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A Criterion for the Onset of Quench for Low Flow Reflood

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Y. Y. Hsu, M. W. Young

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A Criterion for the Onset of Quench for Low Flow Reflood

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U.S. Nuclear Regulatory Commission
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ABSTRACT

This study provides a criterion for the onset of quench for low flow reflood. The criterion is a combination of two conditions:

$T_{clad} < T_{limiting\ quench}$, and (T= Temperature)
$\alpha < 0.95$ (α = Void Fraction)

This criterion was obtained by examining temperature data from tests simulating PWR reflood, such as FLECHT, THTF, PBF, CCTF, and FEBA tests, with void fraction data from CCTF, FEBA, and FLECHT low flood tests. The data show that quenching initiated at $\alpha = 0.95$ and that the majority of quench occurred at void fractions near 0.85. The results show that rods can be completely quenched by entrained droplets even if the collapsed liquid level does not advance. A thorough discussion of the analysis which support this quench criterion is given in the text of this report.

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1.0 BACKGROUND

Existing quench criteria specify a critical temperature, below which quenching is supposed to occur. This temperature has been referred to as: rewet temperature, Leidenfrost temperature, minimum delta-T, etc. In this paper, the quench temperature refers to the "knee" of the clad temperature history when the clad temperature takes its precipitous drop.

Strictly speaking, rapid cooling of a rod means that heat dissipation is much faster than heat generation. Since heat generation during reflood is low, the increase of heat dissipation is more responsible for increased cooling. Increased heat dissipation could arise from initiation of transition boiling corresponding to a decrease of the temperature difference ($T_{surface} - T_{sat}$) or caused by the arrival of more liquid, (i.e., decrease of quality or void), or both.

When there is sufficient liquid, ($\frac{\partial q}{\partial T}$) controls clad temperature. When there is a scarcity of liquid, $\frac{\partial q}{\partial \alpha}$ or $\frac{\partial q}{\partial X}$ is controlling. The former case is for high flow bottom reflood, whereas the latter case is for low flow bottom reflood; or for quench due to spray. A general approach to describing the heat transfer surface is to construct a multidimensional surface of q (X, G, P, ΔT, . . .). A rapid drop of clad temperature would occur if heat dissipation increases rapidly along an operating path.

Most studies until recently addressed the problem of q(ΔT), with an attempt to determine the lower limit of film boiling or the upper limit of temperature at which liquid can still physically be in contact with solid.

Many models have been proposed. These models are based upon heat conduction (e.g., Thompson's Model Ref. 1), upon the hydrodynamic instability limit (e.g., Berenson's Model Ref. 2), upon the thermodynamic instability limitation (e.g., Spiegler Model Ref. 3), or upon combinations (e.g., Henry Model Ref. 4). The review of the various models can be found in Ref. 5. Figure 1 shows the comparison of the various models with quench data from tests in simulated fuel rod bundles. The data shown are the upper limit of quench temperatures (Ref. 6-10, 14, 17).

It should be noted that all these data are from thermocouple readings. No corrections were made for the radial or axial gradient of heat transfer near the solid-liquid interface. For transient conduction of heat to the surface and a rapid change of heat transfer coefficient, the radial gradient near the solid-liquid interface ("skin") can be particularly significant. Upon instantaneous contact between the liquid and the solid, the skin temperature may drop to the limiting liquid temperature momentarily while the solid interior temperature may be much higher than the limiting liquid temperature. Henry obtained the empirical Equation 1 to predict the liquid limiting temperature, T_L:

$$T_L = (T_L)^* + [(T_L)^* - T_b]\ (0.42)\ [\sqrt{\frac{(k\ \rho_\rho C)_\ell}{(k\ \rho\ C_\rho)s}}\ \ \frac{h_{fg}}{C_\rho\ \cdot\ (\Delta T_L\ )_B}\ ]^{0.6} \qquad \text{Eq. 1}$$

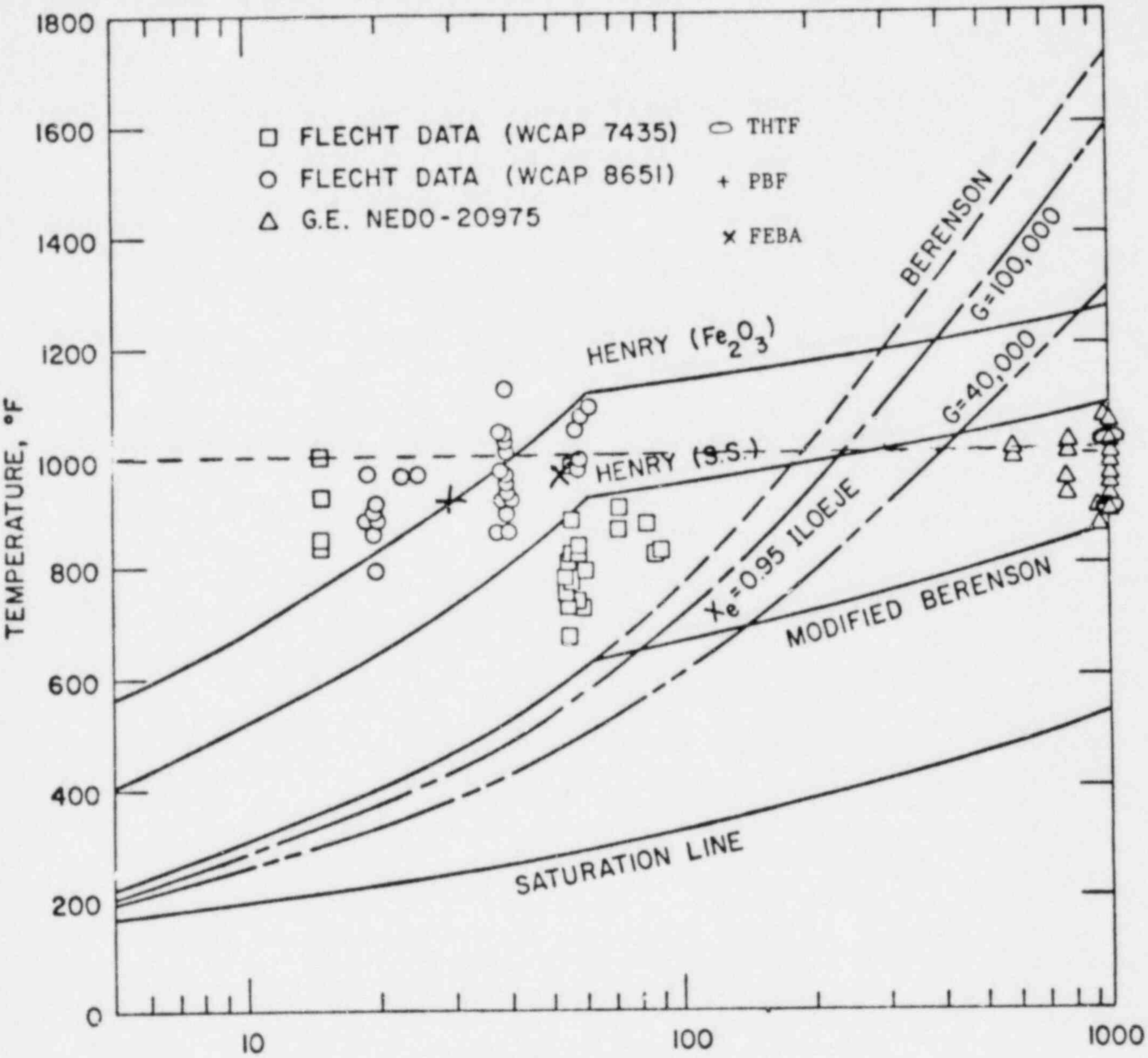


Figure 1. Comparison of Modified Berenson and Henry Correlations with Data

In Henry's equation, T_L^* is the Berensen's minimum -ΔT temperature based upon hydrodynamic instability considerations. T_L^* is controlling in the low pressure range where $\frac{V_g}{V_l}$ is large. For high pressures, T_L^* should be set as a limitation of the liquid state based upon thermodynamic considerations with the classical form being $\frac{27}{32} T_C$. The upper limit of quench temperatures shown in Figure 1 are higher than either the thermodynamic limit or the hydrodynamic limit. It is even higher than Henry's limiting temperature, possibly because of the additional temperature drop across the gap around the sheath of the thermocouple. Since gap resistence is difficult to define when the rod is undergoing a temperature change and since the dependence of the limiting quench temperature or flow condition is unknown, one tentative solution is to set T_{Limit} = 1000°F, pending formulation of a complete quench model.

It is very interesting to note that no quench criteria except Iloje's Eq., have considered the effect of flow on quench. This oversight might be due to the fact that earlier models were formulated for pool boiling. To account for the flow condition, Iloje's equation for quench (Equation 2 subject to modification in Fig. 2) (Ref. 11) was selected by the Rewet Workshop (Reference 12).

$$\frac{(T_L - T_{sat})}{(T_L - T_{sat})_{Berenson}} = 0.29 \left[1 - 0.295 X e^{2.45}\right] \left[1 + (G \times 10^{-4})^{0.49}\right] \qquad \text{Eq. 2}$$

Iloeje's equation shows that quench temperature is a function of flow rate, inlet subcooling, and pressure. The positive dependence of quench on pressure is not surprising. However, the parametric dependency of quench on flow rate G has not been very clear (see Figure 3 for flat profile, Ref. 13). As to subcooling effects, it is difficult to visualize that a quenching process, which is a local phenomena, would depend upon inlet subcooling, which loses its meaning as liquid progresses into the bundle.

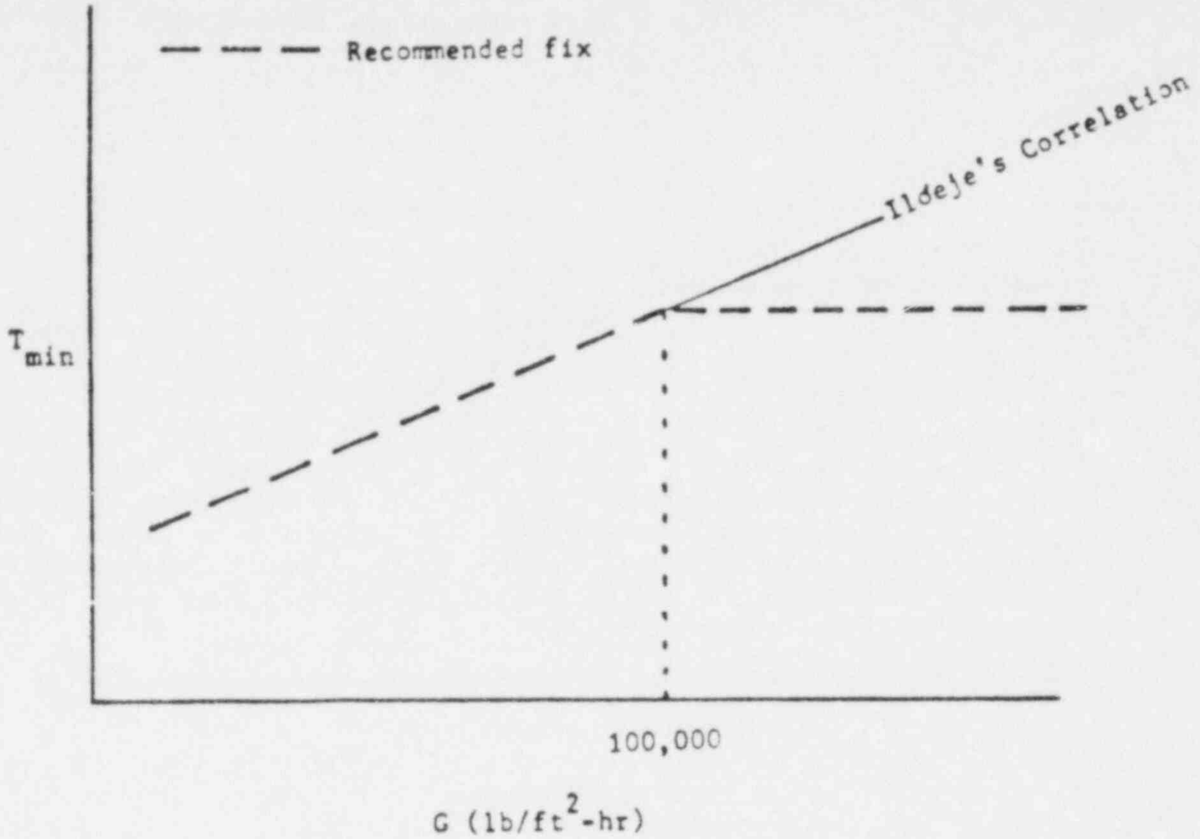


Figure 2a. Recommendation Modification of Iloeje's correlation for T_{min} at high mass flow (Ref. 12)

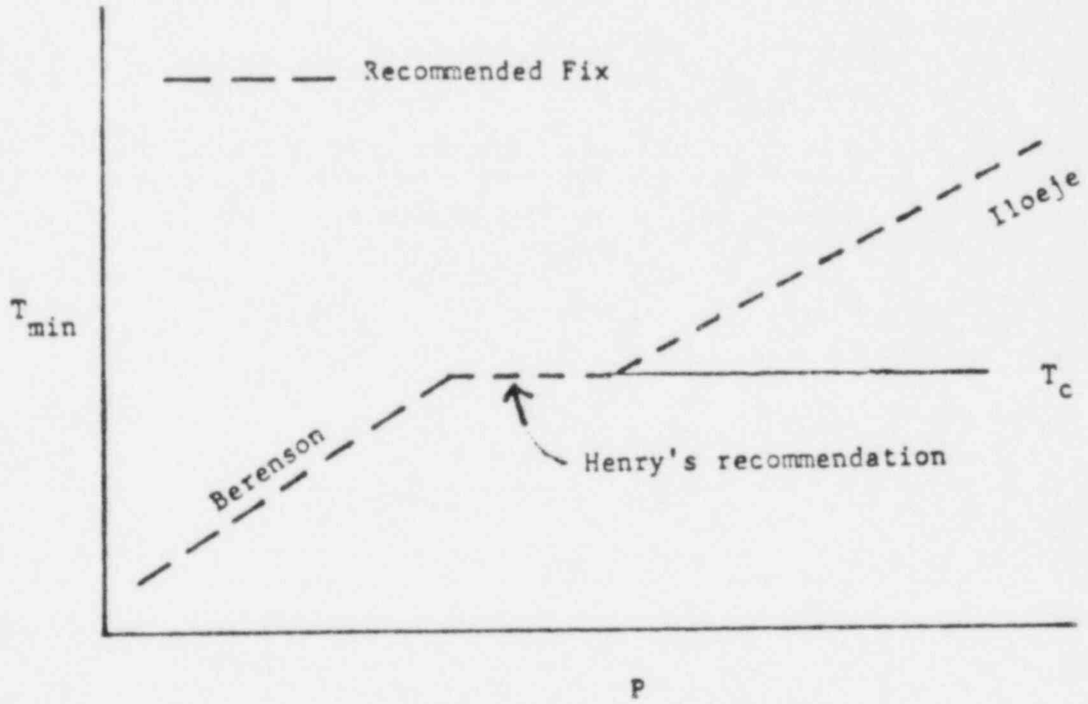


Figure 2b. Recommended modification of Iloeje's Correlation for T_{min} at low pressure (Ref. 12)

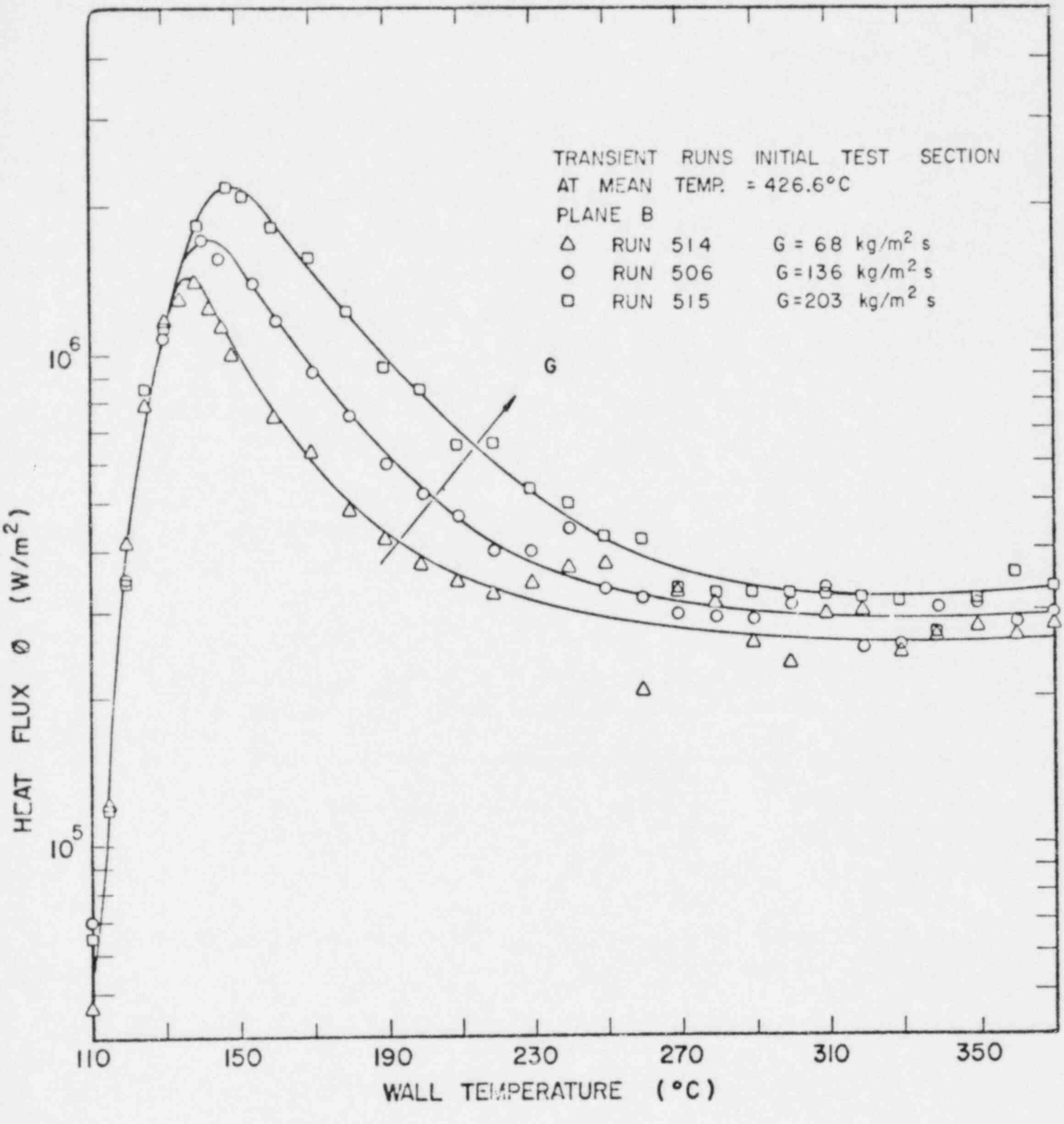


Figure 3. Effect of Mass Flux on Boiling Curves of Distilled Water, Short Block Series for $\Delta T_{SUB} = 0°C$ (Ref. 12)

2.0 ANALYSIS AND DISCUSSION

To reexamine the problem of quenching, it is important to remember that for quenching to occur, two conditions must be satisfied simultaneously; namely, that the clad temperature must be low enough for liquid to make the momentary contacts and that liquid must be present. Clad temperature can simply decrease to any low temperature by precursory cooling before its precipitous drop upon arrival of liquid (see Figure 4). Thus, correlations such as Iloje's equation, which do not consider the effect of void, could predict quench temperatures in error by several hundred degrees. The conservative approach of setting the lower bound of the data as a criterion for quench temperature is not realistic since the lower bound refers to the temperature when water arrives and can be arbitrarily set to a lower level by holding back the water. The above argument shows the absurdity of using quench temperature as the sole criterion without consideration of the need of liquid for cooling. On the other hand, it is important to understand that with the quench temperature criterion met, quenching is possible even though the "solid" water reflood front has not reached the quench elevation, i.e., 100% carryover. Entrained droplets which travel from the reflood elevation up through the voided channel serve to decrease void fraction and satisfy the void fraction criterion for quenching.

The presence of water can be represented by the water fraction, α_l, which is $1-\alpha$, with α being the void fraction. The local void fraction can be determined from local impedance probes at quench elevations, or to a lesser degree of accuracy, from local dp measurements of collapsed static liquid level of each cell.

The void fractions at the quench elevation obtained from interpolation of dp-data of FLECHT tests are shown in Figure 5. As shown, for the data from tests with a low flooding rate, 70 percent of the quenching takes place at void fractions between 0.70 and 0.95 ($.70<\alpha<.95$).

The quenching criteria of $0.70<\alpha<0.95$ is verified by FEBA data (Ref. 14), as shown in Figure 6. As shown below, six data points were available for the quench void, α_q, measured from the time-fraction of dry conditions as measured by local impedance probes. The void fraction at quenching is obtained from the relationship: $\alpha = t_{dry}/(t_{dry} + t_{wet})$, averaged over 10 sec intervals, where t is the time at the dry or wet condition.

Run No.	177			182		
Elevation	HF1	HF2	HF3	HF1	HF2	HF3
α_q	0.92	0.93	0.96	0.88	0.75	0.93

For present PWR designs, quench is due to bottom reflood alone and the quench front was observed to be coincident with the advance of the froth front (which is much higher than the collapsed liquid level) as shown in FLECHT tests (Ref. 15). Then, the quench void fraction is nothing more than the void fraction at the froth front. In some reflood tests, however, the rod is quenched from both top and bottom by cooling from spray or entrained liquid.

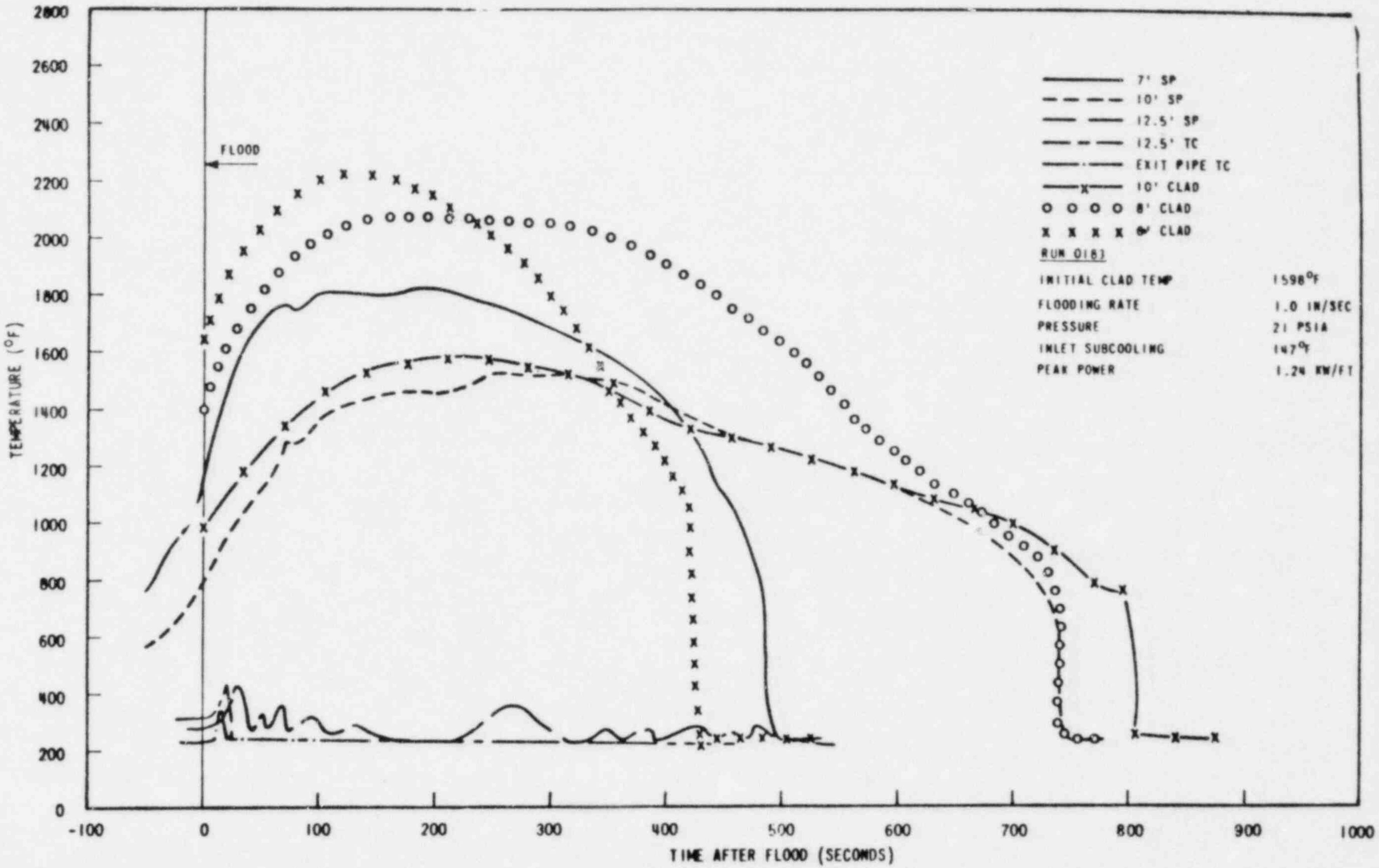


Figure 4. Local Coolant and Clad Temperatures (Run 0183 FLECHT) during Reflood (Ref. 6)

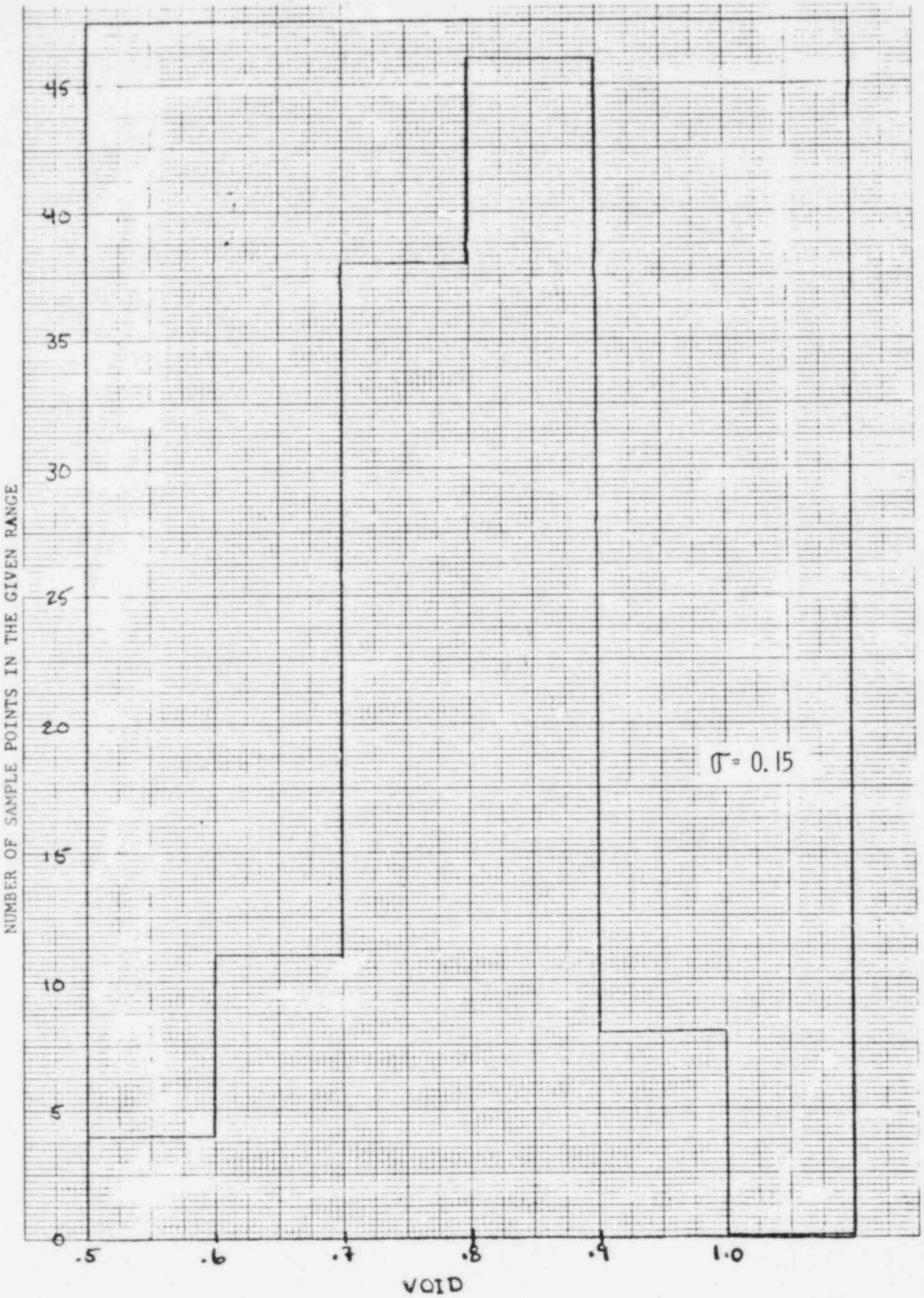


Figure 5a. Statistical Distribution of Quench Void for FLECHT Skew Series

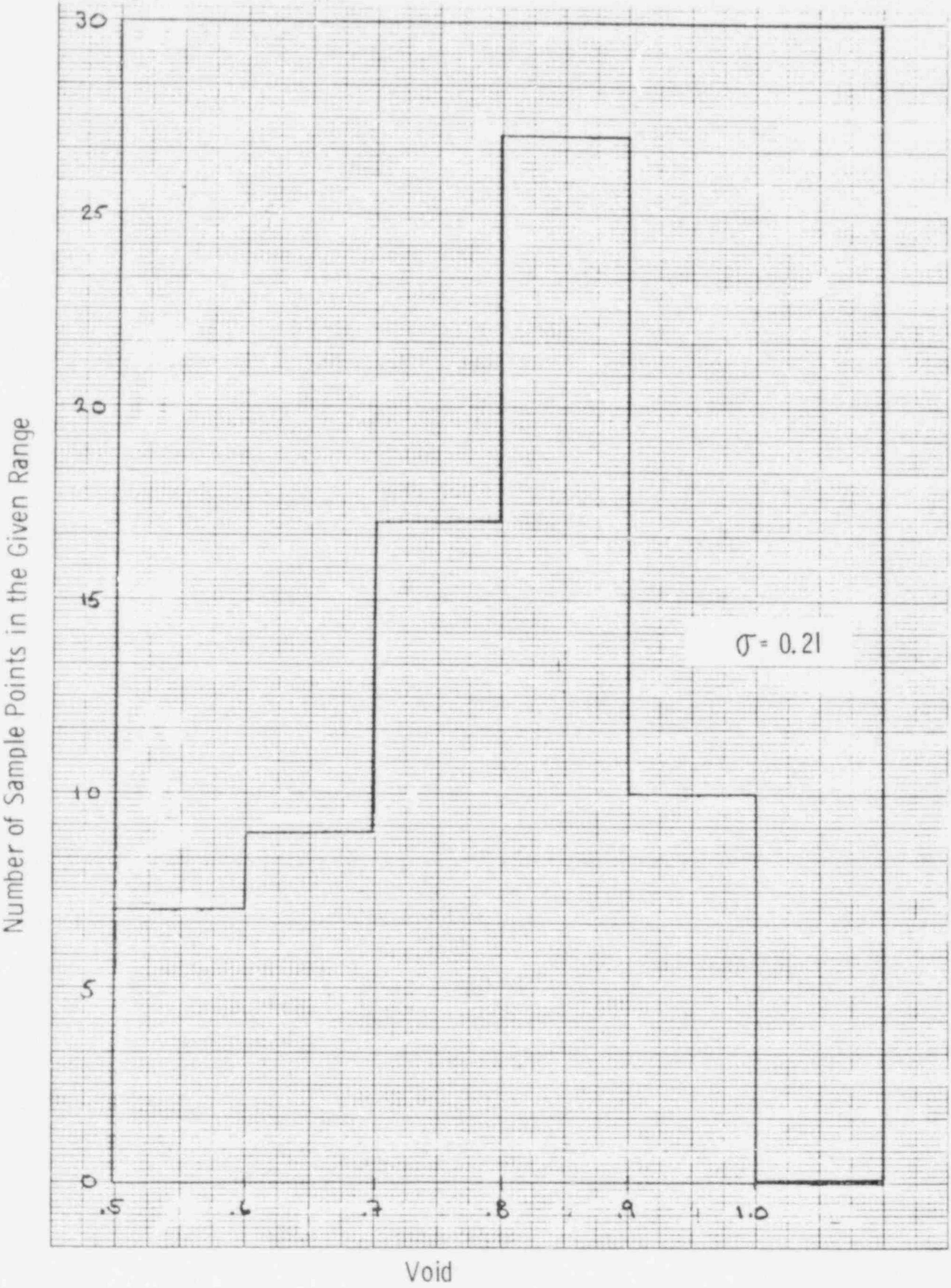


Fig 5-B: Statistical Distribution of Quench Void for FLECHT Skew Series

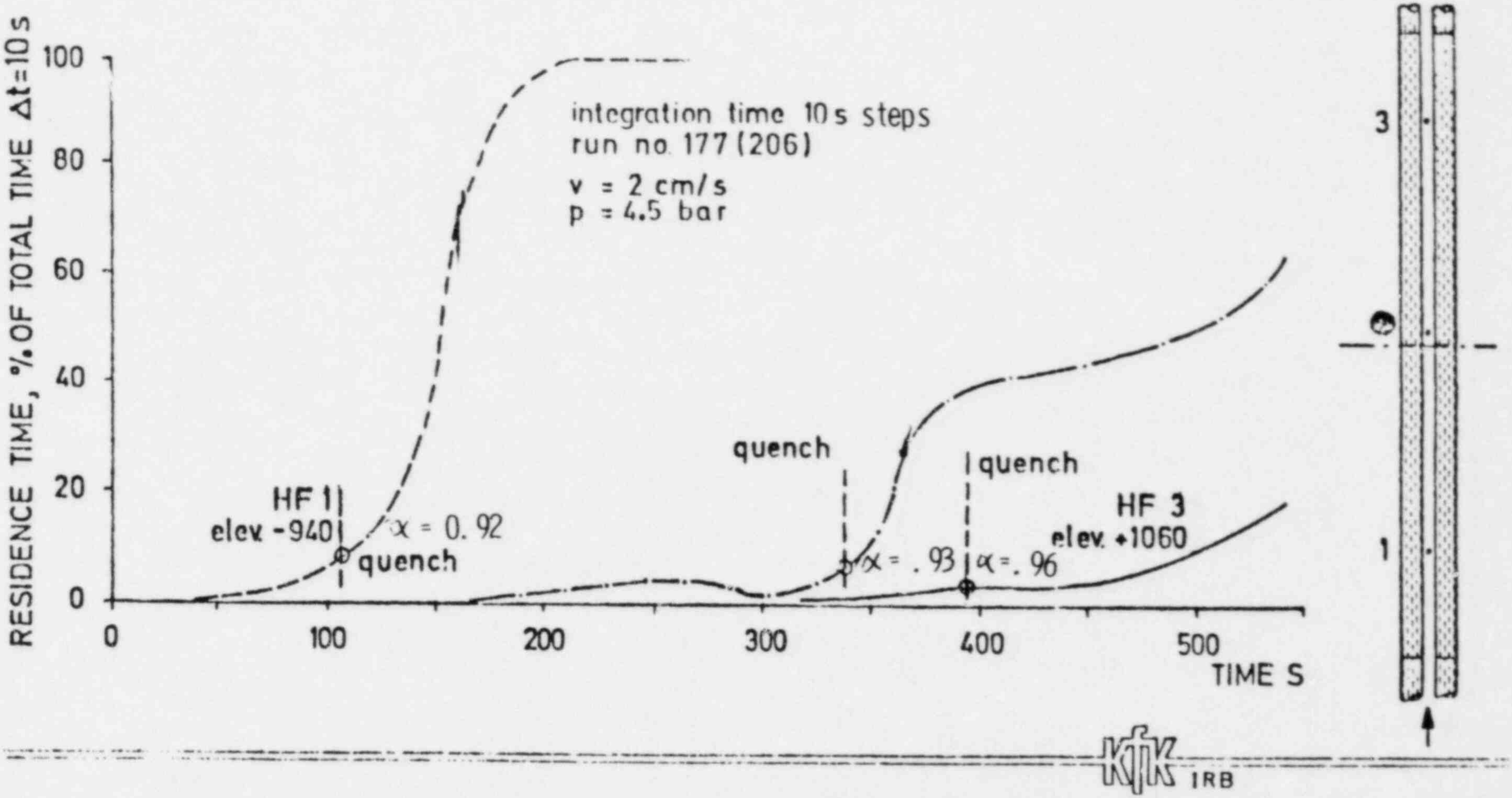


Figure 6. Residence Time of Water at High Frequency Probes (Ref. 14)

In such a case the quench front movement is different from the water front movement. For example, in some large multibundle tests, the water level did not advance beyond 1/3 of the core until after the core was completely quenched. Consequently, there is a need to define a quench void as a quench criterion.

Fig. 7 shows the typical "bubble plots" of liquid level indicators in a proprietary test. If one takes 10 sec intervals and equates the time fraction of the "dry" condition to the void fraction, the bubble plots at various elevations can be converted into "Iso-void" profiles as shown in Fig. 8 (in the form of elevation vs. time). Also shown in the same figure are the profiles of quench fronts. Note that the liquid level ($\alpha = 0.1$) hardly advanced for most of the reflood period, while the quench front is enveloped by profiles of $0.75 < \alpha < 0.95$.

A further confirmation of the proposed void-fraction criterion is from the FLECHT Data Analysis Report (Ref. 16), in which it was shown that the quench front is very close to the froth front. The void fraction of the froth front can be calculated to be in the range of 0.70 to 0.99 as shown in Figure 9 and the Appendix. Figure 9 was based on Yeh's equation, using the parameter K in that equation in the range of 0.01 to 0.001, which is the predominant range for low-flooding rate data. The parameter B in the same equation is a function of pressure and velocity. Figure 9a covers the range of B expected from FLECHT low-flooding tests. Figure 9b shows that for the range of B covered, the void fraction of the froth is 0.70 to 0.99 (Table 1, 2). However, since the void fraction of the froth changed rapidly with elevation and $\alpha = 0.99$ requires an accurate prediction of void fraction, the upper rewet void fraction is set to be 0.95 as a more reliably predicted value. Thus,

$$0.70 < \alpha_{quench} < 0.95 . \qquad \text{Eq. 2}$$

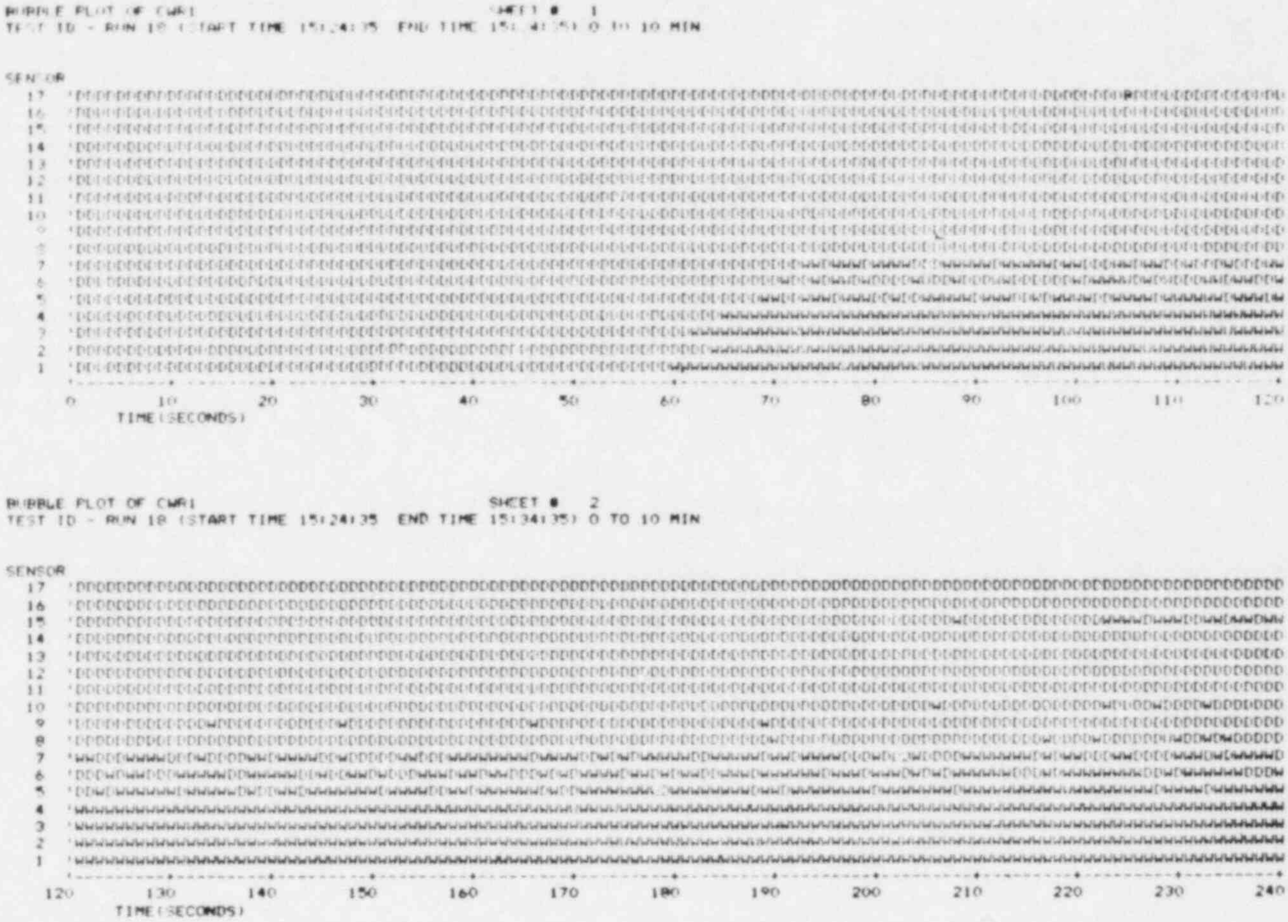


Figure 7. Typical Bubble Plot from Liquid Level Dectector Data (Ref. 15)

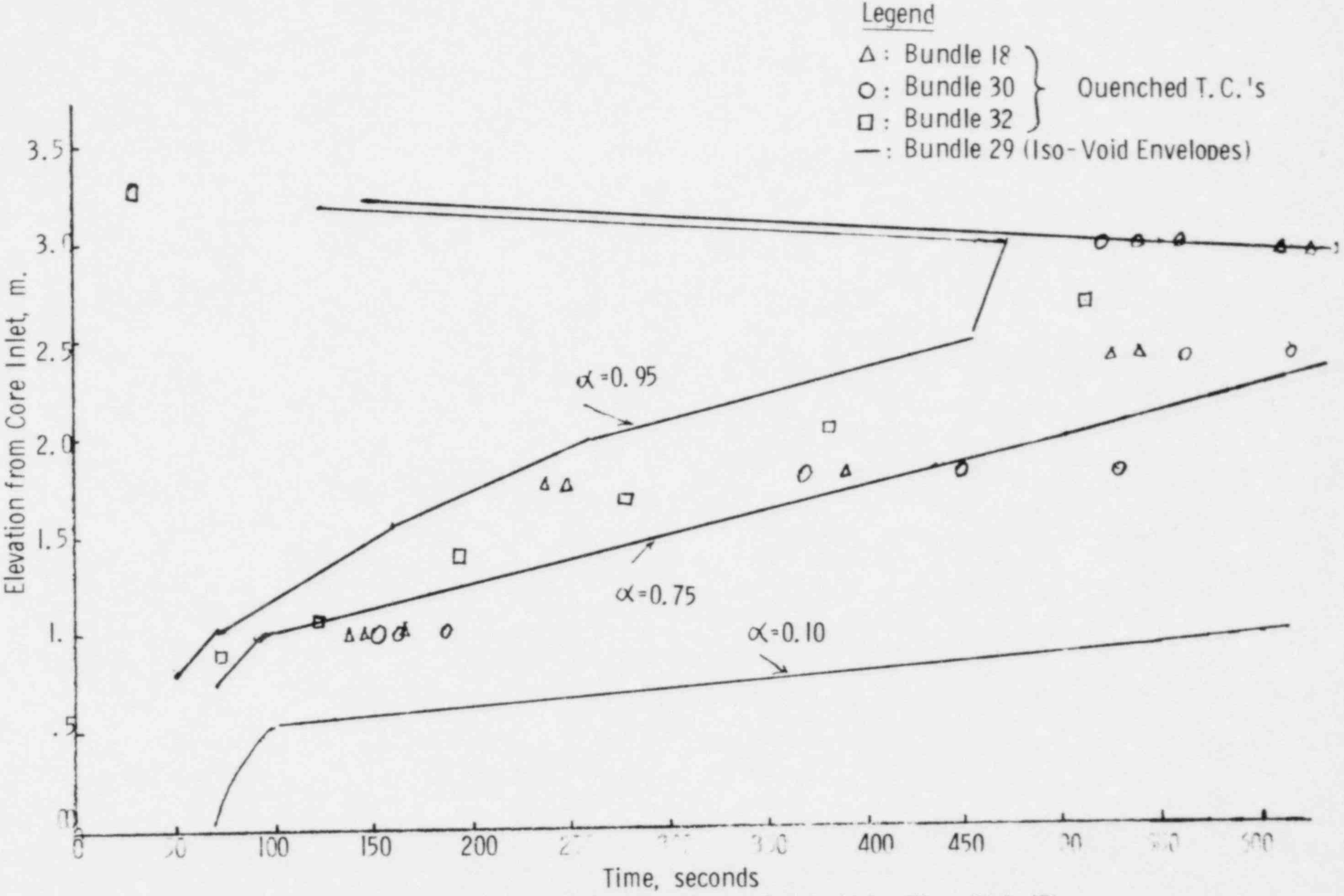


Figure 8: Quenching Elevation Profile and Iso-Void Profiles (Ref. 15)

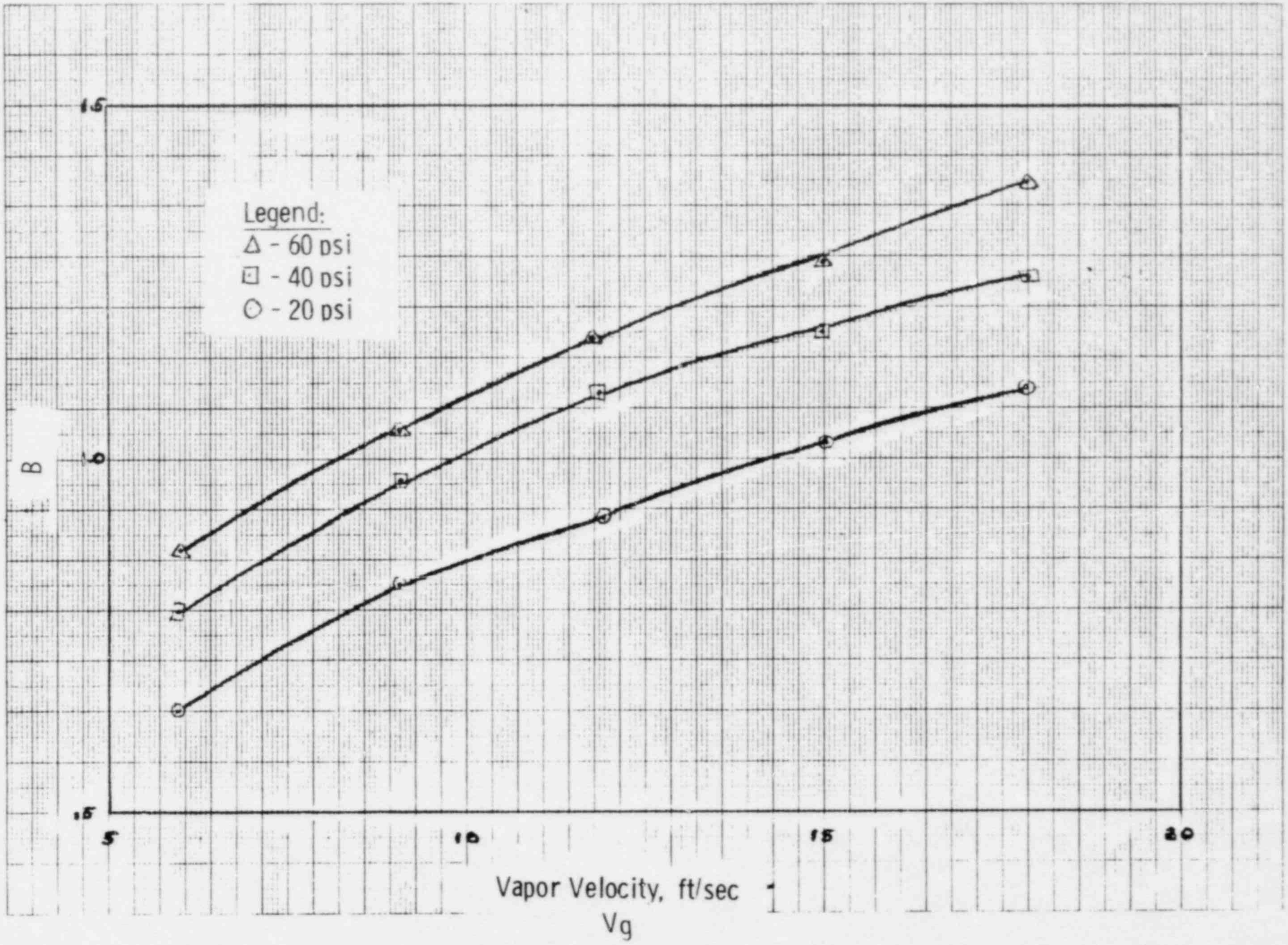
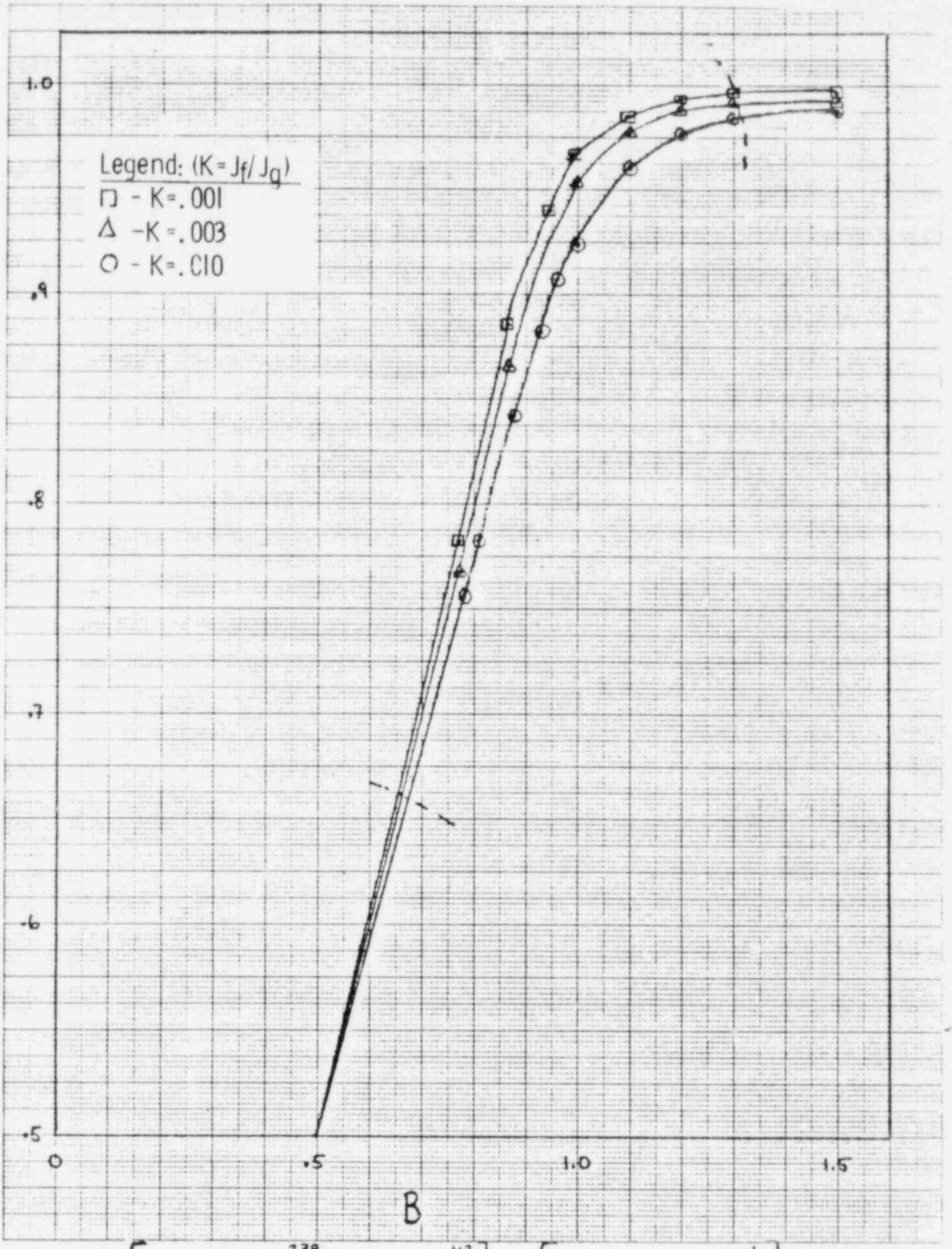


Figure 9a. Function B as function of Vapor Velocity in Covering Typical Range of Conditions



$$B = \left[.925\left(\rho_g/\rho_l\right)^{.239}\left(V_g/V_{BCR}\right)^{.47}\right] \text{ OR } \left[\alpha\left(1+K/(1-\alpha)\right)^{.6}\right]$$

Figure 9b. Void Fraction in Froth Layer as Function of B + K From Yeh's Eq.

Table 1 B as function of Vapor Velocity and Pressure

Ppsi Vgi, ft/sec.	20	40	60
6	0.667	0.79	0.87
9	0.806	0.955	1.05
12	0.920	1.09	1.20
15	1.025	1.21	1.34
18	1.12	1.32	1.46

$$\alpha = 0.925 \left(\frac{\rho_g}{\rho_\ell}\right)^{0.239} \frac{V_g}{V_{bcr}} [1+k]^{-0.6} = B\,[1+k]^{-0.6}$$

$$K = \frac{V_f}{V_g} = \frac{j_f \alpha}{(1-\alpha) j_g}$$

$$B = 0.925 \left(\frac{\rho_\ell}{}\right)^{0.239} \left(\frac{V_{gi}}{V_{bcr}}\right)^{0.47}$$

$$V_{bcr} = \frac{2}{3}\sqrt{g\,R_{bcr}}$$

$$R_{bcr} = \left[\frac{4.59}{2}\right]^2 \sqrt{\frac{\sigma}{g\rho_\ell}}$$

From Yeh's Equation in Ref. 16

Table 2 Void fraction as function of B and K from Yeh's equation (Ref. 16)

	B =	0.34	0.79	0.81	0.87	0.92	0.96	1.0	1.1	1.2	1.3	1.5
K=0.01	α =	0.34	0.77	0.79	0.839	0.88	0.904	0.926	0.9606	0.976	0.983	0.990
K=0.003	α =	0.84	0.78		0.859		0.965	0.959	0.985	0.992	0.9946	0.997
K=0.001	α =	0.34	0.788		0.866		0.949	0.976	0.995	0.9972	0.9982	0.999

3.0 CONCLUSION

From THTF, FLECHT, PBF, FEBA, GE, CCTF data, the limiting quench temperature is found to be 1000°F. From FLECHT, CCTF, and FEBA, the quenching void criterion is found to be:

$$\alpha < 0.95$$

The above two conditions for limiting quench temperature and quenching void fraction must be satisfied simultaneously for quenching to occur. A procedure for application of the above criteria is given in the Appendix.

The implications of a quench void criterion are twofold:

1. Quench temperature alone is not sufficient to determine whether the rod is going to be quenched.
2. Even for the case of 95-100% carryover, i.e., when the collapsed water level does not advance or only advances very slowly, the entrained droplets, with flow void less than 0.95, can quench the rods, provided the rod temperature is below the limiting quench value (say 1000°F).

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APPENDIX

QUENCH VOID DETERMINATION

A.1 PROCEDURE FOR DETERMINING QUENCH VOID

1. Check to see if $T_w < 1000°F$. If $T_w > 1000°F$, no quench is allowed. If $T_w < 1000° F$, proceed to determine void.

2. To determine void:

   a. For quench at the froth front, use a modified Yeh's equation for void fraction:

$$\alpha = B(1 + K)^{-0.6}$$

$$B = 0.925 \left(\frac{\rho_g}{\rho_1}\right)^{0239}\left(\frac{U_g}{U_{b_{cr}}}\right)^{a}$$

$$K = j\ell/(1-\alpha)j_g$$

$$U_{bcr} = \frac{2}{3} \overline{gR_{bc}}, \quad R_{bc} = [\frac{1.53}{2/3}]^2 \overline{\frac{\sigma}{g\rho_1}}$$

$$a = 0.47$$

$$U_g = j_g/\alpha$$

$$j_g = \frac{\int_o^{z_{quench}} q\ z\ dz}{H_{fg}\rho_g A}$$

$$J_\ell = [\ U_{flood}\ A_c\ \rho_\ell - \frac{\int_o^{z_{quench}} q\ z\ dt}{H_{fg}}\ ] / \rho_\ell\ A_\ell$$

Note: The α-equation is implicit since $(1-\alpha)$ appears in K on the right-hand side. It takes iteration to obtain α. When α is close to unity, care must be exercised to avoid numerical oscillation since α has multiple roots and only one is correct. The one root with $\alpha>1$ is not a correct solution. Some of the α curves in terms of B & K are shown in Fig. 9.

b. For quench by entrained liquid droplets:

$$\alpha = \frac{(U_d + j_\ell + j_g) - \sqrt{(U_d + j_1 + j_g)^2 - 4j_gU_d}}{2U_d}$$

with j_1 & j_g same as before, except Z_{quench} refers to the bottom quench elevation. If there is fallback from top, j_1 is a combination of liquid from bottom and top.

$$U_d = (\frac{4\ We^*}{3C_d})^{\frac{1}{4}}\ [\frac{\sigma g\ (\rho\ell - p_g)}{pg^2}]$$

We* is critical weber number, usually about 10-20, but it may vary with grid space geometry.

C_d is drag coefficient, usually 0.45

σ is surface tension, ρ_1 and ρ_g are densities.

3. Check to see if α is less than 0.95, If so, quench is initiated.

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16. ABSTRACT *(200 words or less)*

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17. KEY WORDS AND DOCUMENT ANALYSIS

17a. DESCRIPTORS

Void Fraction
Quench
Reflood

17b. IDENTIFIERS/OPEN-ENDED TERMS

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