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A REVIEW OF BURNOUT STUDIES IN FREON AND DESCRIPTION OF A FREON LOOP

by

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ABSTRACT

The need for simulation in studies of burnout or critical heat flux for application to nuclear reactor design is outlined. The available literature on the suitability of Freon as a model fluid for water is reviewed and discussed. A brief description is given of a Freon loop currently under construction at the A.A.E.C. Research Establishment.

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1. INTRODUCTION

A study of the thermodynamics and fluid mechanics of two phase flow systems is being made by the Engineering Research Division of the A.A.E.C. Research Establishment, with particular emphasis on aspects associated with water cooled nuclear reactors. A number of experimental facilities have been built, or are being considered, for research in this field, one of which utilises a refrigerant, Freon 12 (Dichlorodifluoromethane, CF_2Cl_2), as a model fluid for water in burnout investigations.

This report briefly outlines the role of the Freon loop, reviews the literature on the suitability of Freon as a model fluid for water in the study of burnout and describes the salient features of the A.A.E.C. loop.

2. THE NEED FOR SIMULATION IN BURNOUT STUDIES FOR NUCLEAR APPLICATION

In water cooled nuclear reactors, a marked increase in fuel cladding temperature can occur if the relatively efficient combination of forced convection and boiling heat transfer is inhibited and replaced by a process in which heat is transferred to single phase vapour. This condition is often termed burnout, though only where the resulting cladding temperature exceeds its melting point does physical burnout take place*.

To maximise the thermal output for a given size of reactor core the margin between the operating and burnout heat fluxes should be small, consistent with centre metal temperature limitations and stability and safety considerations. This requirement places a premium upon accurate specification of the conditions under which burnout occurs and in recent years considerable effort throughout the world has been devoted to this topic. A substantial part of this effort has been spent in the acquisition of experimental data because the problem is not amenable to analytical solution.

It is current practice to determine the burnout characteristics of reactor fuel elements in out-of-pile facilities which are capable of operation at reactor conditions of heat flux, coolant flow, pressure and temperature etc., but which use electrical, not nuclear, heating. These facilities are large and costly,

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* For consistency the term burnout is used to indicate the point at which a sudden increase in surface temperature is obtained with a heat flux controlled surface (Barnett 1963).

involving, typically, heat inputs of 1 to 10 megawatts, at pressures in excess of 1,000 p.s.i.a. and temperatures around 600°F. Clearly it is most desirable to relax these stringent test conditions if at all feasible, both to reduce costs and to ease experimentation, provided that the data requirements of the designer are safeguarded. Considerable progress has been made to this end, but the techniques are not yet fully established. The main objective of the Freon loop is to obtain experimental data relatively cheaply, at reduced pressures and temperatures, in order to give reliable predictions of burnout in water systems.

3. THE CHOICE OF FREON AS A MODEL FLUID FOR WATER

Barnett (1963) derived similarity relationships for burnout in terms of the system-describing parameters, (that is, the variables under the direct control of the experimenter; in the case of uniformly heated round tubes these are ϕ, L, D, G, ΔH and P) and the physical properties of the fluid (see Appendix 1 for notation). He indicated that the requirements for complete similarity were so many and diverse that it was impractical to satisfy them all in a realistic scaling-laws model. He argued that certain of these requirements must be omitted owing to the lack of data (for example, physical properties of the heater material and surface characteristics) and that others could probably be omitted without any significant loss of accuracy (for example, gravity, viscosity, surface tension, thermal conductivity and specific heat of the vapour phase).

Considering different sets of the important fluid properties, Barnett arrived at three possible non-dimensional expressions for relating the onset of burnout in geometrically similar systems using different fluids.

SET 1: Using ρ_L, ρ_V, λ, K_L, C_L as the important properties of the fluid and assuming that heat and kinetic energy can be measured in terms of the same physical units,

$$\frac{\phi_B}{\rho_L\,\lambda^{3/2}} = f\left[\left(\frac{L\rho_L\lambda^{\frac{1}{2}}C_L}{K_L}\right)\left(\frac{D\rho_L\lambda^{\frac{1}{2}}C_L}{K_L}\right)\left(\frac{G}{\lambda^{\frac{1}{2}}\rho_L}\right)\left(\frac{\Delta H}{\lambda}\right)\left(\frac{\rho_L}{\rho_V}\right)\right] .$$

SET 2: Using ρ_L, ρ_V, λ, K_L, C_L and σ (surface tension) as the important properties of the fluid and treating heat and kinetic energy as fundamentally different physical quantities,

$$\frac{\phi_B K_L}{\lambda\rho_L\sigma C_L} = f\left[\left(\frac{L}{D}\right)\left(\frac{L\rho_L\sigma C_L^{2}}{K_L^{2}}\right)\left(\frac{G K_L}{\rho_L\sigma C_L}\right)\left(\frac{\Delta H}{\lambda}\right)\left(\frac{\rho_L}{\rho_V}\right)\right] .$$

SET 3: As for set 2 but using β (the rate of change of the saturation temperature with pressure) instead of σ,

$$\frac{\phi_B\,\beta^{\frac{1}{2}}C_L^{\frac{1}{2}}}{\lambda^{3/2}\rho_L^{\frac{1}{2}}} = f\left[\left(\frac{L}{D}\right)\left(\frac{LC_L^{\frac{1}{2}}\lambda^{\frac{1}{2}}\rho_L^{\frac{1}{2}}}{K_L\;\beta^{\frac{1}{2}}}\right)\left(\frac{G\beta^{\frac{1}{2}}C_L^{\frac{1}{2}}}{\lambda^{\frac{1}{2}}\rho_L^{\frac{1}{2}}}\right)\left(\frac{\Delta H}{\lambda}\right)\left(\frac{\rho_L}{\rho_V}\right)\right] .$$

Common to all three expressions is the single all-fluid property group ρ_L/ρ_V. Barnett considered this group to be predominant in the scaling of forced convection burnout since, on physical grounds, its presence ensures correct scaling of the vapour volume flow fraction for a given quality. The remaining dimensionless groups all contain a mixture of system-describing parameters and fluid properties. Thus if the group ρ_L/ρ_V is made the same for two geometrically similar systems using different fluids, values of the system-describing parameters can then be chosen to give equality of each individual group, and hence overall similarity of the two systems.

At Winfrith Heath, U.K., a special loop for use with suitable model fluids was used to assess the reliability of these similarity relationships by providing experimental data which could be compared with existing water data. Freon was chosen as the model fluid for a variety of reasons (Stevens, Elliott and Wood 1964), including particularly the following:

(a) The required operating temperature and pressure was quite low. For example, data for burnout in water at 1,000 p.s.i.a. and 545°F (approximate conditions for the Steam Generating Heavy Water Reactor) existed for which the value of the group ρ_L/ρ_V was 20.6. This same value was obtained in Freon 12 at a pressure of 155 p.s.i.a. and 112°F.

(b) The low latent heat of boiling of Freon 12 (approximately 90 BTU/lb compared with 550 BTU/lb for water) reduced the power requirements in Freon to between 5 and 10 per cent of those for water.

(c) The desired range of water inlet subcooling, expressed non-dimensionally as $\Delta H/\lambda$, could easily be simulated in Freon 12.

(d) There was already in existence much practical experience because substances in the Freon family have wide application in refrigeration engineering. Freon is relatively safe to handle, permits the use of mild steel containment and its important physical properties are readily available.

4. COMPARISON OF BURNOUT DATA IN FREON/WATER SYSTEMS

4.1 Qualitative Comparison

Stevens, Elliott and Wood (1964) made a qualitative comparison of the burnout data obtained in the Freon loop (155 p.s.i.a. 112°F, ρ_L/ρ_V = 20.6) for a number of uniformly heated round tubes, with the corresponding water data (1,000 p.s.i.a. 545°F, ρ_L/ρ_V = 20.6). The qualitative similarity of the burnout curves was good. For example (see Figure 1) the Freon data showed a linear increase of $\emptyset_B$ with ΔH (fixed L, D, P) and a linear decrease of $\emptyset_B$ with exit quality (fixed D, P), both of which are characteristic of burnout in water (Macbeth 1963, Lee and Obertelli 1963). In addition the form of Macbeth's (1963) basic (zero subcooling) burnout curve for water ($\emptyset_{B0}$ versus G, fixed D, P) which shows the existence of the high and low velocity burnout regimes, was well reproduced in Freon. The Freon results also indicated that the form of these burnout curves changed at certain L/D ratios and mass velocities as shown in the diagrams in Figure 1. Subsequent checks confirmed that similar changes were present in the water data but had previously been obscured, owing to scatter and paucity of data.

The relationship between the applied heat flux and the flow rate of liquid Freon along the heated wall was examined over a wide range of exit qualities. In all cases, burnout corresponded to conditions that just caused disappearance of the liquid film. This result, which had previously been demonstrated for water (Hewitt, Kearsey, Lacey and Pulling 1963) indicated that the same fundamental mechanisms of burnout were operative in both fluids.

4.2 Quantitative Comparison

4.2.1 Barnett's similarity relationships

Following an examination of the Freon data for uniformly heated round tubes, Barnett (1964) concluded that none of the three expressions given in Section 3 adequately related the Freon data to the water data of Lee and Obertelli (1963) over the range of conditions examined. However, by slightly modifying the choice of fluid properties but retaining ρ_L/ρ_V as the sole all-fluid property group, predictions were obtained which were reasonably consistent and which related the uniformly heated round tube data for water and Freon (ρ_L/ρ_V = 20.6) to within ± 6 per cent. This non-dimensional relationship is given below; in its derivation the important physical properties of the fluid were taken to be ρ_L, ρ_V, λ, K_L, C_L and γ (the rate of change of ρ_L/ρ_V with pressure). These are the same as Set 3 but with β replaced by γ:

$$\frac{\emptyset_B\,\gamma^{\frac{1}{2}}}{\lambda\,\rho_L^{\frac{1}{2}}} = f\left[\left(\frac{L}{D}\right)\left(\frac{DC_L\rho_L^{\frac{1}{2}}}{K_L\;\gamma^{\frac{1}{2}}}\right)\left(\frac{G\;\gamma^{\frac{1}{2}}}{\rho_L^{\frac{1}{2}}}\right)\left(\frac{\Delta H}{\lambda}\right)\left(\frac{\rho_L}{\rho_V}\right)\right] .$$

Barnett and Wood (1965) confirmed the validity of this relationship for uniformly heated round tubes using three fluids, Freon 12, Freon 21 (Dichloromonofluoromethane $CH\,CL_2F$) and water. The tests were made at two values of ρ_L/ρ_V (20.6 and 41.4) corresponding to water at 1,000 p.s.i.a. and 560 p.s.i.a. respectively. In this case agreement was to within ± 7 per cent; a typical result is shown in Figure 2. However, slight systematic differences in the compared values suggested that the agreement might be marginally improved if an additional all-fluid property group $\lambda\gamma/\beta C_L$, resulting from the addition of β to the above group of fluid properties, was included in the similarity relationship, namely,

$$\frac{\emptyset_B\,\gamma^{\frac{1}{2}}}{\lambda\,\rho_L^{\frac{1}{2}}} = f\left[\left(\frac{L}{D}\right)\left(\frac{DC_L\rho_L^{\frac{1}{2}}}{K_L\;\gamma^{\frac{1}{2}}}\right)\left(\frac{G\;\gamma^{\frac{1}{2}}}{\rho_L^{\frac{1}{2}}}\right)\left(\frac{\Delta H}{\lambda}\right)\left(\frac{\rho_L}{\rho_V}\right)\left(\frac{\lambda\gamma}{\beta C_L}\right)\right] .$$

By comparing the results for the two Freons which have nearly the same value of $\lambda\gamma/\beta C_L$, the agreement was improved to ± 3 per cent. However the Prandtl number $\frac{C_L\,\mu_L}{K_L}$, which appears in the similarity relationship if μ_L is added to the set of fluid properties, is also very similar for the two Freons. Though Barnett considered viscosity to be a relatively unimportant fluid property, the improvement may have been due to the inclusion of either or both of the groups $\frac{\lambda\gamma}{\beta C_L}$ and $\frac{C_L\,\mu_L}{K_L}$; the data do not permit assessment of their individual contributions. Strictly therefore the liquid phase Prandtl number should be included in the above relationship.

4.2.2 Scaling factor method

Stevens and Kirby (1964) adopted a less rigorous approach to determine the quantitative relationships between the burnout data for water at 1,000 p.s.i.a. and those for Freon 12 at 155 p.s.i.a. (that is, ρ_L/ρ_V Freon = 20.6 = ρ_L/ρ_V water) but their comparison included annuli and rod clusters as well as round tubes. The method is wholly empirical; at best it is only an approximation. Its virtue lies in its ease of application and its ability to relate the onset of burnout in a water system to that in the corresponding Freon system, as defined by equality of ρ_L/ρ_V , within the limits of experimental accuracy.

The method is briefly outlined below.

The Freon data for uniformly heated round tubes were correlated graphically by plotting*:

$$4 \left(\frac{L}{D}\right) \left(\frac{\varnothing_B}{\lambda G}\right) - \left(\frac{\Delta H}{\lambda}\right) \text{ versus } \left(GD^{\frac{1}{4}}\right) 10^{-4} \frac{D^{0.59}}{L^{0.59}} .$$

(note that the L.H.S. represents the exit quality and is dimensionless : the R.H.S. has units $\frac{lb.in^{\frac{1}{4}}}{hr.ft^2}$). A family of curves was obtained, each curve referring to one particular value of subcooling $\Delta H/\lambda$.

The water data from three different sources (Lee and Obertelli 1963, Matzner and Griffel 1963, and Lee and Morris, 1964) were correlated in a similar manner (± 15 per cent) but to bring the resulting family of curves into coincidence with the Freon family the term $(GD^{\frac{1}{4}})$ was replaced by $(0.658\ GD^{\frac{1}{4}})$.

The relationships between corresponding Freon and water systems were obtained by making the numerical values of the individual component groups in the correlation (those in parenthesis) equal in both systems, namely:

$$\left(\frac{L}{D}\right)_{FREON} = \left(\frac{L}{D}\right)_{WATER} \quad \text{or} \quad D_W = \left(\frac{L_W}{L_F}\right) D_F = F_1\ D_F$$

$$\left(\frac{\Delta H}{\lambda}\right)_{FREON} = \left(\frac{\Delta H}{\lambda}\right)_{WATER} \quad \text{or} \quad \Delta H_W = \left(\frac{\lambda_W}{\lambda_F}\right) \Delta H_F = F_2\ \Delta H_F$$

$$\left(GD^{\frac{1}{4}}\right)_{FREON} = \left(0.658\ GD^{\frac{1}{4}}\right)_{WATER} \quad \text{or} \quad G_W = \left(\frac{D_F^{\frac{1}{4}}}{0.658\ D_W^{\frac{1}{4}}}\right) G_F = F_3\ G_F$$

$$\left(\frac{\varnothing_B}{\lambda G}\right)_{FREON} = \left(\frac{\varnothing_B}{\lambda G}\right)_{WATER} \quad \text{or} \quad \left(\varnothing_B\right)_W = \left(\frac{\lambda_W G_W}{\lambda_F G_F}\right) \left(\varnothing_B\right)_F = F_4 \left(\varnothing_B\right)_F$$

F_1, F_2, F_3, F_4 are called the scaling factors and the subscripts F and w refer to Freon and water respectively.

In this method only four scaling factors are required to determine the relationships between the five system-describing parameters ($\varnothing_B$, ΔH , L, D, G; note P is fixed once equality of ρ_L/ρ_V is specified) whereas with Barnett's method the values of all five system-describing parameters are fixed uniquely from the dimensionless groups. This additional degree of freedom, which Stevens and Kirby suggest is due to the relative insensitivity of $\varnothing_B$ to changes in D once $L/_D$, $GD^{\frac{1}{4}}$ are fixed, allows an arbitrary choice of the scale factor F_1.

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* The form of the correlation was deduced by inspection of the data and hand calculation.

For uniformly heated round tubes the method predicts the onset of burnout in water from the corresponding Freon data to within the accuracy of the experimental water results (± 15 per cent) for values of F_1 ranging from 0.6 to 4.4. A typical result is shown in Figure 3.

The results of tests made to check the reliability of this method for annuli and three variations of a nineteen-rod cluster were reported by Stevens and Wood (1966) again for ρ_L/ρ_V equal to 20.6, corresponding to water at 1,000 p.s.i.a. and Freon 12 at 155 p.s.i.a. For annuli the predictions from the Freon data agreed with the experimental water data to within ± 10 per cent for F_1 equal to one and two: for F_1 equal to three the agreement worsened slightly but the same trends were indicated.

For the clusters (F_1 equal to one), burnout was found to occur in the same relative positions in the cluster and the predictions agreed closely with the experimental water data. This is illustrated in the table below, in which the reference burnout power, as measured with water on the tubular grid cluster, is arbitrarily set at 100 per cent.

Type of Cluster	Relative Burnout Power	
	Experimental Water Data	Predictions from Freon Data
Castellated grid	118%	118%
Tubular grid	100%	102%
Wrapped cluster	70%	74%

4.3 Discussion

The ability of the Freon system to produce burnout curves which are qualitatively similar to those characteristic of high pressure water, emphasised by the revealing of important details of the fine structure of the graphical relationships which were previously obscured by inadequacies in the water data, suggests that the fundamental processes involved in burnout are similar for the two systems. This view is further supported qualitatively by tests showing that burnout in both systems is closely related to the disappearance of the liquid film on the heater surface.

The work of Barnett, though by no means exhaustive, indicates that similarity of Freon/water systems requires simultaneous equality of at least two, possibly three, <u>all-fluid</u> property groups (ρ_L/ρ_V and either or both $\frac{\lambda\gamma}{\beta C_L}$ and $C_L\ \mu_L/K_L$). However it appears to be reasonably established by experiment that ρ_L/ρ_V is the predominant group and that equality of this group alone allows prediction to within ± 7 per cent for uniformly heated round tubes. This is fortunate since simultaneous equality of more than one group is an extremely restrictive criterion. It could not be achieved with Freon. For example at ρ_L/ρ_V equal to 20.6, $C_L\ \mu_L/K_L$ is approximately 0.9 for water and 3.1 for Freon; $\lambda\gamma/\beta C_L$ is approximately 111 for water and 75 for Freon.

The scaling factor approach reported by Stevens and Kirby, based on equivalence of ρ_L/ρ_V, shows that similarity criteria derived for round tubes are also applicable to more complex geometries (annuli and rod clusters) and gives predictions within the scatter of the experimental water data. The method allows an arbitrary choice of model dimensions thereby facilitating experimentation. In Appendix 2 a comparison is made of the predictions from this method with those from Barnett's method. It is shown that the agreement depends upon the water data used; good agreement is obtained if the scaling factor correlation (Section 4.2.2) is based on the single source of water data used by Barnett.

The above considerations justify the use of Freon as a model fluid for water at 1,000 p.s.i.a. in a study of burnout for nuclear application. Experimentation is considerably eased and cheapened yet the accuracy of prediction lies within the scatter to be expected from different water loops. It is unlikely that the design of reactor fuel elements would be based solely upon experimental data from a Freon loop but such a loop should be well suited for comparative testing. It could be used, for example, to establish the best of a number of designs and to assess the effect of design modifications; or in a more fundamental role to investigate methods of improving burnout, the effects of axial and radial flux shapes and optimisation of cluster geometry. Also it could readily be adapted for fundamental studies of other two phase flow characteristics such as pressure loss, voidage determination, flow patterns and zone boundaries.

It is important that the limitations of the similarity criteria discussed in this report be appreciated. Barnett's analysis, though of potential general application, is restricted by the supporting experimental data to Freon/water systems at two values of ρ_L/ρ_V only and uniformly heated round tubes; also the possibility of a systematic error in the water data used should not be overlooked (Appendix 2). The tests on annuli and clusters reported by Stevens and Kirby suggest that the analysis may well apply to geometries other than round tubes but this, and its use with other fluids, has yet to be established : even extrapolation to different values of ρ_L/ρ_V for Freon/water systems should be checked by experiment. This latter comment also applies to the scaling factor approach of Stevens and Kirby since its application has been demonstrated for only a single value of ρ_L/ρ_V. In addition there is a need to establish reliable limits over which the freedom of choice of linear dimension may be exercised, especially for rod clusters.

The reliability of the Winfrith Freon data is discussed in a recent paper by Behar (1967). Results are given for a single round tube, using Freon at 155 p.s.i.a., which are in reasonable agreement with the Winfrith data when plotted according to the correlation given in Section 4.2.2 but diverge slightly at high mass velocities. Tests in progress are reported to confirm the reliability of prediction at a value of ρ_L/ρ_V equal to 7.5 (equivalent to water at 2,000 p.s.i.a.).

A Freon loop is under construction at the A.A.E.C. Research Establishment, Lucas Heights. Commissioning should commence late 1968 followed by measurements of burnout in uniformly heated round tubes for comparison with the Winfrith data.

In the following section a brief description of the loop is given:

5. <u>DESCRIPTION OF THE A.A.E.C. FREON LOOP</u>

The A.A.E.C. Freon loop is basically similar to the one at Winfrith Heath. A diagramatic arrangement is shown in Figure 4.

A glandless motor pump, capable of delivering 85 g.p.m. at 140 ft head, circulates the Freon around a closed loop of 2 in. nominal bore, mild steel pipe-work. From the pump, subcooled Freon passes through a metering section to a preheater comprising eighteen U type immersion heaters. The preheater can deliver up to 80 kW at a maximum heater flux of 4 W cm^{-2}. The Freon then passes to the test section which is limited to lengths of less than 16 ft. Power to the test section is taken from a 150 kW, silicon rectified, d.c. unit of 50V, 3,000A or 25V, 6,000A supplied by a regulator*.

The two phase mixture of liquid Freon and its vapour leaving the test section then passes to twin, segmentally baffled, shell-U-tube heat exchangers which have cooling tower water circulating on the shell side. These remove the

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* The existing regulator limits the power supply to 90 kW.

heat supplied in the preheater and test section and maintain the thermal equilibrium of the loop. From the heat exchangers the subcooled Freon then returns to the pump and the cycle is repeated.

For given Freon conditions at inlet to the heat exchangers the power dissipated (hence outlet Freon temperature) depends on the cooling water temperature. This can vary by approximately 20°F through the year. Assuming a maximum wet bulb temperature of 66°F it is anticipated that these exchangers will dissipate 150 kW with an outlet Freon temperature not exceeding 85°F. At high Freon flows this may limit the performance of the loop, owing to cavitation at pump inlet, and increased cooling capacity may be necessary; alternatively Freon 21 may be used. A Freon temperature of 85°F at outlet from the heat exchangers also limits the subcooling available at the test section inlet to below that reported in the literature. A proposed small refrigeration unit (or 'negative preheater'), located after the metering section is shown in Figure 4.

The loop is designed for operation at pressures up to 300 p.s.i.a. and the maximum temperature at inlet to the pump is restricted to 160°F. The Freon is charged to the loop, and discharged from it, via a dump tank which can either be heated or cooled by water circulation. A vacuum pump is available for purging and initial charging of the loop.

5.1 Loop Control

The pressure level in the loop is set by reference to a communicating vessel containing Freon which is independently heated and cooled. Varying rig pressures are obtained by altering the temperature of the Freon in the communicating vessel. At any desired level the loop pressure is maintained by a control mechanism which actuates the heater supply according to variations from a demand pressure.

The flow of Freon to the test section is varied by manual control of valves in the main and bypass lines. These valves have linear characteristics over most of their range. The flowrate is metered by one of five orifice plates, covering a range from 0.2 g.p.m. to 85 g.p.m. The design permits the changing of orifice plates without dismantling any parts of the loop.

Control of the Freon temperature at inlet to the test section is provided to offset any changes in ambient conditions. This is achieved by raising or lowering the preheater power supply according to variations from a demand temperature.

The power supply to the test section is controlled manually by means of the regulator.

Pressures and temperatures are monitored at a number of stations around the loop and safety trips are incorporated on the pump, preheater and test section power supplies to cater for abnormal or fault conditions. The loop is enclosed in a ventilated tent to minimise the spread of Freon vapour in the event of a leak developing.

6. ACKNOWLEDGEMENTS

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APPENDIX 1

NOTATION

C	specific heat at constant pressure
D	diameter of tube (in)
F	scaling factor
G	mass velocity (lb hr^{-1} ft^{-2})
K	thermal conductivity
L	length of tube (in)
P	system pressure
x	dryness fraction
β	the rate of change of saturation temperature with pressure $\frac{d\theta_s}{dp}$
γ	the rate of change of the liquid to vapour density with pressure, $-\,d/dp\,(\rho_L/\rho_V)_S$
ΔH	subcooled enthalpy at inlet (BTU lb^{-1})
θ	temperature
λ	latent heat (BTU lb^{-1})
μ	viscosity
ρ	density
σ	surface tension
ϕ	heat flux (BTU hr^{-1} ft^{-2})

Subscripts

B	burnout value
BO	burnout value at $\Delta H = 0$
F	Freon
L	liquid phase
S	saturation conditions
V	vapour phase
W	water

APPENDIX 2

COMPARISON OF PREDICTIONS FROM BARNETT'S SIMILARITY RELATIONSHIP WITH THOSE FROM THE SCALING FACTOR METHOD

Comparison of the two methods of prediction is restricted by Barnett's relationship to round tubes with a scale ratio given by:

$$\left(\frac{DC_L\rho_L^{\frac{1}{2}}}{K_L\ \gamma^{\frac{1}{2}}}\right)_{WATER} = \left(\frac{DC_L\rho_L^{\frac{1}{2}}}{K_L\ \gamma^{\frac{1}{2}}}\right)_{FREON}$$

or

$$\frac{D_W}{D_F} = \left(\frac{C_{LF}}{C_{LW}}\right)\left(\frac{K_{LW}}{K_{LF}}\right)\left(\frac{\rho_{LF}}{\rho_{LW}}\right)^{\frac{1}{2}}\left(\frac{\gamma_W}{\gamma_F}\right)^{\frac{1}{2}}$$

Using the property values given by Barnett (1964):

$$\frac{D_W}{D_F} = \frac{1}{5.18} \times 7.11 \times \left(\frac{1}{0.6}\right)^{\frac{1}{2}} \times (0.164)^{\frac{1}{2}}$$

$$= 0.72 \quad .$$

From Barnett's relationship the factor for mass velocity is obtained by equating the groups:

$$\left(\frac{G\ \gamma^{\frac{1}{2}}}{\rho_L^{\frac{1}{2}}}\right)_{WATER} = \left(\frac{G\ \gamma^{\frac{1}{2}}}{\rho_L^{\frac{1}{2}}}\right)_{FREON}$$

or

$$\frac{G_W}{G_F} = 1.91 \quad .$$

Similarly the factor for burnout heat flux is obtained from:

$$\left(\frac{\phi_B\ \gamma^{\frac{1}{2}}}{\rho_L^{\frac{1}{2}}}\right)_{WATER} = \left(\frac{\phi_B\ \gamma^{\frac{1}{2}}}{\rho_L^{\frac{1}{2}}}\right)_{FREON}$$

or

$$\frac{\phi_{BW}}{\phi_{BF}} = 22.43 \quad .$$

Continued...

Scaling Factor Method

The length scale factor $F_1 = \frac{L_W}{L_F} = \frac{D_W}{D_F}$, derived from the similarity requirement $\left(\frac{L}{D}\right)_W = \left(\frac{L}{D}\right)_F$, is chosen to be 0.72 as given by Barnett's analysis.

The scaling factor for mass velocity F_3 is given by:

$$F_3 = \frac{G_W}{G_F} = \frac{1}{0.658} \times \left(\frac{D_F}{D_W}\right)^{\frac{1}{4}} = 1.65 \quad .$$

The scaling factor for burnout heat flux F_4 is given by:

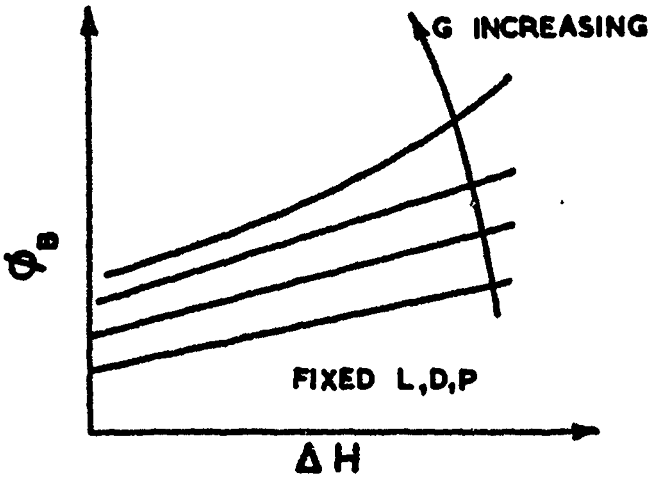
$$F_4 = \frac{\phi_{BW}}{\phi_{BF}} = \left(\frac{\lambda_W}{\lambda_F}\right)\left(\frac{G_W}{G_F}\right) = 19.4 \quad .$$

F_3 and F_4 are approximately 14 per cent lower than the corresponding factors from Barnett's analysis.

In assessing the validity of his similarity relationships Barnett used only a single source of water data (Lee and Obertelli 1963). Stevens and Kirby on the other hand used three sources of water data in developing their scaling factors, including the data of Lee and Obertelli. They note that systematic differences exist between the three sources of water data which give rise to a scatter about their correlation curve of ± 15 per cent. A fairer comparison is therefore achieved if the same water data are used in both cases. This is because the co-ordinates of the water correlation curve, and hence the value of the constant used to bring the water/Freon correlation curves into coincidence (Section 4.2.2), are affected by any systematic differences in the water data. If the correlation is based solely on the water data of Lee and Obertelli the correlation constant 0.658 (see Section 4.2.2) is reduced to approximately 0.6 (extracted from Figures 7 and 16 of Stevens and Kirby 1964) and the agreement is significantly improved as shown in the table below.

Continued...

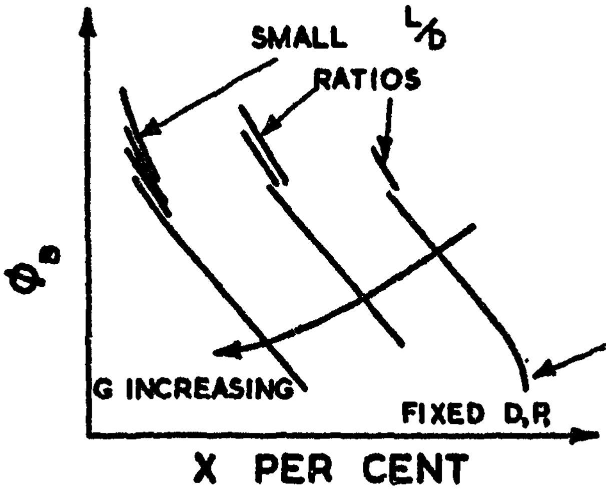
Predictions Using Barnett's Similarity Relationship	Predictions Using the Empirical Scaling Factor Method	
	Based on three sources of water data Correlation constant = 0.658	Based on the water data of Lee and Obertelli as for Barnett's method. Correlation constant = 0.6
Length factor = 0.72	Length scaling factor F_1 = 0.72	= 0.72
Mass velocity factor = 1.91	Mass velocity scaling factor F_3 = 1.65	= 1.82
Burnout heat flux factor = 22.43	Burnout heat flux scaling factor F_4 = 19.4	= 21.2



RELATIONSHIP PRECISELY LINEAR FOR LARGE L/D RATIOS AND MODERATE MASS VELOCITIES

PRONOUNCED UPWARD CURVATURE AS L/D DECREASES AND MASS VELOCITY INCREASES

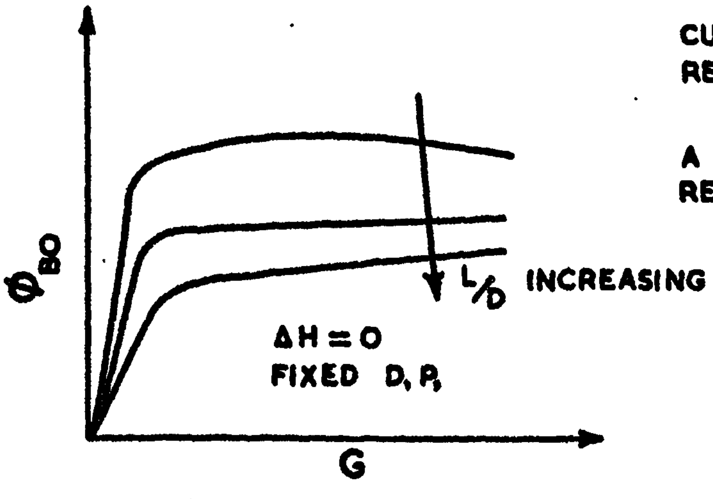
BURNOUT HEAT FLUX AND INLET SUBCOOLING



BURNOUT HEAT FLUX NOT UNIQUE FUNCTION OF QUALITY FOR SMALL L/D RATIOS AND HIGH MASS VELOCITIES

LONG LENGTH AND LOW MASS VELOCITIES GIVE RISE TO DOWNWARD CURVATURE AT HIGH QUALITIES

BURNOUT HEAT FLUX AND QUALITY



CURVES SHOW LOW AND HIGH VELOCITY REGIMES

A MAXIMUM OCCURS IN HIGH VELOCITY REGIME AT SMALL L/D RATIOS

BURNOUT HEAT FLUX AND MASS VELOCITY

FIGURE 1. TYPICAL BURNOUT CURVES OBTAINED WITH FREON

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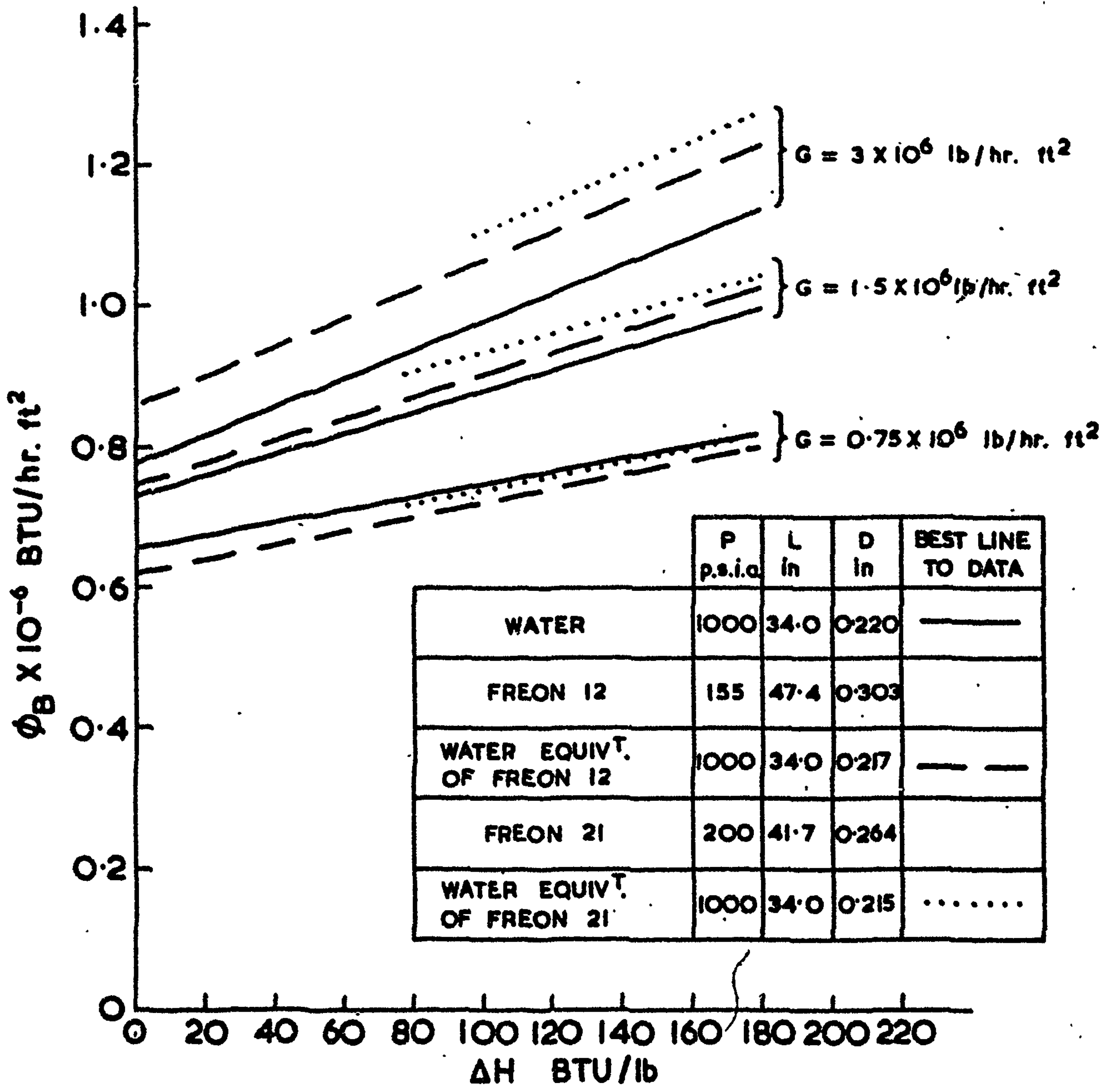

	P p.s.i.a.	L in	D in	BEST LINE TO DATA
WATER	1000	34·0	0·220	———
FREON 12	155	47·4	0·303	
WATER EQUIV^T. OF FREON 12	1000	34·0	0·217	— —
FREON 21	200	41·7	0·264	
WATER EQUIV^T. OF FREON 21	1000	34·0	0·215	……

FIGURE 2. COMPARISON OF BURNOUT IN WATER AND FREON FOR UNIFORMLY HEATED ROUND TUBES - BARNETT'S METHOD

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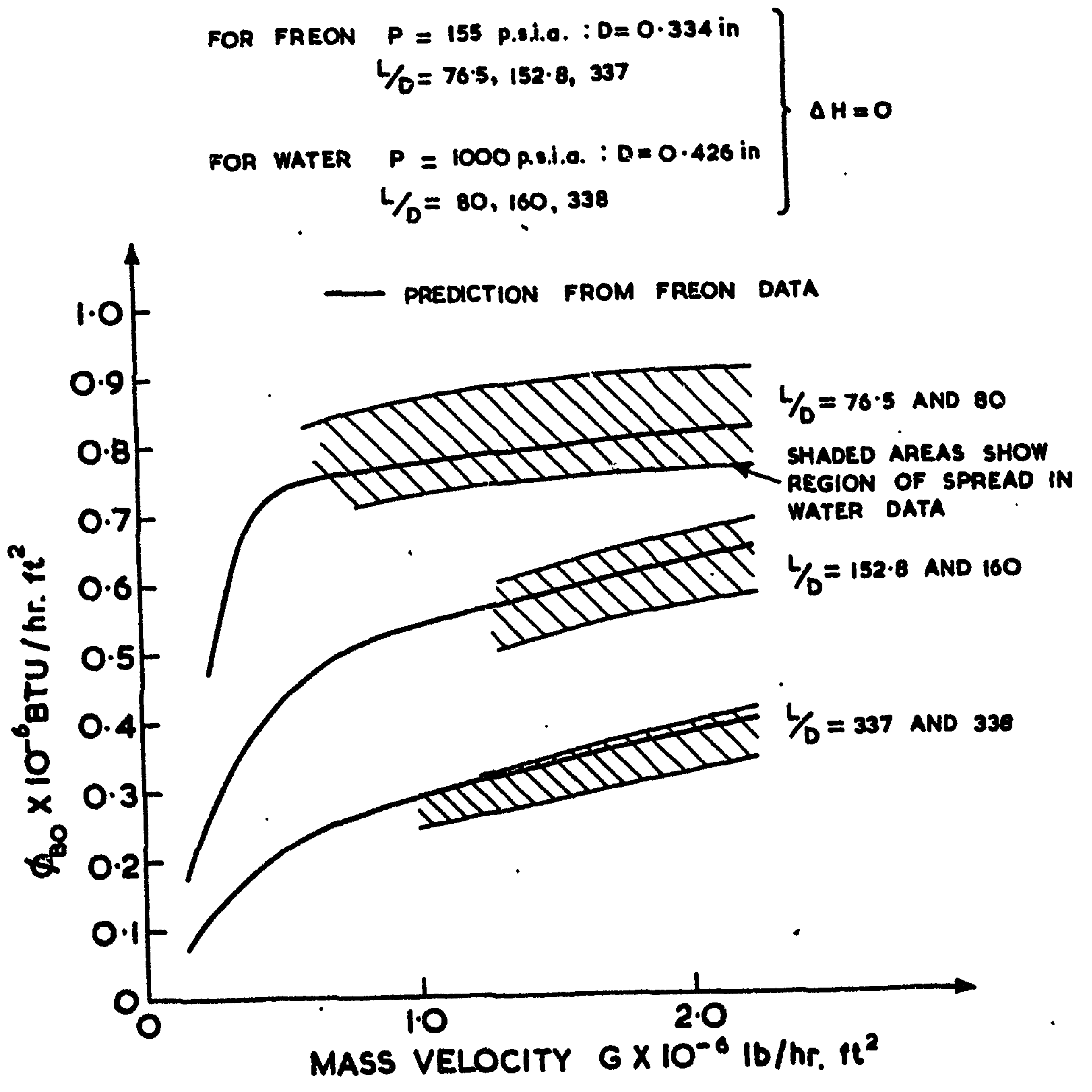

FIGURE 3. COMPARISON OF BURNOUT IN WATER AND FREON FOR UNIFORMLY HEATED ROUND TUBES - SCALING FACTOR METHOD

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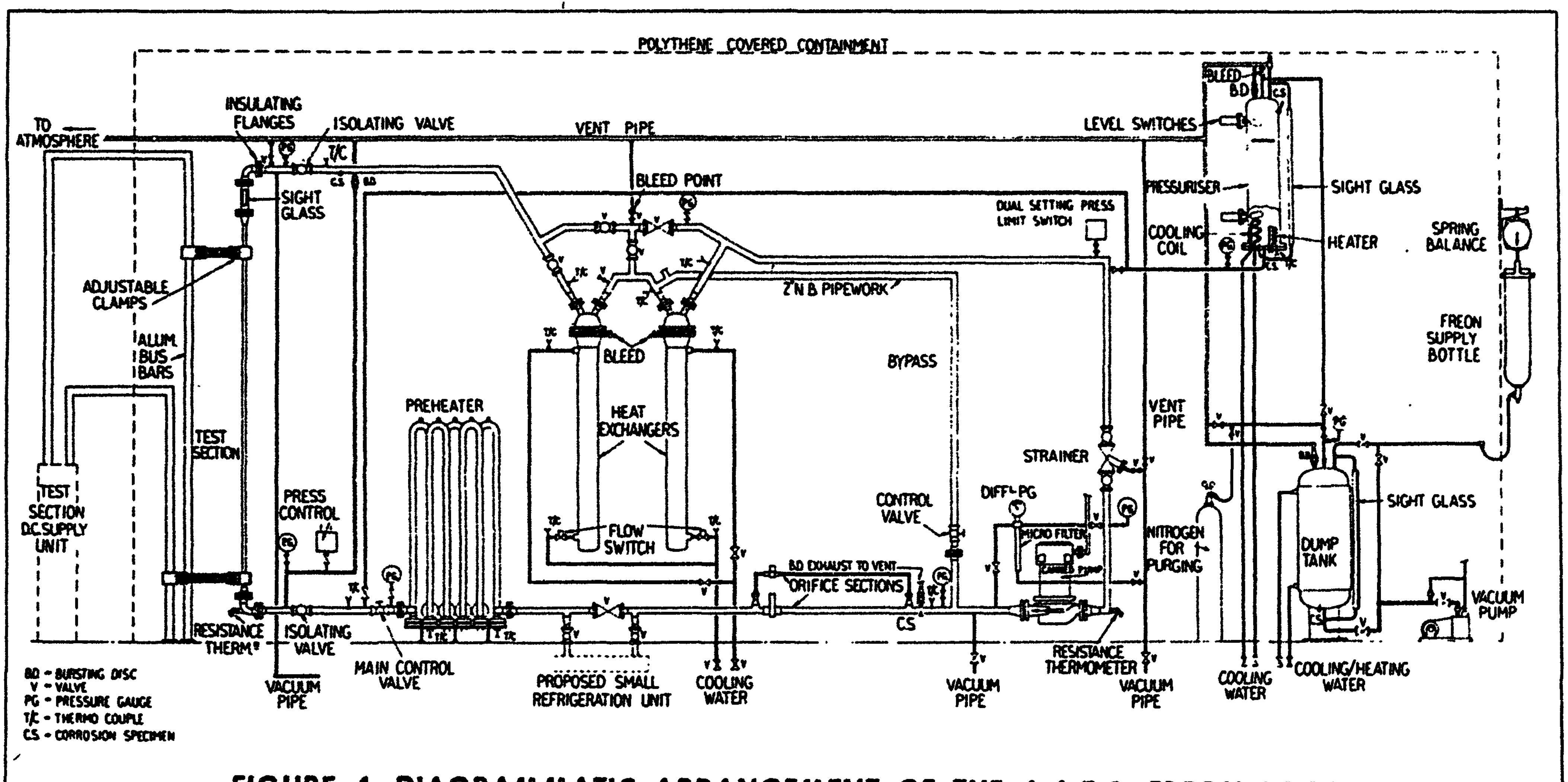

FIGURE 4. DIAGRAMMATIC ARRANGEMENT OF THE A.A.E.C. FREON LOOP