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ANNULAR FLOW REGIME BURNOUT WITH "FREON-11" IN A UNIFORMLY HEATED TUBULAR TEST SECTION

by

Monte Bryce Parker

A Thesis Submitted to the
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The Requirements for the Degree of
MASTER OF SCIENCE

Major Subject: Nuclear Engineering

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NOMENCLATURE

Symbol	Term	Units
D	Diameter of test section	ft.
G	Mass flowrate	$\frac{lb.}{ft.^2 hr.}$
H	Latent heat of vaporization	$\frac{BTU}{lb.}$
h	Heat transfer coefficient	$\frac{BTU}{ft.^2 hr. °F}$
q	Heat Flux	$\frac{BTU}{ft.^2 hr.}$
v	Specific volume	$\frac{ft.^3}{lb.}$
X	Quality or weight percent vapor present	
μ	Viscosity	$\frac{lb.}{ft.hr.}$
Subscripts		
bo	Burnout condition	
g	Gas phase	
l	Liquid phase	

INTRODUCTION

One of the most efficient means of transferring heat is by forced convection boiling heat transfer. By efficient heat transfer is meant a minimum temperature difference between heater surface and coolant for a given heat flow per unit area of surface normal to the coolant flow (heat flux).

As the heat flux of a system is continually increased, a point is reached where the efficiency of the cooling process is drastically reduced. At this point, for a constant heat flux, the temperature of the heating surface will rise rapidly. The extremely rapid rise in heater surface temperature may result in the melting or failure of the heating surface and is referred to as burnout. The term burnout can also be generalized to mean the point at which the heat transfer mechanism goes from an efficient to an inefficient form whether the material breaks down or not.

Burnout presents one of the principal limitations in the design of liquid or wet steam-cooled nuclear reactors. As a result of this, the subject of burnout has received considerable attention during the past decade. Although much work has been done in this field, burnout still cannot be predicted with the degree of accuracy desired. It can occur both for liquids where the bulk fluid temperature is below saturation and for liquids which are boiling or evaporating. The former is a subcooled liquid and burnout there is referred to as "departure from nucleate boiling". The latter type of burnout is called "quality burnout" or "annular flow burnout". This type occurs in high quality regions where a core of vapor flows through a thin annular film of liquid.

In the design of more efficient boiling water reactors, it is extremely important that precise correlations as to the condition when burnout will occur are available. A great deal of work has been done on nucleate boiling and burnout in that region. Very little work, however, has been done in the area of "annular flow burnout". Since the heat transfer coefficient in this region is very high and drops off suddenly at burnout, deciding on a value which is conservative while trying to avoid overdesigning could prove to be one of the most important problems facing reactor engineers. It is precisely for this reason, that the present study is being undertaken.

Reactor designers must be provided with an "annular flow burnout" correlation and as always, it is desirable to get the best results possible in the simplest way. Boiling water systems involve pressures normally in the 2000 to 3000 psi. range. In order to avoid these high pressures while still operating with a boiling system, data from a heat transfer loop with a low boiling liquid will be analyzed. "Freon-11" is the fluid used to form the basis for an "annular flow burnout" correlation which would hold for not only "Freon-11", but for a water system, also. "Freon-11" is used because of its low boiling point which will allow for lower temperature, pressures and heat fluxes than would a water-steam system.

REVIEW OF THE LITERATURE

Much research has been carried out in the area of two-phase flow. Since many flow patterns exist in two-phase flow, it is important to describe these patterns in order to know what is meant when they are mentioned. Many authors (8, 9, 14) have described types of two-phase flow patterns. The following are those listed by Grace (8) for two-phase vertical flow in the order of increasing gas velocity.

1. Bubble flow - bubbles of gas move along the pipe at about the same velocity as the liquid.

2. Plug flow - alternate plugs of liquid and gas move along the pipe.

3. Slug flow - a wave is picked up periodically by the more rapidly moving gas to form a frothy slug which passes through the pipe at a much greater velocity than the average liquid velocity.

4. Annular flow - the liquid flows in a film around the inside of the pipe, while gas flows at a high velocity as a central core.

5. Spray, fog or mist flow - most liquid is entrained as spray by the gas.

In research carried out with boiling heat transfer these flow patterns can be used to describe the type of flow in a particular heat transfer region.

In order to understand how burnout occurs in the annular flow region, i.e., the region of interest in this thesis, it is necessary to describe the hydrodynamic and heat transfer conditions in a heated vertical channel which is cooled by a liquid. A description has been given by Collier (6) and will now be reviewed.

Consider a long vertical tube with a uniform heat flux applied to the wall (Figure 1). Cold liquid is introduced under forced convection at the base. In the lowest section, A, the liquid is simply increasing in temperature. As the temperature of the water rises and approaches the boiling point, the surface temperature which is higher than the bulk temperature finally reaches the saturation temperature. When the surface temperature is larger than the saturation temperature by a few degrees, the liquid in contact with the heated surface is superheated a sufficient amount to allow bubble formation at favored points of nucleation. The vapor bubbles grow large enough to detach and travel into the cooler bulk stream where they collapse. This section, B, is known as the "subcooled boiling region".

When the temperature of the liquid in the bulk stream reaches the saturation value, the bubbles no longer condense but become dispersed in the turbulent liquid. This region, C, is known as the "bulk boiling region", and the corresponding flow pattern is "bubble flow".

Further up the tube, the bubbles increase in density to the extent that they begin to coalesce to form larger

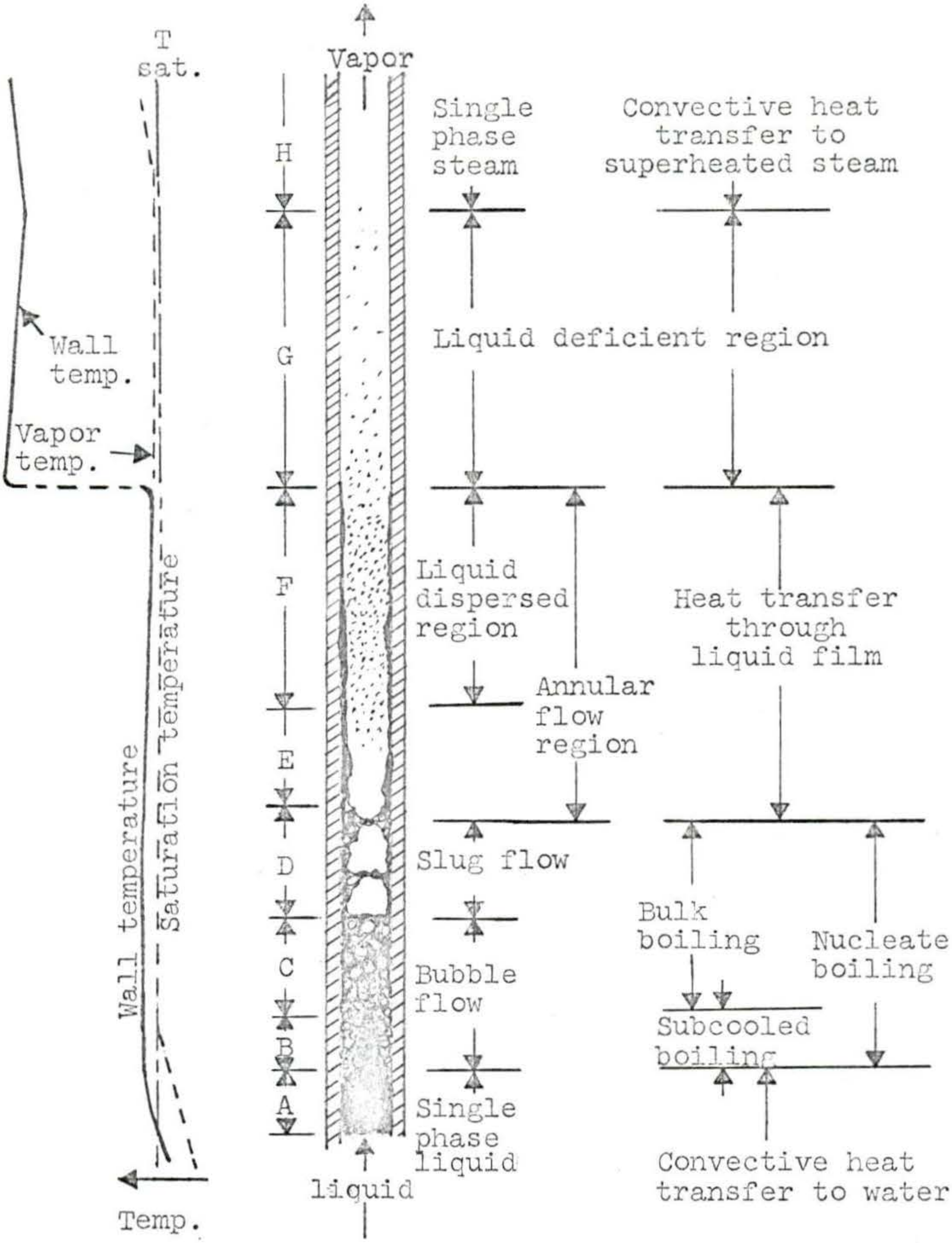

Figure 1. Regimes of two-phase flow

bubbles or slugs. Region D represents an unstable condition in which the flow changes from a continuous liquid phase to a continuous vapor phase. The flow pattern in this region is called "slug flow".

In region E, the vapor has become the continuous phase and the liquid has been displaced to the walls and is in the form of a thin slow moving film while the vapor flows at a high velocity in a central core. There is also some liquid in the core in the form of tiny drops or spray. This flow pattern is termed "annular flow".

Continuing along the heated tube, the vapor velocity in the core has become high enough for the resulting shear forces between the vapor and the liquid film to begin dispersing the liquid in the film by disrupting the film surface. Further increase in vapor velocity results in the bulk of the liquid flowing as dispersed droplets and thus this is called the "dispersed region" (F). No sharp boundary exists between E and F.

The thickness of the liquid film on the wall decreases throughout region E and F until a point is reached where the film vanishes, region G. In this region, the "liquid deficient region", there is simply a dispersion of droplets. With more heating, there is simply a change over to dry or superheated vapor which is depicted diagrammatically by region H.

Almost all work on burnout problems in nuclear reactors has been done in the area of "nucleate boiling", i.e., in regions B, C, and D in the above description. In these regions the rate of vapor bubble formation on the heating surface increases with increasing heat flux. The bubble centers can become so dense that they interfere with each other forming small vapor patches on the heating surface. This unstable vapor patch momentarily insulates the heating surface causing a local rise in the surface temperature. This is the mechanism of "burnout" for the "nucleate boiling region". It is also commonly called "departure from nucleate boiling" or "critical heat flux" depending on the author's preference.

In the last few years some work has been done on burnout in the region that Collier (6) calls the "two-phase forced convection region". Griffel (9) terms burnout in this region as "annular flow burnout" and that is what it will be termed throughout this paper.

Collier mentions that two of the important characteristics of the annular flow region are that the heat transfer coefficient in this region is very high and that it increases as quality increases. These facts can be seen qualitatively in comparison to other regions in Figure 2.

Griffel describes how heat transfer through the liquid film in the annular flow region is governed by the conditions of the film (i.e., its thickness, velocity, etc.). These conditions in turn are determined largely by the

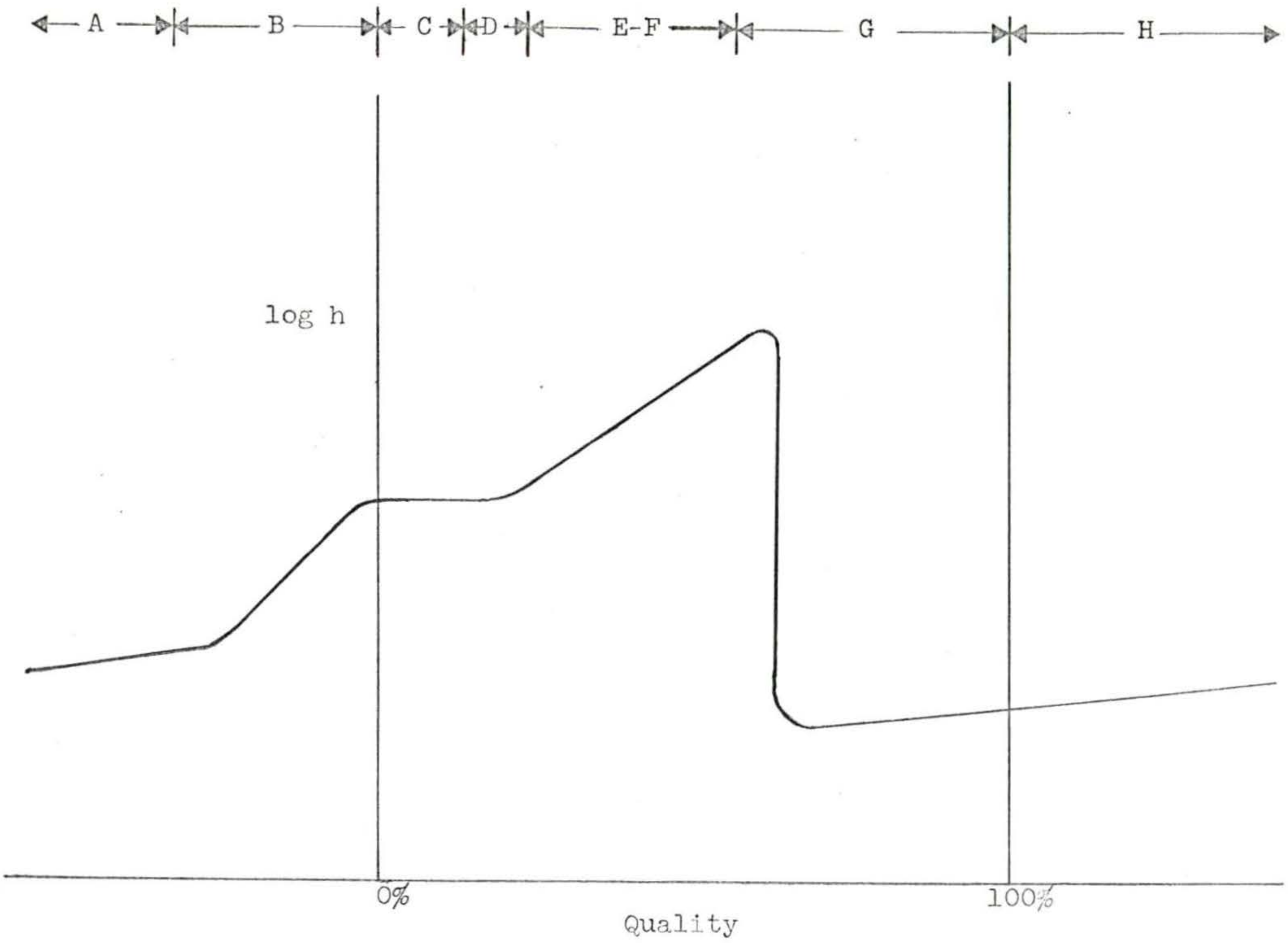

Figure 2. Comparison of values of h for different regions

conditions of the vapor core. In most cases, the liquid film is very thin (between one and ten thousandths of an inch) (4) and with high heat fluxes it would be evaporated in a short distance. It is only the fact that it is being replenished by absorbing droplets from the vapor core that prevents its disappearance. Also, the surface of the liquid film is wavy and the shearing forces of the vapor tend to re-entrain liquid from the film and disperse it in the core as droplets.

There are two theories regarding burnout in the annular flow region. These theories differ in their definition of the source of the film flow.

One theory put forth by Vanderwater et al. (15) and Goldman et al. (7), suggests that burnout is governed by the diffusion of liquid droplets. They postulate that burnout occurs when the rate of liquid entering the film becomes less than the rate of liquid being evaporated from the film.

Collier (5) and Grace (8) state that the burnout condition results from evaporation and entrainment of the liquid in the film. Grace explains, in contrast to the previous theory, that liquid diffusion plays a negligible role in comparison to evaporation. Both of these men feel that the film flowrate is greater than that believed by the proponents of the first theory.

The experimental work done on "annular flow burnout" is not nearly as extensive as that done for "nucleate boiling burnout". However, some general trends have been established. For steam-water systems it has been found that the heat flux at burnout increases monotonically with inlet quality, that it decreases with increasing mass flowrate, and that it is dependent only slightly at the very most on the pressure of the system (3, 7, 9, 13, 15).

The most extensive experimental work to date has been done by Griffel (9). He used a dimensional analysis approach to form his correlation and seems to be the first to use this approach for the study of "annular flow burnout". (Such an approach has been used very effectively to correlate boiling water data in the "nucleate boiling region" (2, 11).)

Griffel found that the most important variables controlling the value of q_{bo} were, G, D, μ_{mix}, X, v, and H. These variables can be put into dimensionless groups by using Buckingham's "pi theorem", and the functional relationship,

$$\frac{q_{bo}}{HG} = f\left[\frac{DG}{\mu_{mix}},\ \frac{v_g}{v_l}\right] \qquad (1)$$

results.

In physical terms this relationship says that the dimentionless term involving the burnout heat flux is a function of the Reynolds number for two-phase flow and a dimensionless term involving specific volumes. The effective viscosity, μ_{mix}, used here was defined by Griffel as

$$\frac{1}{\mu_{mix}} = \frac{X}{\mu_g} + \frac{1 - X}{\mu_1} \qquad (2)$$

Since such a relationship exists between μ_{mix} and X, he did not use X as a variable in his correlation.

It can be seen that Griffel used only three "pi terms" in the above relationship. However, in his final analysis he found that there was an additional dependence on pipe diameter, D, and his correlation was

$$q_{bo} = \frac{0.18 \times 10^6 \left(0.0683 \frac{v_g}{v_1} + 1.0\right) DGH}{\left(\frac{DG}{\mu_{mix}}\right)^{1.5}} \qquad (3)$$

with D expressed in inches.

Grace (8) also did experimental work in the annular flow region. In his work he found that whenever "annular flow burnout" was being studied it was necessary to suppress any burnout due to "nucleate boiling". "Nucleate boiling", he states, was suppressed if the flow pattern at the inlet to the test section was at least plug flow.

In experimental work on burnout it has been found that water is not necessarily the only fluid which will provide data for a burnout correlation. "Freon-12" is an example of one fluid that has been used successfully in such correlations by Barnett and Stevens et al. (2, 12), though this was in the "nucleate boiling region".

EXPERIMENTAL APPARATUS AND PROCEDURE

An experimental loop was designed and assembled in order to make measurements of q, G, v, μ, and H at "annular flow burnout" conditions. The loop consisted of copper tubing, a centrifugal pump, a flowmeter, a preheater, a storage tank, a condenser, valves, pressure gauges and a test section. Auxiliary electrical equipment, consisting of three strip chart recorders, a V.T.V.M., a precision potentiometer, thermocouples, two variable voltage supplies, a current transformer, and the necessary switches, resistors, etc., was used with the flow loop. A picture (Figure 3) and a schematic diagram (Figure 4) show the entire heat transfer loop as it was designed and assembled for experimental work. This loop along with its auxiliary equipment can easily be divided into three sections (the flow loop, the test section, and the electrical equipment) and each section is described separately below. The procedure for operating and taking data with the loop is then also explained.

Flow Loop

The flow loop components of the experimental loop consisted of a storage tank, a centrifugal pump, a flowmeter, a preheater, four globe valves and a condenser. They were connected to each other by 3/8 inch copper tubing. Each

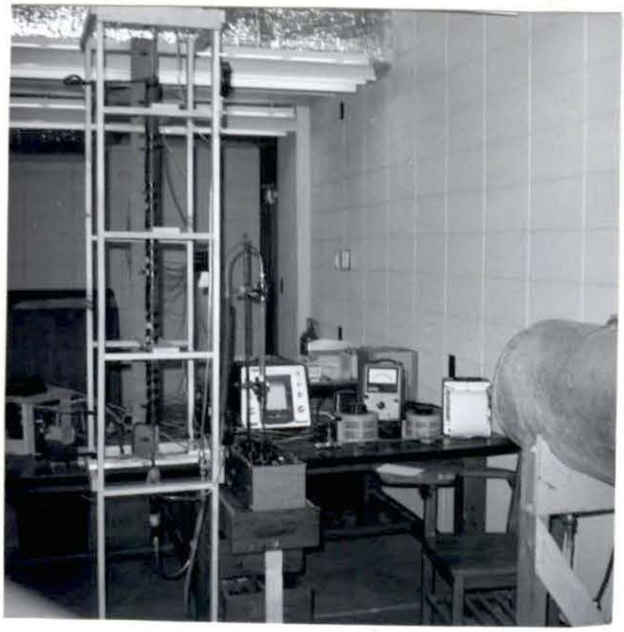

Figure 3. Experimental apparatus

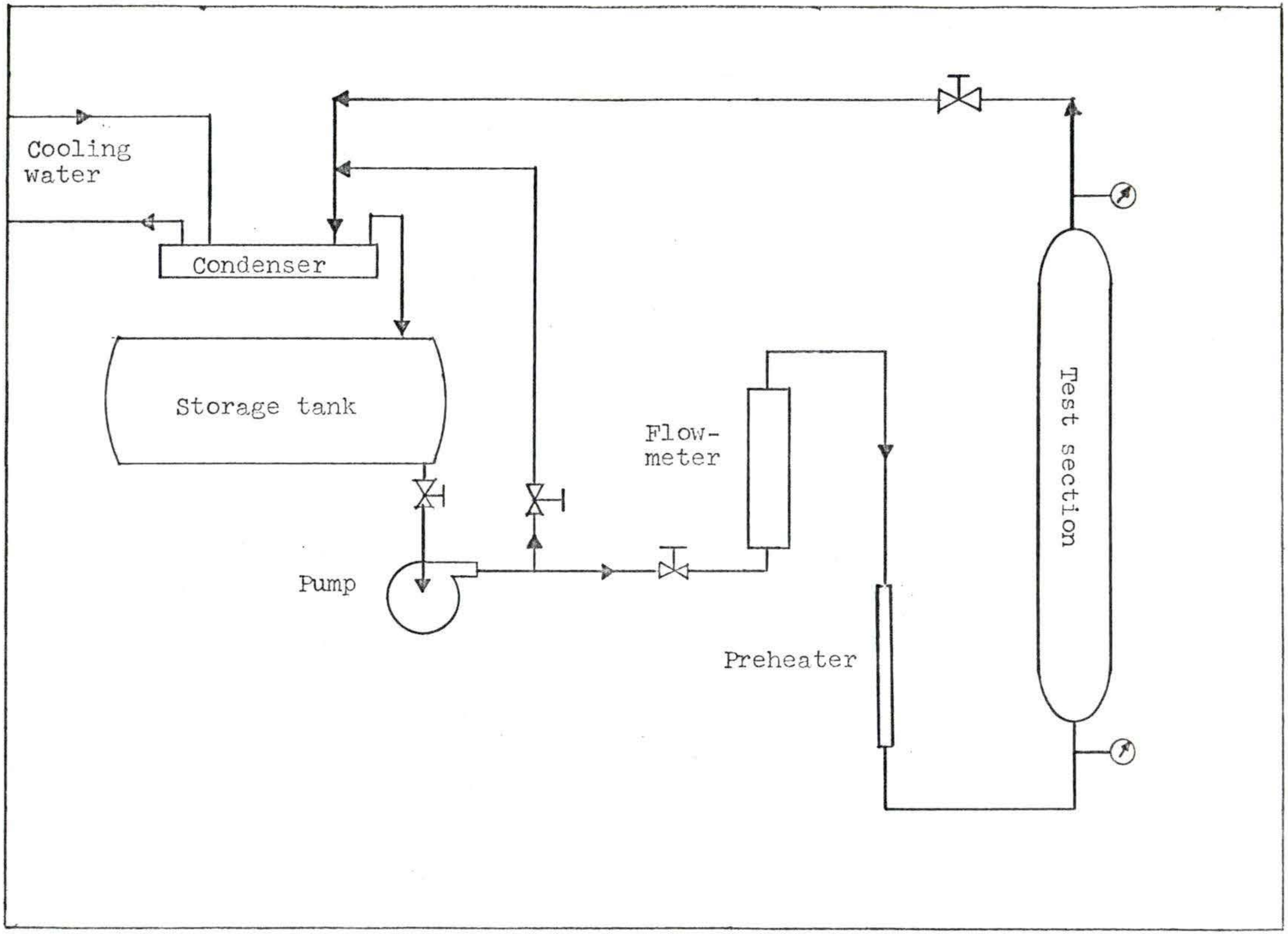

Figure 4. Schematic diagram of flow loop

component will be described in relation to its location in the flow loop after a description of the loop coolant and some of its physical properties is provided.

The fluid used as a coolant in this flow loop was Trichloromonofluoromethane which has the trade name "Freon-11". It is referred to as "Freon" throughout this thesis. "Freon-11" has a boiling point of 74.7°F at atmospheric pressure and has a density of about 92.5 lb./ft^3 at room temperature and 1 atmosphere of pressure.

The "Freon" was stored in a 30 gallon galvanized steel tank. This tank had a working pressure rating of 75 psi. and contained about 100 lbs. of "Freon" during the experiment. It was located 4 feet above the ground so that the advantage of a back pressure on the pump in the loop could be realized.

A 1/15 horsepower centrifugal pump was located directly below the outlet of the storage tank at ground level. The "Freon" was pumped from the storage tank through a flowmeter and preheater before entering the test section.

The flowmeter which measured the "Freon" flow was a flotation type meter which consisted of a glass tube of variable inside diameter placed in a vertical position with a weight which was free to move up and down. It was calibrated in percent of maximum flow where maximum flow was found to be 7.50 ft^3/ hr.

Following the flowmeter, the "Freon" entered a preheater which was used to vary the condition of the fluid at the test section input. The preheater consisted of 32 gauge copper wire wound around the flow tube. The copper wire was covered with 3/4 inch insulation to help direct the heat into the loop.

After the preheater the fluid passed through the test section and entered the condenser. The condenser was a copper, tube-shell, counter flow variety heat exchanger which was cooled by 10°C water. The "Freon" passed from this condenser into the storage tank again after being condensed and cooled.

At low flowrates, the pump would either vaporlock or cause an uneven flowrate. To alleviate this situation a bypass line was connected between the downstream side of the pump and the upstream side of the condenser. This allowed the pump to operate at higher flowrates while still allowing any range of flowrates in the system.

The flowrate in the loop was controlled by four globe valves. Two were located on either side of the test section, a third on the bypass line, and the final one between the storage tank and pump.

Test Section

Heating of the "Freon" in the experimental loop occurred primarily in the test section which was set up to resemble an upflow coolant channel for a fuel element in a nuclear reactor. Electrical heating in the vertical uniform test section simulates the heating that would take place due to the fission reaction in a fuel element if heating were uniform along the element. The uniform test section will now be described in detail.

The test section was an internally, electrically heated stainless steel tube of $\frac{1}{4}$ inch outside diameter and 20 mil thickness with tolerances of 1 mil on I.D. and O.D. and 1% on eccentricity. The composition of the stainless steel is shown in Table 1.

Table 1. Composition of stainless steel tube excluding Fe

Element	C	Mn	P	S	Si	Ni
Composition (%)	.14	1.40	.015	.008	0.38	20.12
Element	Cr	Mo	Cb+Ta	N	W	Co
Composition (%)	21.03	3.05	1.06	0.15	2.53	19.14

The stainless steel tube was $47\frac{1}{2}$ inches long and had a resistance of 0.14 ohm at 140°F, i.e., at the temperatures at which burnout occurred.

The maximum current which passed through the test section was in the range of 100 amps. Thus, the maximum power developed or the maximum heat transferred from the test section to the fluid was 1.4 kilowatts. Since the tube was covered with two inches of insulation, it was assumed that all this heat flowed inward from the test section.

Nine 22 gauge iron-constantan thermocouples were attached to the tube by simply twisting them around the tube. They were located at positions which were the following number of inches from the top of the tube; 0, 3, 6, 12, 20, 29, 38, and 47. Most of the couples were positioned near the top of the tube since it was assumed that burnout would occur at the top end of the test section. After it was found that burnout actually did occur only at the position of the top thermocouple, only this couple was used to detect when burnout occurred. One thermocouple was also located in the coolant stream seven inches on either side of the test section to determine entrance and exit temperature of the fluid. These thermocouples were positioned in the flow stream so that the actual temperature of the fluid could be obtained rather than using a temperature for the fluid as obtained from a tube wall temperature.

Also located on either side of the test section were pressure gauges of 30 psi. rating. The pressure gauges were located at the same positions as were the thermocouples used to measure the fluid temperatures at the inlet and exit to the test section.

A $\frac{1}{4}$ inch glass tube 4 inches long was fastened to both ends of the test section. This tube served the purpose of allowing visual observation of the incoming and exiting flow and also to electrically insulate the test section from the rest of the loop. This glass tubing was fastened to the steel tubing by means of 1 inch long pieces of tygon tubing and wire clamps. The glass could not be directly glued or fastened to the stainless steel tube because the slight thermal expansion of the steel when heated would break the glass. The glass along with 4 inches of $\frac{1}{4}$ inch copper tubing also served the purpose of a calming section at the input to the test section.

Electrical Instrumentation

The electrical instrumentation in the loop was used for supplying power to the preheater and the test section and for recording power inputs and temperatures required as experimental data.

The current to the preheater was supplied by a variable voltage supply with a range of 0 - 140 volts and 0 - 12 amps. Another variable voltage supply with a range of 0 - 140 volts and 0 - 20 amps was used in conjunction with a current transformer to supply power to the test section. The current in both of these cases was supplied by a 110 volt wall outlet.

The current transformer was designed and built to get an eleven to one current step-up to the test section. It had a 34.8 pound iron core with over all dimensions of 9 1/8 in. x $5\frac{1}{2}$ in. x 4 in. The primary of the core was wound with 110 turns of 12 gauge copper wire and the secondary had 10 turns of 3-"0" gauge stranded copper wire.

Input to the primary was through the aforementioned variac. The maximum current supplied to the test section from the secondary of the transformer during the experiment was 100 amps.

In order to measure the resistance of the test section while it was at its operating temperature, a circuit was set up that connected the test section to a V.T.V.M. (vacuum tube voltmeter) when the power to the section was interrupted. A switch was positioned in the transformer secondary circuit and when this switch was opened another circuit was closed that connected the test section to the V.T.V.M. This V.T.V.M. was used to measure the resistance of the test section. Thus, the resistance of the test section could be determined in a very short time after power to the test section was interrupted. Such a procedure was needed because the resistance of the stainless steel changes with temperature. It was found, however, that because of the low maximum temperature at the burnout point of about 150°F, the resistance of the test section changed only slightly. At burnout the resistance of the test section was found to be 0.140 ohm for all the runs.

The power to the test section was measured continuously by a strip chart recorder. This recorder was an A.C. millivolt recorder with a full scale deflection of 100 millivolts. A simple diode tube and voltage divider were used to convert the A.C. voltage of the transformer secondary to the D.C. millivolt range of the recorder. The recorder was calibrated by the use of a Simpson V.O.M. (volt ohmmeter) which had been calibrated by the I.S.U. electronics shop.

A strip chart recorder was also used to monitor the temperature of the top thermocouple on the test section so that the occurrence of burnout could be readily detected. This recorder had a full scale deflection of 10 millivolts.

A third strip chart recorder was attached to the thermocouple in the fluid stream prior to the test section in order to record incoming fluid temperature.

A precision potentiometer was used to check all the other thermocouples in the system. A switching circuit was set up so that any thermocouple could be quickly connected to the potentiometer.

Experimental Procedure

To operate the experimental heat transfer loop to obtain annular flow burnout demanded not only a certain experimental operating procedure but also a specific designation of the parameters it was important to measure and the way in which they were measured. The operating procedure for this loop will now be discussed followed by a review of the parameters recorded for this study.

Flow in the loop was initiated by opening all of the valves and starting the pump. The "Freon" was allowed to flow through the loop for 10 or 15 minutes so that all of the fluid in the tank was cooled and the pressure in the system was lowered. The flowrate was then set at some fixed value by adjusting the control valves at either side of the test section. The preheater power supply was turned on and the variac controlling it was set so that the "Freon" was heated enough to result in two-phase flow at the input to the test section. Since the data recorded were to be for low quality input, the flow pattern at input to the test section had to be "plug flow".

The next step in the operating procedure was to start all the strip chart recorders simultaneously with the initiation of power to the test section. The power to the test section was slowly increased, while still maintaining a constant flowrate, until burnout occurred. At burnout, the pressure gauges and the output temperatures were read. The secondary circuit of transformer was then quickly opened and the resistance of the test section was read at this operating temperature.

Burnout for this experiment was defined to occur when the strip chart recorder used to record the output of the top thermocouple showed a drastic increase in the voltage it was reading. Figure 8 in Appendix B shows an example of what this strip chart would look like at burnout.

The procedure for operation of the loop was followed repeatedly for the same flowrate but with a different input pressure and temperature. This would keep the quality at approximately the same value but the fluid would be at a different temperature and pressure. After a number of runs were taken at this fixed flowrate, the flowrate would be changed and the same procedure would be followed at another value.

Seven data parameters were recorded at burnout. They were (a) visual observation of the type of flow, (b) pressure and temperature of the fluid on either side of the test section, (c) fluid flowrate and (d) temperature at the top of the test section.

EXPERIMENTAL RESULTS

Eight variables were considered important to this experimental burnout heat transfer analysis. They were q_{bo}, μ_g, H, v_1, v_g, G, D, and X. With these variables the following relationship of dimensionless quantities can be found (Appendix A).

$$\frac{q_{bo}}{HG} = f\left[\frac{GD}{\mu_g}, \frac{v_g}{v_1}, \frac{DH^{\frac{1}{2}}}{v_1\mu_g}, X\right] \tag{4}$$

This functional relationship was reduced in this work since the quality in the experimental loop was assumed to be constant. Also, it was found that the quantity $\frac{H^{\frac{1}{2}}}{v_1\mu_g}$ was virtually constant and since all the measurements were done for one test section, the dimensionless term $\frac{DH^{\frac{1}{2}}}{v_1\mu_g}$ was neglected. (If different test sections of different diameters were used, it would be necessary to reinsert this term.) Thus, the previous relationship for annular burnout was reduced to

$$\frac{q_{bo}}{HG} = f\left[\frac{GD}{\mu_g}, \frac{v_g}{v_1}\right]. \tag{5}$$

The term $\frac{GD}{\mu_g}$ is a "Reynolds number" and the term $\frac{v_g}{v_1}$ is the ratio of specific volumes of the gas and liquid in the saturated fluid. The latter term gives the temperature and pressure variation at the input.

Figure 5 is a plot of $\frac{q_{bo}}{HG}$ as a function of $\frac{v_g}{v_1}$ for

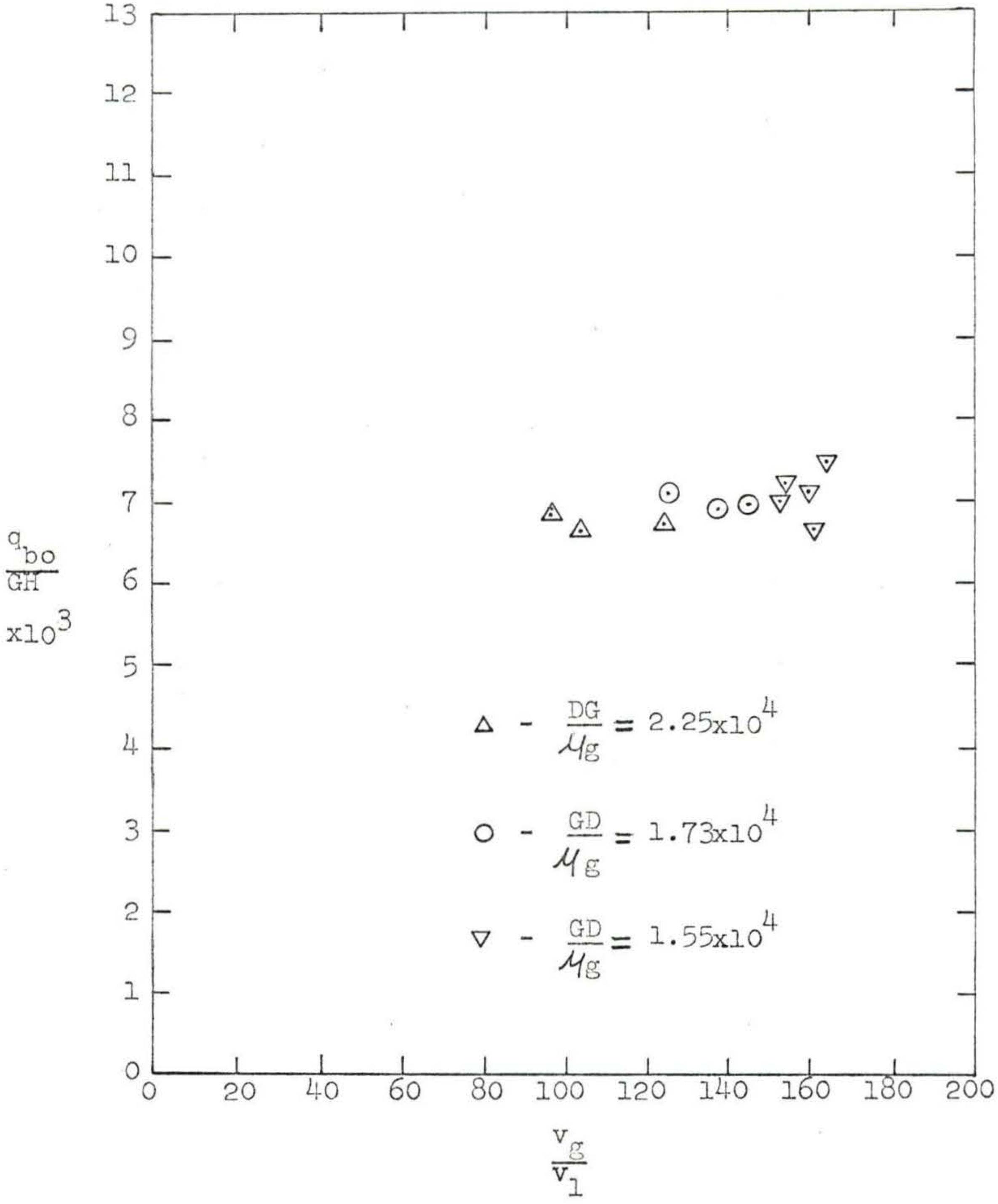

Figure 5. Plot of $\frac{q_{bo}}{GH}$ vs. $\frac{v_g}{v_l}$

given values of $\frac{GD}{\mu_g}$. A good relationship for any value of $\frac{GD}{\mu_g}$ is not apparent. In Figure 6, log $\frac{q_{bo}}{HG}$ is plotted as a function of log $\frac{GD}{\mu_g}$ for given values of $\frac{v_g}{v_l}$. In this figure, $\frac{q_{bo}}{HG}$ varies as $\left(\frac{GD}{\mu_g}\right)^{-0.160}$ no matter what value of $\frac{v_g}{v_l}$ is used. The fact that the value of $\frac{v_g}{v_l}$ is not important in the range considered becomes more apparent in Figure 7 where $\left(\frac{q_{bo}}{HG}\right)\left(\frac{GD}{\mu_g}\right)^{0.160}$ is plotted as a function of $\frac{v_g}{v_l}$. Thus the equation giving the relationship for the burnout heat flux for "Freon-11" flowing vertically upward with constant quality in a uniformly heated flow channel of constant diameter is

$$q_{bo} = .0332\ HG\ \left(\frac{GD}{\mu_g}\right)^{-0.160} \qquad (6)$$

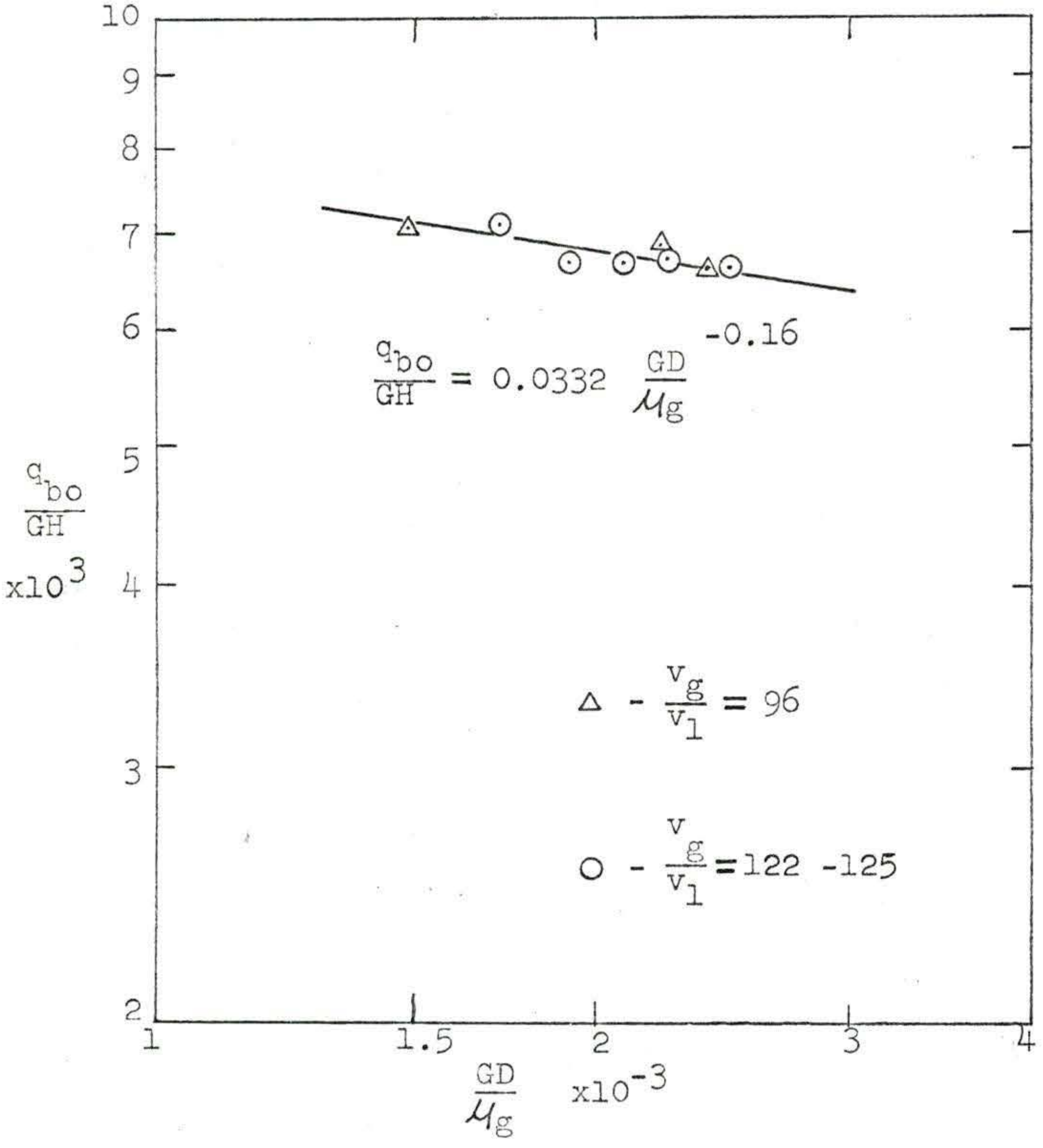

Figure 6. Plot of $\frac{q_{bo}}{GH}$ vs. $\frac{GD}{\mu_g}$

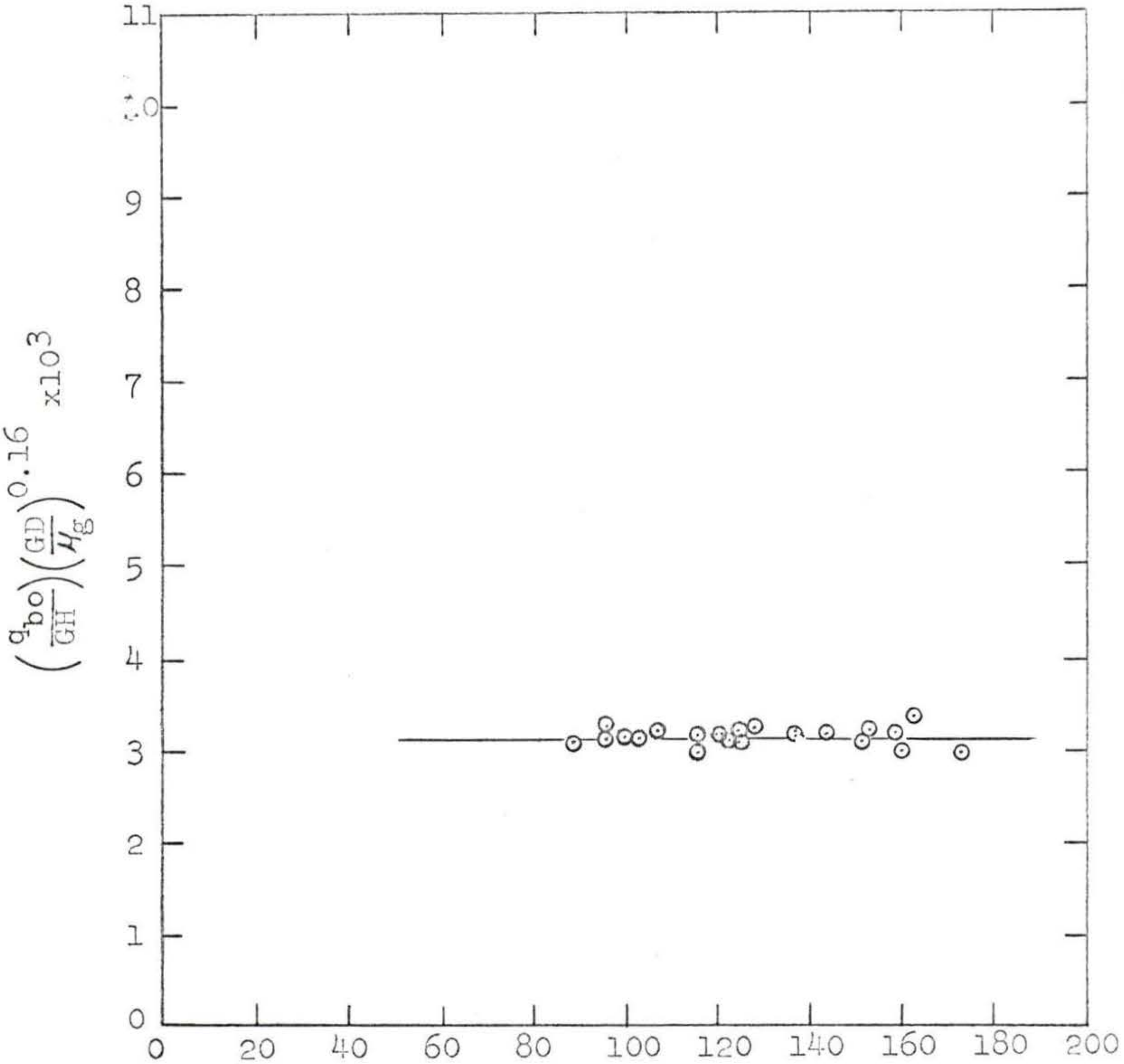

Figure 7. Plot of $\left(\frac{q_{bo}}{GH}\right)\left(\frac{GD}{\mu_g}\right)^{0.16}$ vs. $\frac{v_g}{v_l}$

DISCUSSION OF RESULTS

It is important to discuss and compare the burnout heat flux correlation found in this experimental analysis with those found by previous investigators. Though no previous burnout correlation has been prepared for "Freon-11", several have been prepared, in the annular flow regime, for water (3, 7, 8, 9, 15) and these will be the basis of the comparison.

The results of this study (Equation 6) show that under the conditions of the experiment the annular flow burnout heat flux is a function of only flowrate, heat of vaporization and Reynold's number. By combining terms in this equation, it can be seen that q_{bo} varies directly with $G^{0.849}$. Since H and μ_g vary only slightly, the burnout heat flux depends only on mass velocity when D and X are constant. This fact can be compared to results obtained by Bell (3), Griffel (9) and Vanderwater (15).

Bell found that for constant quality, the annular burnout heat flux varies approximately directly with $G^{-0.7}$. Griffel found that q_{bo} is proportional to $G^{-0.5}$ in the annular flow region. This agrees approximately with Bell's correlation. Vanderwater (15) found experimentally that q_{bo} varies with $G^{-0.5}$ if quality and pressure in the system are constant. Theoretically he determined that, if the droplet diffusion model (mentioned in the

Review of Literature) were used, the mass transfer of droplets would be proportional to $G^{0.8}$ instead of $G^{-0.5}$. This fact would lead to speculation that the results found in this study might be influenced more by droplet diffusion than by the mechanism suggested by Collier (5). Collier (5) theorized that as the mass flowrate was increased the extra liquid present went into droplets in the vapor core and did not enter the liquid film. The film, however, decreased in thickness due to both the higher vapor velocity and the resulting shear stresses when the mass flowrate was increased. This decrease in film thickness would result in burnout occurring sooner and thus would explain the inverse relationship between heat flux at burnout and mass flowrate that Bell, Griffel and Vanderwater found. Grace (8) found that his experimental results also agreed with Collier's suggested mechanism since in his water-steam system droplet diffusion was negligible.

As was stated above, the results of this work suggested that for a system using "Freon-11" at relatively low pressure, the liquid droplet diffusion process played a more important role than did Collier's mechanism. This may have been due in part to the small diameter of the test section which might have allowed the droplets to enter the liquid film more easily. It may also have been that with "Freon-11", more variables would have to be considered in order to compare it to a water-steam system. Perhaps the surface tension of the two liquids would have to be considered. Norman et al. (11) have suggested that surface tension differences play an important role in heat and mass transfer. They show experimentally that for a film of liquid on a vertical surface there is a correlation between the film thickness and product of two surface tension quantities. The first quantity is the liquid surface tension and the second is the difference in the surface tension of the liquid in the film and the surface tension of the bulk liquid.

It must be kept in mind that the data taken during this experiment were for a quality that was constant only by visual observation, but some variation in it probably existed. Although the lack of precision quality values would leave the analysis and subsequent correlation open to some speculation, the small amount of scatter of data for the quality used suggest that this fact could not be very significant.

A final observation that should be made is that the results of this experiment did not show any functional dependence on the pressure of the system over the short range of pressures investigated. The maximum pressure used in the system, however, was only 30 psig, and since this is not very high the system pressure may indeed play a role at higher values. Both Bell (3) and Griffel (9) found only a small dependence on pressure for experiments they did with steam-water systems.

In conclusion it can be stated that on the basis of the study done here a "Freon-11" heat flux burnout correlation in the annular flow region is not of the same form as the water-steam annular flow burnout correlations prepared to date.

SUMMARY

A heat transfer loop has been designed and built in order that an experimental study could be carried out on the variables affecting heat flux at burnout. The burnout in this case was in the annular flow region or the high quality region and the heat transfer medium was "Freon-11".

The variables were put in dimensionless groups and the following equation resulted.

$$\frac{q_{bo}}{HG} = f\left[\frac{GD}{\mu_g}, \frac{v_g}{v_l}, \frac{DH^{\frac{1}{2}}}{\mu_g v_l}, X\right] \tag{7}$$

Two terms of this equation, X and $\frac{D\sqrt{H}}{\mu_g v_l}$, were neglected since they varied only slightly in this study and thus, the function was simplified to

$$\frac{q_{bo}}{HG} = f\left[\frac{GD}{\mu_g}, \frac{v_g}{v_l}\right]. \tag{8}$$

When the data were analyzed, it was found that there was no dependence on specific volumes and the dependence of the flux burnout term on Reynolds Number was

$$\frac{q_{bo}}{HG} = \left(\frac{GD}{\mu_g}\right)^{-.160} . \tag{9}$$

Thus, the final correlation for burnout heat flux was

$$q_{bo} = HG\left(\frac{GD}{\mu_g}\right)^{-0.160} \tag{10}$$

The final correlation does not agree with experimental work done in the annular flow region with water-steam systems as far as the flowrate dependence is concerned. Several suggestions were made in an attempt to explain this difference.

SUGGESTIONS FOR FUTURE STUDY

Certain alterations in the heat transfer loop used for this experiment would make a more detailed analysis of the burnout problem possible and might also result in a better correlation between "Freon-11" and water systems.

One of the things that could improve the experimental system used for this study would be to add the necessary apparatus needed to measure the quality. Such an additional capability would allow one to see the effect of input quality on the heat flux at burnout, an effect that experimenters (3, 7, 8, 9, 15) have found to be significant in steam-water systems. An addition to the system which would allow quality measurements might be accomplished by building a bypass line around some section of the loop other than the test section. Two valves could then be closed which would isolate the section of the loop where it was desired to know the quality. At this time the flow in this section of the loop would be rerouted through the bypass line. The amount of liquid in the isolated section could then be measured and the quality determined. The problem with this method is that the quality cannot be measured continuously while the other data are being taken. Another method which might be used to determine quality would be to use some type of radiation source and detector. The source could be either a light source or gamma source. The section of the loop in which it was desired to know the quality would be placed between the source and the detector. It would be necessary to calibrate this method in some way, but this method would have the advantage of allowing continuous measurement of quality.

To see the effect of some other variables on annular flow burnout, the test section itself could be altered. The effect of a change in the diameter and length of the heat section of the loop could be measured if the size of the test section were changed. In water systems, Griffel (9) found a direct dependence of q_{bo} on the diameter of the test section whereas Bell (3) found no dependence on either the length or the diameter of the test section. Questions arising from these divergent results could at least be resolved. Also, the thickness of the test section could be changed so that non-uniform heat fluxes could be analyzed. This would make it possible to check whether or not a non-uniform heat flux causes any difference in the results.

Another recommendation would be concerned with increasing the heat flux from the test section. By making some changes in the number of turns on the current transformer and the resistance in the transformer secondary, the power to the test section could be increased. Using even the same voltage supply as was used for this study, there is a capability of about twice the test section power or heat flux by making changes in the current transformer. The use of higher heat fluxes would then allow greater variation and range in the parameters measured at burnout, especially flowrate.

The whole flow loop could be improved to allow the use of higher pressures. The biggest problem here would be to find some way to fasten glass tubing to metal tubing in a way that would withstand high pressure. The use of high pressure is necessary to determine whether q_{bo} is independent of pressure over a greater range than used in this analysis.

A final suggestion is that different liquids of varying surface tensions be used as the coolant in the loop. The effect of surface tension on annular flow burnout could then be determined. If a strong dependence on surface tension were found this could have profound effects on existing correlations because of surface tension differences due to temperature changes.

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APPENDIX A

Dimensional Analysis of Annular Burnout

It was decided that the most important variables affecting q_{bo} were D, G, H, μ_g, v_g, v_l, and X. This fact can be expressed as the following mathematical function.

$$q_{bo} = f\ (D,\ G,\ \mu_g,\ v_g,\ v_1,\ H,\ X) \qquad (A\text{-}1)$$

This function can be expressed in the form

$$K\ (q_{bo})^a\ (D)^b\ (G)^c\ (\mu_g)^d\ (v_g)^e\ (v_1)^f\ (H)^g\ (X)^h = 1 \qquad (A\text{-}2)$$

where K is a dimensionless coefficient (10). If the dimensions used are mass, length, and time, the dimensional equation becomes,

$$\left(\frac{M}{T^3}\right)^a\ (L)^b\ \left(\frac{M}{L^2T}\right)^c\ \left(\frac{M}{LT}\right)^d\ \left(\frac{L^3}{M}\right)^e\ \left(\frac{L^3}{M}\right)^f\ \left(\frac{L^2}{T^2}\right)^g = 0. \qquad (A\text{-}3)$$

Since equation A-1 is assumed to be dimensionally homogeneous, the exponent of the primary dimensions on the left side of equation A-3 must equal those on the right side.

Thus, for the following dimensions,

$$T:\quad -3a - c - d - 2g = 0 \qquad (A\text{-}4)$$

$$M:\quad a + c + d - e - f = 0 \qquad (A\text{-}5)$$

$$L:\quad b - 2c - d + 3e + 3f - 2g = 0 \qquad (A\text{-}6)$$

There are seven unknowns but only three equations. Arbitrary values will therefore be assigned to four of the unknowns. The exponents a, b, e, f, will be chosen here with the resulting equations being independent.

From Buckingham's "Pi Theorem", there should be five "pi terms" since there are eight variables and three dimensions. Since X is already dimensionless, it will be chosen as one "pi term" leaving four more to be found. Four sets of arbitrary values must therefore be assigned to the above four unknowns. These will be chosen as

$$\begin{array}{llll} a = 1 & a = 0 & a = 0 & a = 0 \\ b = 0 & b = 1 & b = 0 & b = 1 \\ e = 0 & e = 0 & e = 1 & e = 0 \\ f = 0 & f = 0 & f = -1 & f = -1 \end{array}$$

to obtain convenient dimensionless ratios. The resulting "pi terms" are

$$\frac{q_{bo}}{HG} , \frac{DG}{\mu_g} , \frac{v_g}{v_1} \text{ and } \frac{D\sqrt{H}}{v_1 \mu_g} .$$

Equation A-2 can then be written as

$$\frac{q_{bo}}{HG} = f \left[\frac{DG}{\mu_g} , \frac{v_g}{v_1} , \frac{D\sqrt{H}}{v_1 \mu_g} , X \right] \qquad (A-7)$$

This is the final result of the dimensional analysis and the form of the function must be found experimentally.

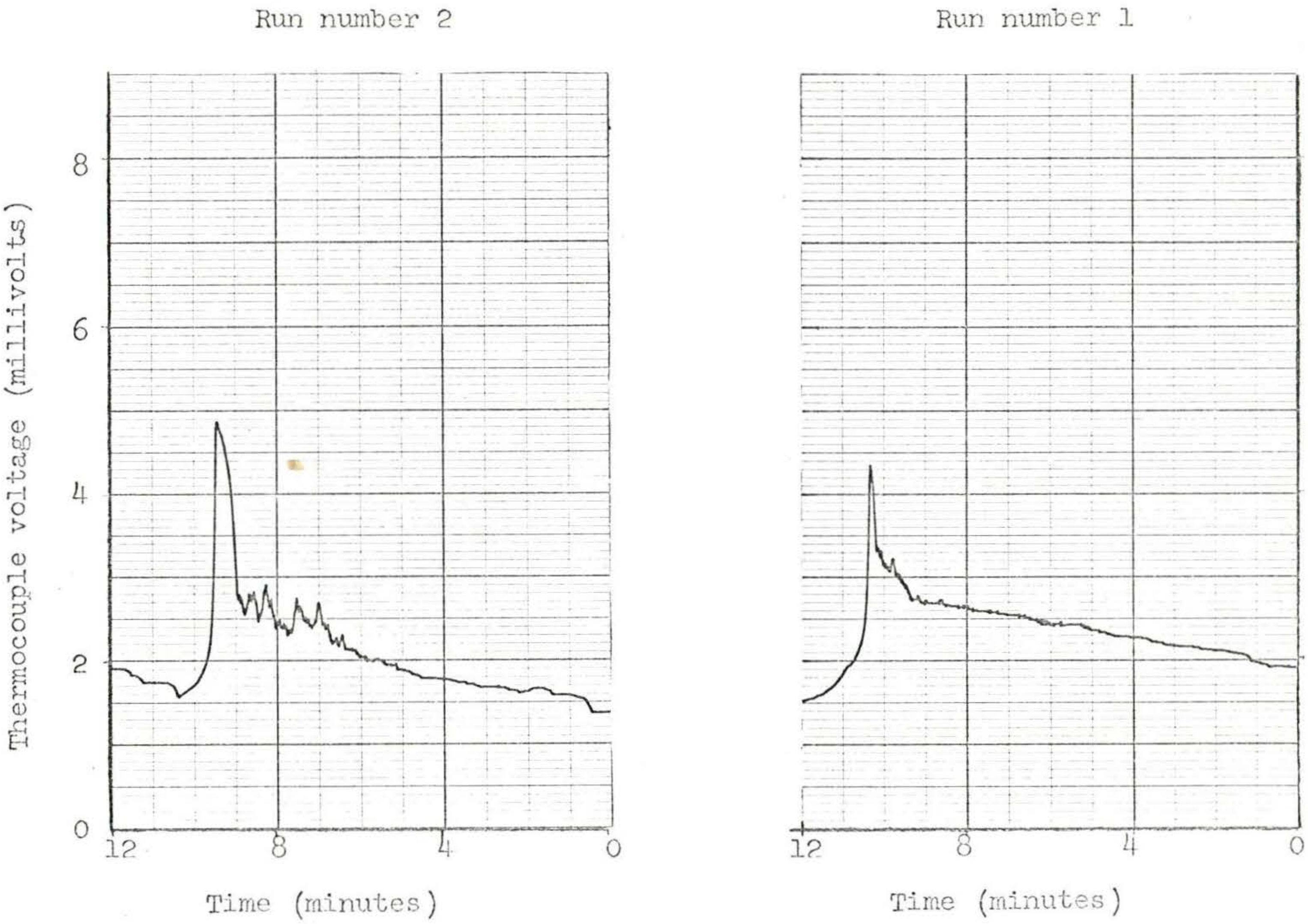
APPENDIX B

Table 2. Values of variables from experimental runs

Run No.	Input Temp. °F	Input Press. psi	v_g $\frac{ft.^3}{lb.}$	v_l $\frac{ft.^3}{lb.}$	G $\frac{lb.}{ft.^2 hr.}$	μ_g $\frac{lb.}{ft.hr.}$	H $\frac{BTU}{lb.}$	q_{bo} $\frac{BTU}{hr.ft.^2}$
1	116	21.2	1.37	1.126	32571	.0273	74.50	16189
2	105	12.7	1.69	23951	23951	.0269	75.55	12710
3	100.5	12.0	1.76	1.109	23951	.0271	75.99	12995
4	99	11.8	1.80	1.108	23951	.0269	76.12	13730
5	99.5	11.1	1.77	1.109	23951	.0271	76.08	12352
6	102	12.9	1.70	1.111	23951	.0271	75.84	13119
7	106	15.2	1.60	1.115	26823	.0271	75.46	14819
8	109	15.5	1.53	1.118	26823	.0271	75.18	14057
9	103.5	19.2	1.41	1.124	26823	.0273	75.70	14433
10	109	14.5	1.53	1.118	29699	.0271	75.18	15496
11	114	16.5	1.40	1.124	29699	.0271	74.70	14818
12	118.5	18.8	1.31	1.129	29699	.0273	74.25	15103
13	112.5	16.2	1.44	1.123	32571	.0271	74.85	16951
14	123.5	22.5	1.12	1.135	32571	.0276	73.76	16595
15	114.5	18.5	1.40	1.125	35447	.0276	74.65	17788
16	118.5	19.0	1.31	1.129	35447	.0271	74.25	16595
17	126	23.8	1.17	1.137	35447	.0276	73.51	17311
18	130	26.5	1.10	1.142	35447	.0268	73.11	17788
19	130.5	26.6	1.10	1.142	35447	.0278	73.05	17788
20	116	19.0	1.36	1.126	38319	.0271	74.50	18965
21	127.5	25.3	1.15	1.139	38319	.0281	73.36	18559
22	135	29.3	1.02	1.147	38319	.0283	72.59	18157
23	95.5	7.3	1.91	1.104	46942	.0271	76.44	9587
24	131	7.5	1.09	1.143	23951	.0283	73.00	12353

Table 3. Values of dimensionless variables used

Run No.	$\frac{q_{bo}}{GH}$ x 10^3	$\frac{DG}{\mu_g}$	$\frac{v_g}{v_1}$	$\frac{D\ H}{\mu_g v_1}$
1	6.672	20879	121.7	246
2	7.024	15582	152.0	252
3	7.140	15467	158.7	254
4	7.530	15582	162.5	256
5	6.779	15467	159.6	254
6	7.223	15467	153.0	253
7	7.321	1732	143.5	252
8	6.971	17321	136.9	251
9	7.108	17190	125.4	248
10	6.940	19178	136.9	251
11	6.678	19178	124.6	248
12	6.849	19038	116.0	245
13	6.953	21033	128.2	249
14	6.909	20600	106.6	240
15	6.723	22476	124.4	243
16	6.305	22890	116.0	246
17	6.643	22476	102.9	240
18	6.863	22314	96.3	236
19	6.871	22314	96.3	236
20	6.643	24745	120.8	248
21	6.602	23864	101.0	236
22	6.527	23695	88.9	232
23	6.952	11633	173.0	256
24	7.067	14811	95.4	232


Run number 2

Run number 1

Figure 8. Typical burnout detector traces