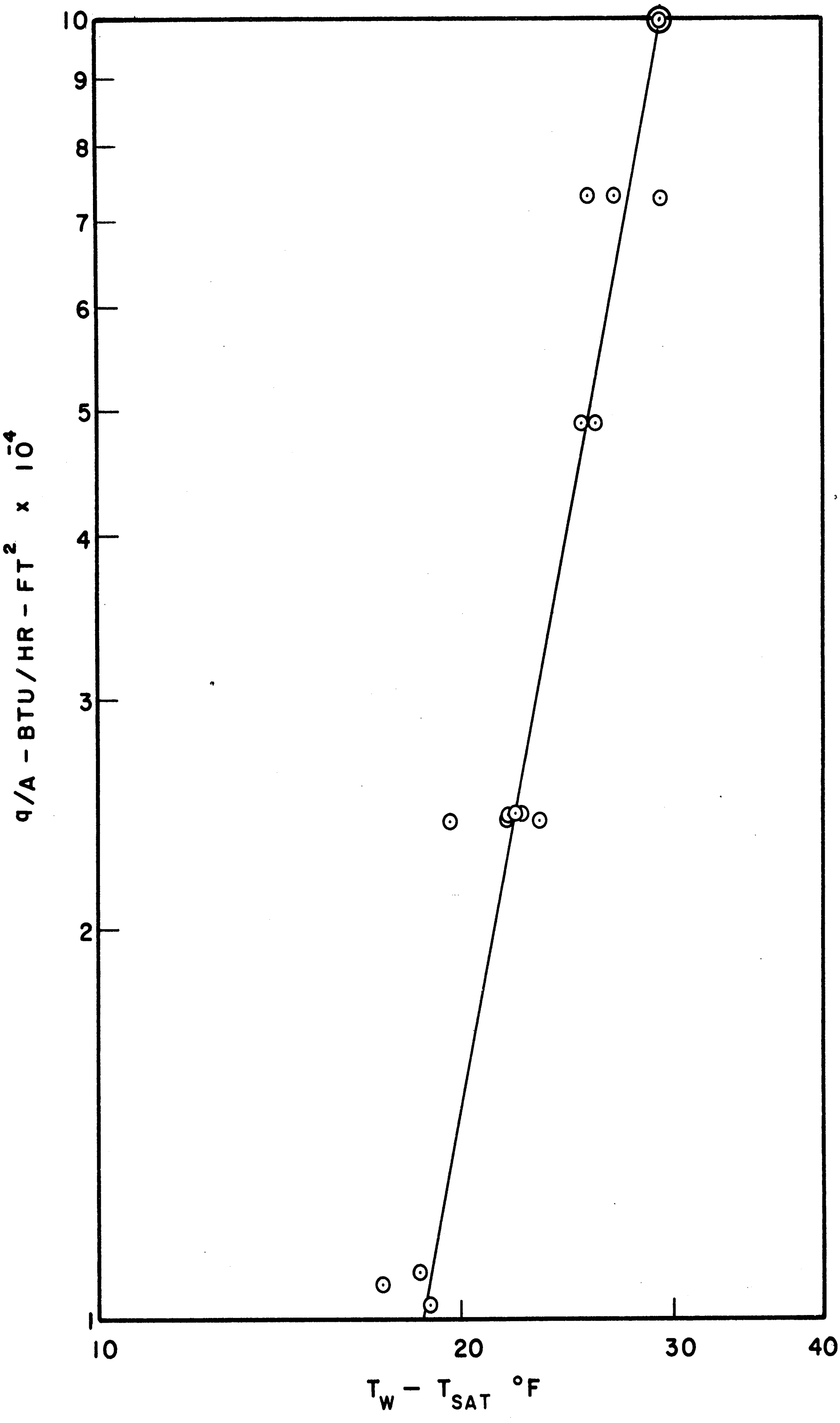


Figure 5. Plot of q/A vs. $T_W$-$T_{sat}$ for Boiling in Standard Gravitational Field.

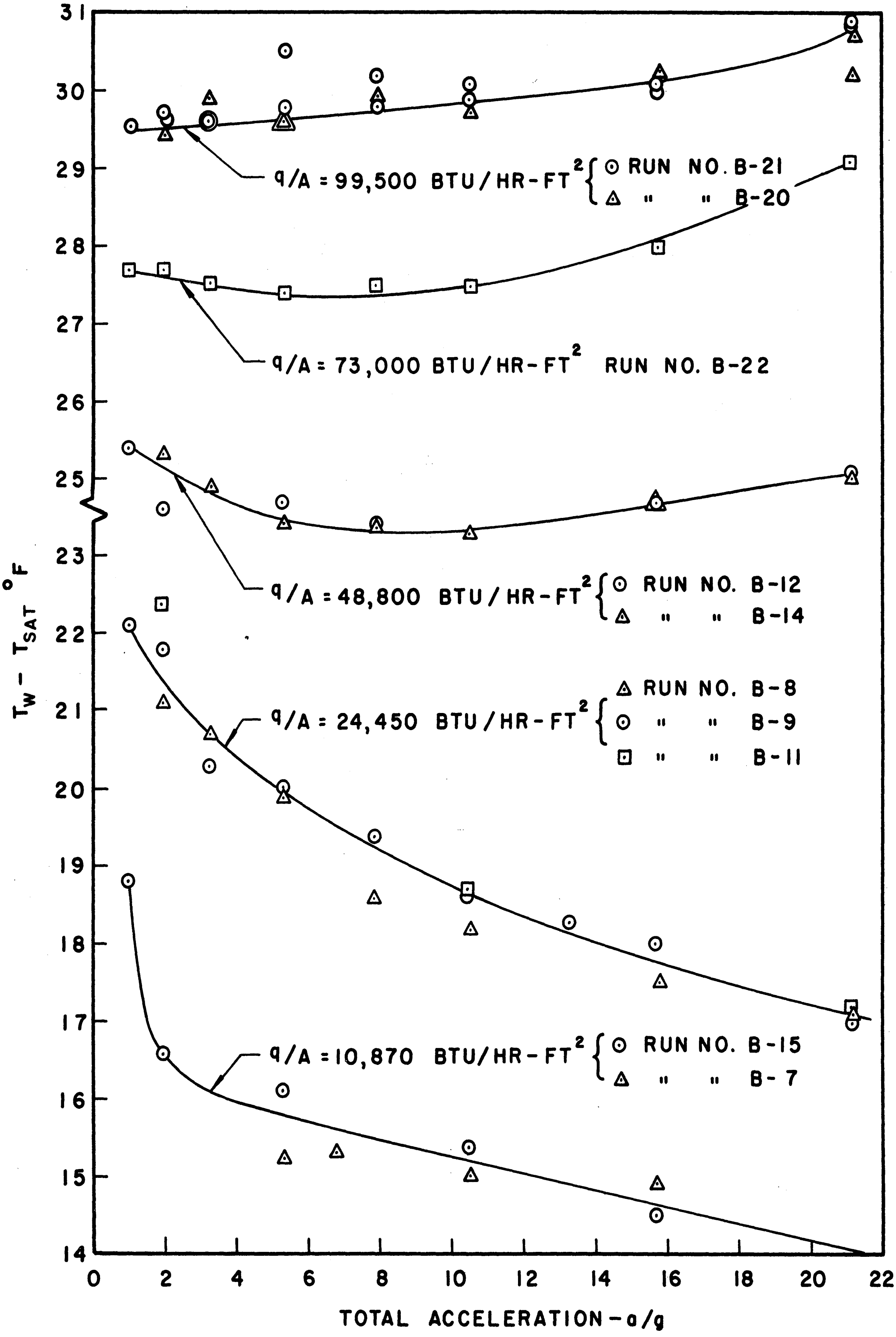


Figure 6 . Influence of Acceleration on $T_W$-$T_{sat}$ with Pool Boiling to Saturated Water.

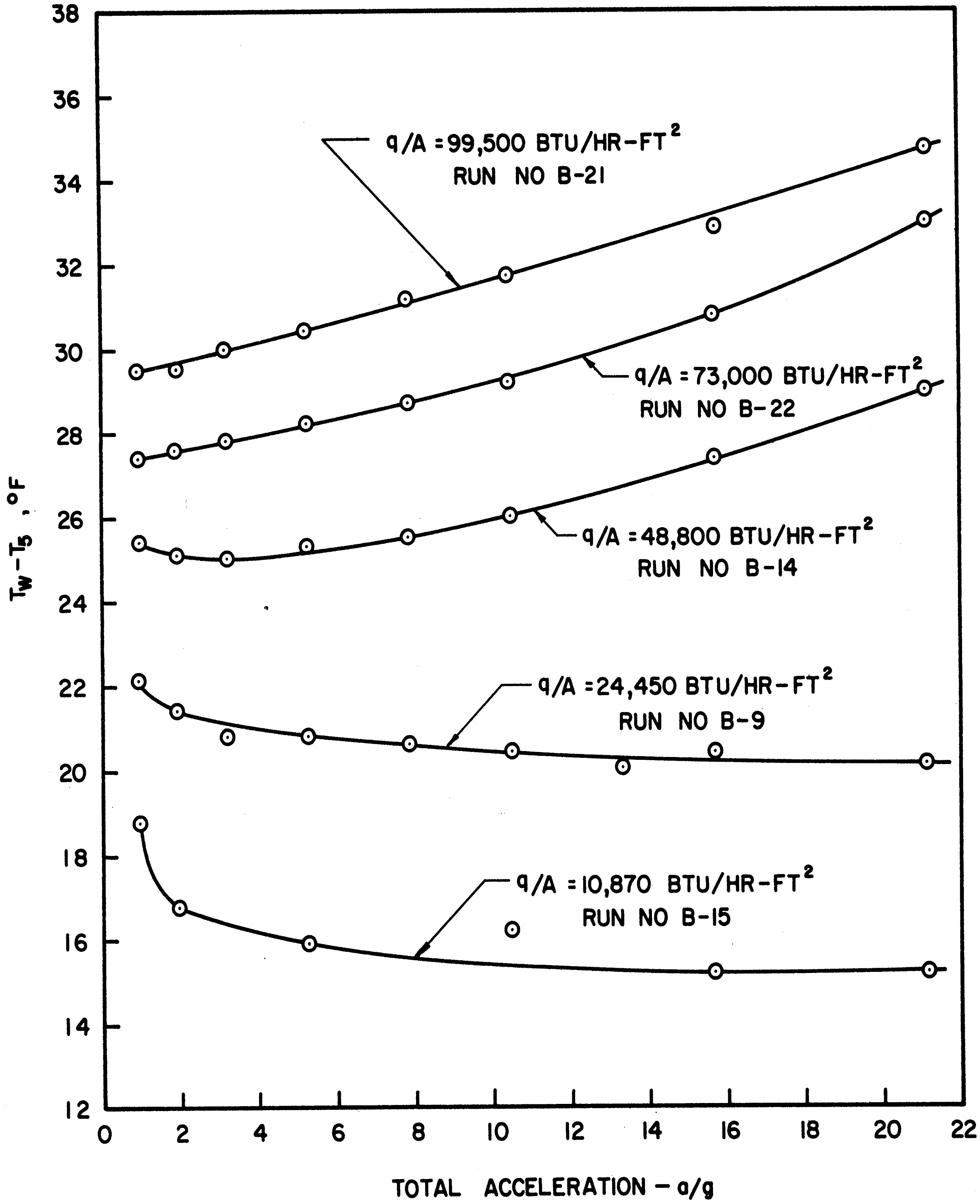


Figure 7. Plot of $T_W$-$T_5$ vs. Acceleration with Pool Boiling to Saturated Water.

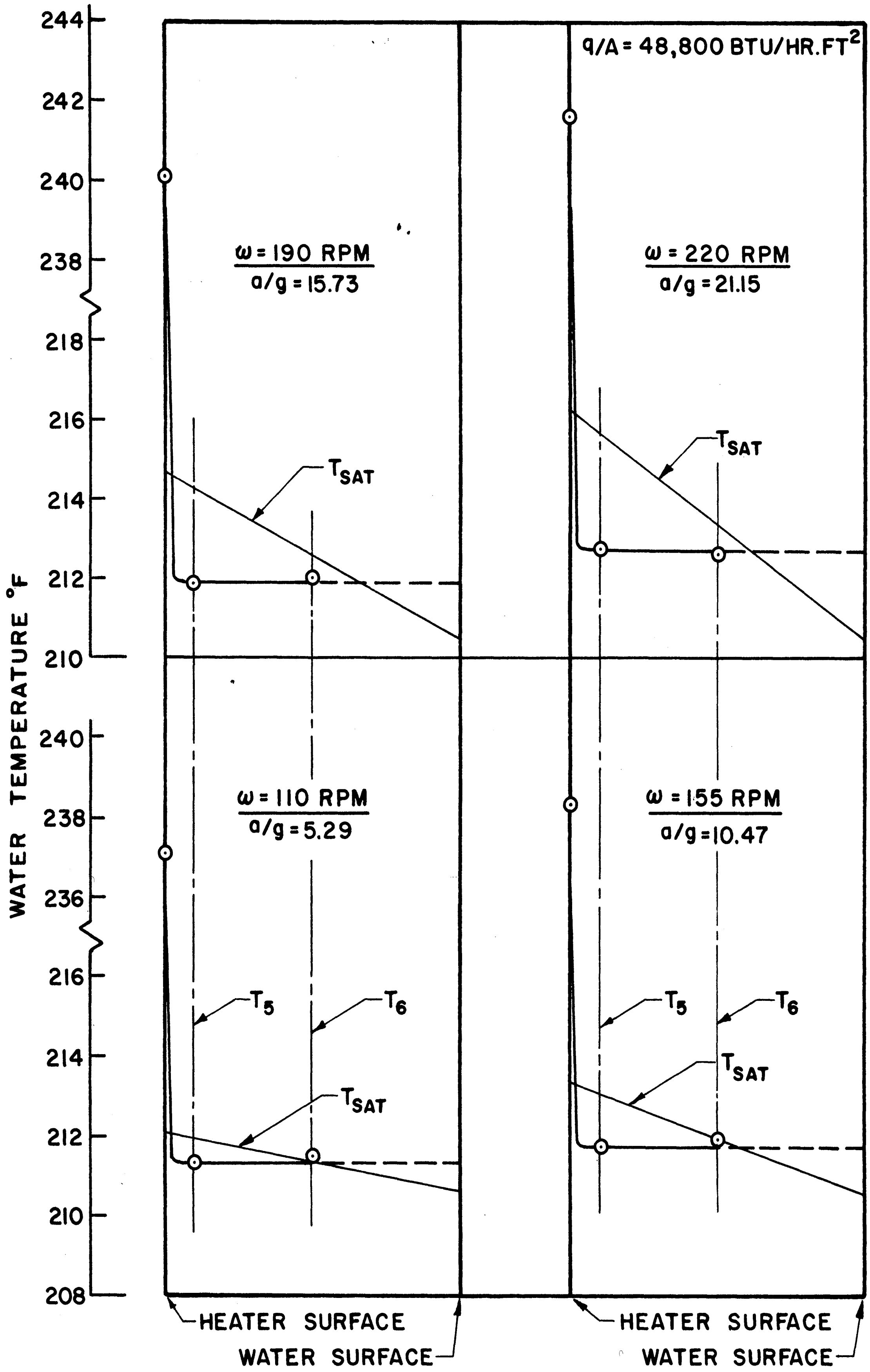


Figure 8. Run No. B-14. Temperature Profile between Heater and Water Surface for Various Accelerations.