8005120021

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FORM EG&G-398
(Rev. 11-79)

INTERIM REPORT

Accession No. ____________

Report No. EGG-CAAP-5123

Contract Program or Project Title: Code Assessment and Applications Program

Subject of this Document: Preliminary Evaluation of the FLECHT-SEASET Systems Effects Test Facility As A Natural Circulation And Reflux Mode Experiment

Type of Document: Preliminary Assessment Report (PAR)

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Date of Document: March 1980

Responsible NRC Individual and NRC Office or Division: A. L. Hon, NRC-RSR

This document was prepared primarily for preliminary or internal use. It has not received full review and approval. Since there may be substantive changes, this document should not be considered final.

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Idaho Falls, Idaho 83415

Prepared for the
U.S. Nuclear Regulatory Commission
Washington, D.C.
Under DOE Contract No. DE-AC07-76ID01570
NRC FIN No. A6039

INTERIM REPORT

NRC Research and Technical
Assistance Report

ABSTRACT

The results from a preliminary evaluation of the use of the FLECHT-SEASET System Effects Test Facility for reflux and natural circulation mode experiments are presented. Conclusions regarding scaling relative to a full scale reactor design, potential behavior of the heated bundle and steam generator, hot leg insulation requirements and test instrumentation accuracy requirements are given. Recommendations for further study are made. The evaluation described in this report was made as part of the INEL support to the NRC for Industry Cooperative Programs.

EGG-CAAP-5123

March 1980

PRELIMINARY EVALUATION OF THE FLECHT-SEASET SYSTEMS EFFECTS TEST FACILITY AS A NATURAL CIRCULATION AND REFLUX MODE EXPERIMENT

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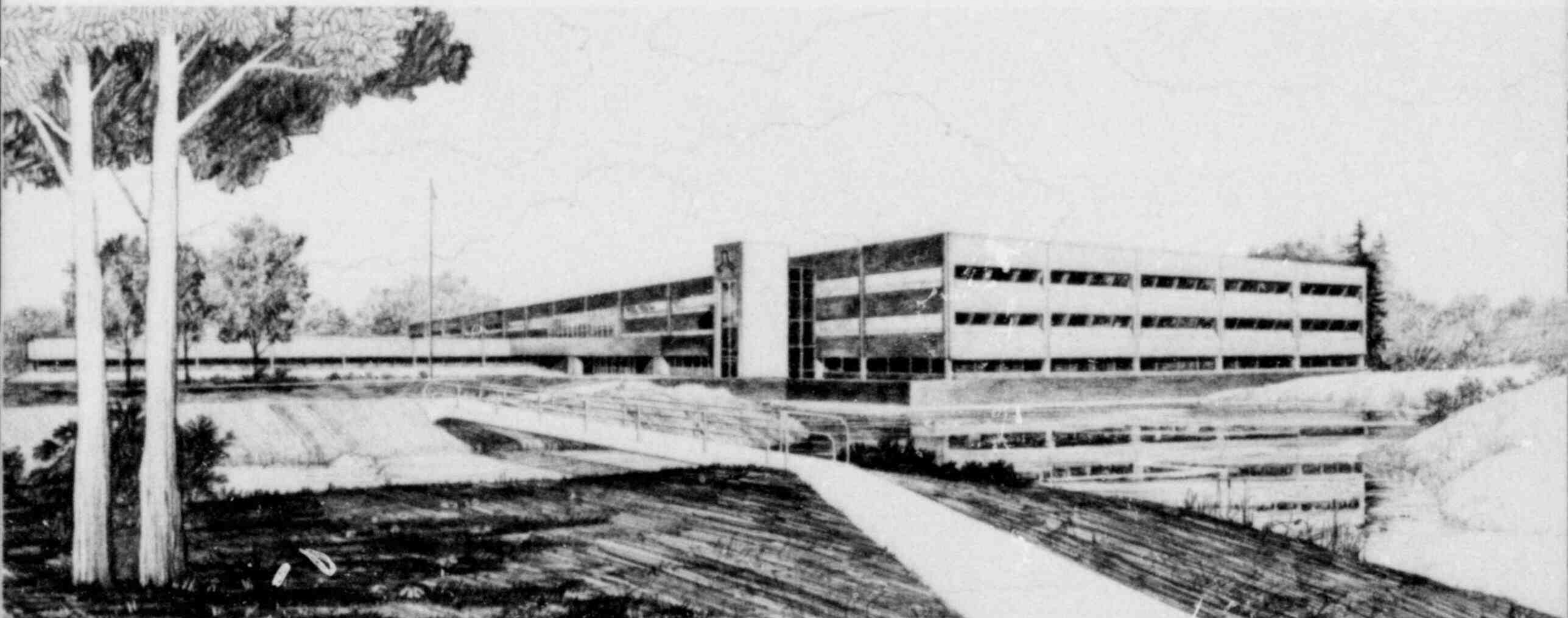

This is an informal report intended for use as a preliminary or working document

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SUMMARY

Incorporated within the NRC/EPRI/Westinghouse FLECHT-SEASET experimental reflood program is a system effects test facility. The original and primary objective for this facility is to provide a sub-scale thermal/hydraulic data base representative of a nuclear reactor undergoing a postulated loss of coolant accident during the reflood time frame. Recently this facility has been identified as potentially useful for tests with other accident scenarios. To gain insight as to the suitability of the test facility for these alternate modes of operation a selective and preliminary evaluation has been performed. The study was limited to the reflux condensation and natural circulation (both single and two phase) modes of operation. Natural circulation is considered the mode of primary interest with the reflux condensation mode being of secondary importance.

The results of a scaling review of the conservation equations during the single phase, natural circulation mode indicate that it will not be possible to achieve similarity in the conservation of mass, momentum and energy simultaneously. Similarity in individual parameters can probably be achieved only by compromising other parameters. A further scaling consideration is loop resistance. Calculations indicate that the FLECHT-SEASET loop resistances will need to be adjusted to account for the PWR to FLECHT-SEASET density ratio if loop resistances are to be properly scaled.

Other calculations indicate that during single phase, natural circulation a fiberglass mat (or equivalent), 0.0635 m (2.5 inch) to 0.0762 m (3 inch) thick will provide the desired maximum limit on the hot leg ambient heat loss. This study did not address the bundle or steam generator insulation requirements. We recommend the experimenter provide an independent assessment of the insulation requirements throughout the system.

A theoretical, turbulent flow model (suggested by Kays) has been developed for the difference in heater rod surface temperature and bundle bulk liquid temperature as a function of elevation and bundle power level. For the single phase, natural circulation mode those results imply that to operate successfully at the minimum proposed bundle power (0.2 percent), requires instrumentation with uncertainties in the subject parameter in the order of ±1.1 K ($\pm 2^{\circ}F$).

By making several simplifying (but acceptable) assumptions relative to single phase, natural circulation flow, a transendental model relating mass flow, heat transfer, density, elevation and loop flow resistance has been developed for the system. This model, applied to the Zion Plant, produced system mass flow and core temperature change within 5 percent and 1 percent, respectively, of those predicted by a detailed RELAP4/MOD6 model. This simplified model combined with a steam generator heat transfer model indicates:

(a) Under the best of operating conditions the instrumentation uncertainty in the steam generators must be low.

(b) Operations at the lower bundle power levels, suggested by the experimenter, may produce system ambient heat losses equal to, or a large percentage of, the bundle power. This condition has implications for the steam generator instrumentation in particular and the remaining system instrumentation in general.

In addition to the results listed above, calculations with the single phase natural circulation model indicate that frictional pressure drops in the test loop will be quite small and may present a problem in terms of instrumentation.

We were unable to develop a simple system model for the two phase, natural circulation operating mode nor have we been able to schedule a more sophisticated study to date. It is our feeling that there are definite uncertainties associated with successful operation in this mode and although we have not examined these uncertainties in depth we recommend the experimenter perform the necessary scoping type analyses required to establish the probability of successful operation in this mode.

A scaling review of the test facility for the reflux mode indicates perfect scaling relative to the reference reactor will not be achieved for all desirable scaling factors. Equal superficial vapor velocity and equal mass flux scaling are considered important considerations. These are not mutually achievable throughout the experimental system. Test operations to ensure equal superficial vapor velocity will probably support formation of the desired flow patterns, but will also produce a reduced potential for condensation in the Steam Generator U-tubes. This operating mode will require reduced bundle power levels, therefore, we recommend the experimenter determine that the power control system will accurately produce these reduced levels. Test operations to ensure equal mass flux will tend to develop the desired condensation behavior in the U-tubes, but may also produce atypical flow patterns in the hot leg.

Ambient heat loss calculations for the reflux mode indicate that the hot leg can be easily insulated to the degree required to produce equal or less fluid temperature change in FLECHT-SEASET relative to the reference reactor for expected maximum power levels. We recommend the experimenter perform the necessary calculations to determine the adequacy of insulation for the bundle and steam generator under similar conditions. We also recommend the experimenter determine the minimum bundle power level where the achievable ambient heat loss through-out the system remains at an acceptable operational level.

Counter Current Flow Limiting (CCFL) calculations, at the expected maximum bundle power level during the reflux mode, indicate the highest potential for CCFL occurs at the steam generator U-tube inlet. However, the calculations show that CCFL will not occur at these locations for either equal superficial vapor velocity or equal mass flux operating conditions, although the equal mass flux mode is approaching the point of concern. Should higher bundle power levels be used, CCFL is likely at the U-tube inlets for equal mass flux conditions.

The estimated, reflux mode, condensation behavior in the steam generator U-tubes for equal superficial vapor velocity and equal mass flux at maximum expected bundle power has been developed and compared with two levels of temperature measurement uncertainty. These comparisons indicate a need for instrumentation with uncertainties in the order of ± 0.1 K ($\pm 2^{\circ}$F) for the primary-secondary side temperature differential in the equal superficial vapor velocity mode of operation. Less stringent instrumentation uncertainties are required for the equal mass flux case; however, we expect that reduced bundle power levels will require smaller levels of uncertainty in the data. Therefore we recommend the experimenter consider the analysis techniques given here to determine the proper match between achievable levels of uncertainty and minimum usable bundle power.

I. INTRODUCTION

As part of the NRC (Nuclear Regulatory Commission)/EPRI (Electric Power Research Institute)/Westinghouse FLECHT-SEASET (Full Length Emergency Cooling Heat Transfer-Separate Effects and System Effects Tests) PWR (Pressurized Water Reactor) reflood program, a series of system effects tests will be conducted. The original and primary objective for this facility is to provide a sub-scale thermal/hydraulic data base representative of a nuclear reactor undergoing a postulated LOCA (Loss-of-Coolant Accident) during the reflood time frame. This data will be used to help develop and assess reflood predictive methods.

Recently the system effects test facility has been identified as potentially useful for tests with other accident scenarios. To gain insight as to the suitability of the test facility for these alternate modes of operation a selective and preliminary evaluation has been performed and is described in this report.

The study was limited to the reflux condensation and natural circulation (both single and two phase) modes of operation. Natural circulation is the mode of primary interest with reflux condensation of secondary importance. These modes and the facility are described in Section II. The study results are given in Sections III, IV and V, respectively, for tests operations in the single phase natural circulation, two phase natural circulation and reflux condensation modes. Our conclusions and recommendations derived from the study results are provided in Section VI. References from which important information was taken are listed in Section VII.

II. EXPERIMENTAL FACILITY

A description of the test facility, followed by a description of the potential new operating modes, is given in this section.

1. FACILITY DESCRIPTION

The FLECHT-SEASET System Effects Facility[1] will generally be volumetrically scaled (ratio - 1:327) to a 4 x 4, 3425 MW Westinghouse PWR. This plant design has many characteristics which are similar to four loop reactors marketed by other vendors. The proposed system designs[2] for the original reflood tests and the subsequent alternate mode tests are shown schematically and respectively in Figures 1 and 2. These figures were taken in total from Reference 2 and represent the designs as they existed at the time that document was issued. Subsequent design changes may occur; however, those changes are not considered likely to significantly affect the study given in this report. The reflood system shown in Figure 1 is included here to identify the baseline from which the system of Figure 2 will be developed. The need to have both reflood and alternate mode facilities has implications as to the cost effective design of the second system. However, because operation of the reflood facility is not germane to the study herein no further details are given for that configuration.

As shown in Figure 2, the experimental system is representative of a reactor design in that simulations are provided for the lower plenum, core (test vessel), fuel rods (electrically heated rods), upper plenum, broken and unbroken loop steam generators, pump loop seals, and downcomer. The unbroken loop steam generator is representative of three of the four loops in the reference reactor, while the broken loop steam generator simulates the remaining loop in the full scale design. Provisions are made for secondary side flow (feedwater system) in both experimental steam generators. Cold leg

FIGURE V-1

FLECHT-SEASET SYSTEM EFFECTS FACILITY SCHEMATIC

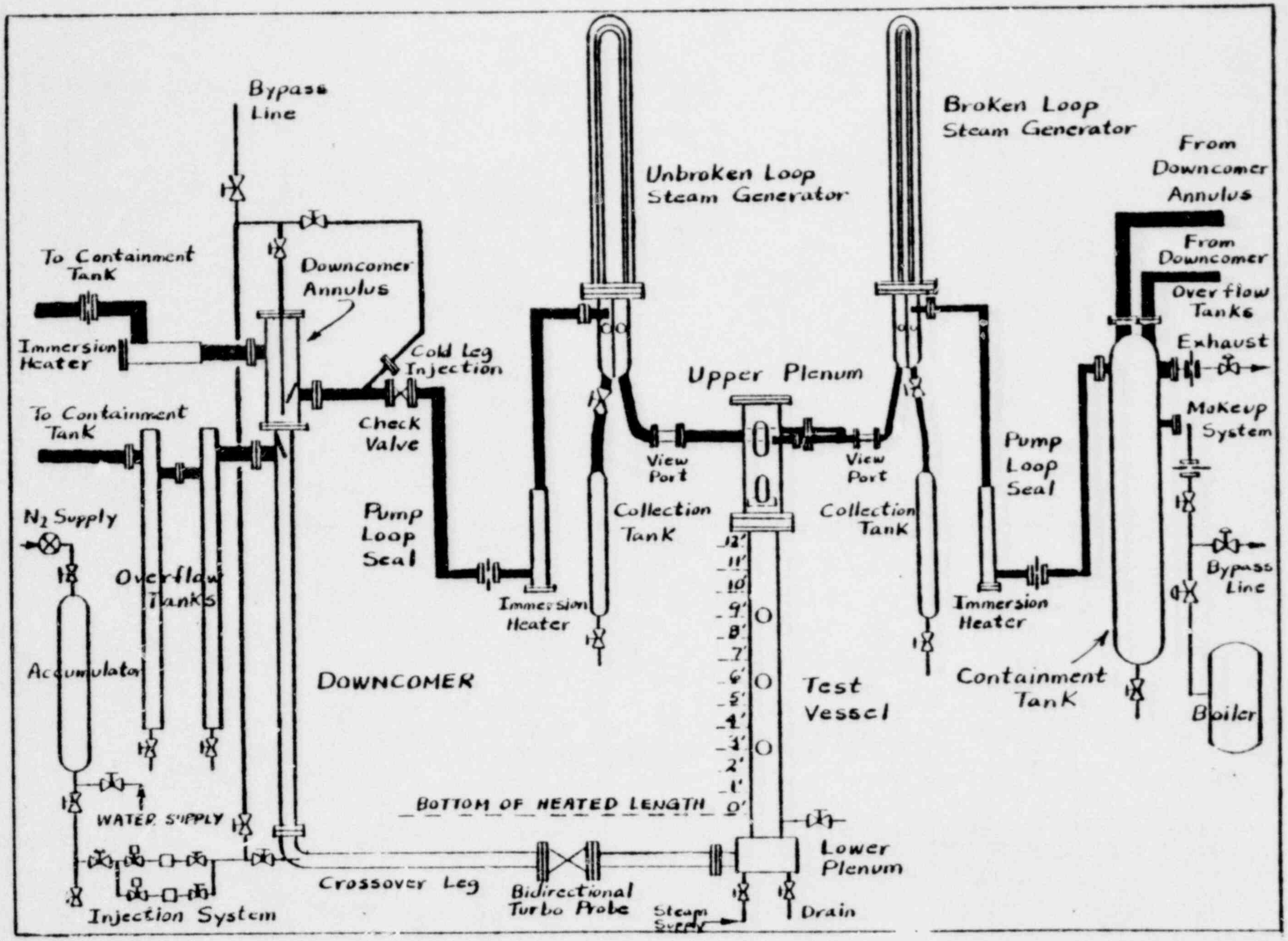

Figure 1. FLECHT-SEASET system effects facility schematic.

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FIGURE V-2
FLECHT-SEASET NATURAL CIRCULATION FACILITY SCHEMATIC

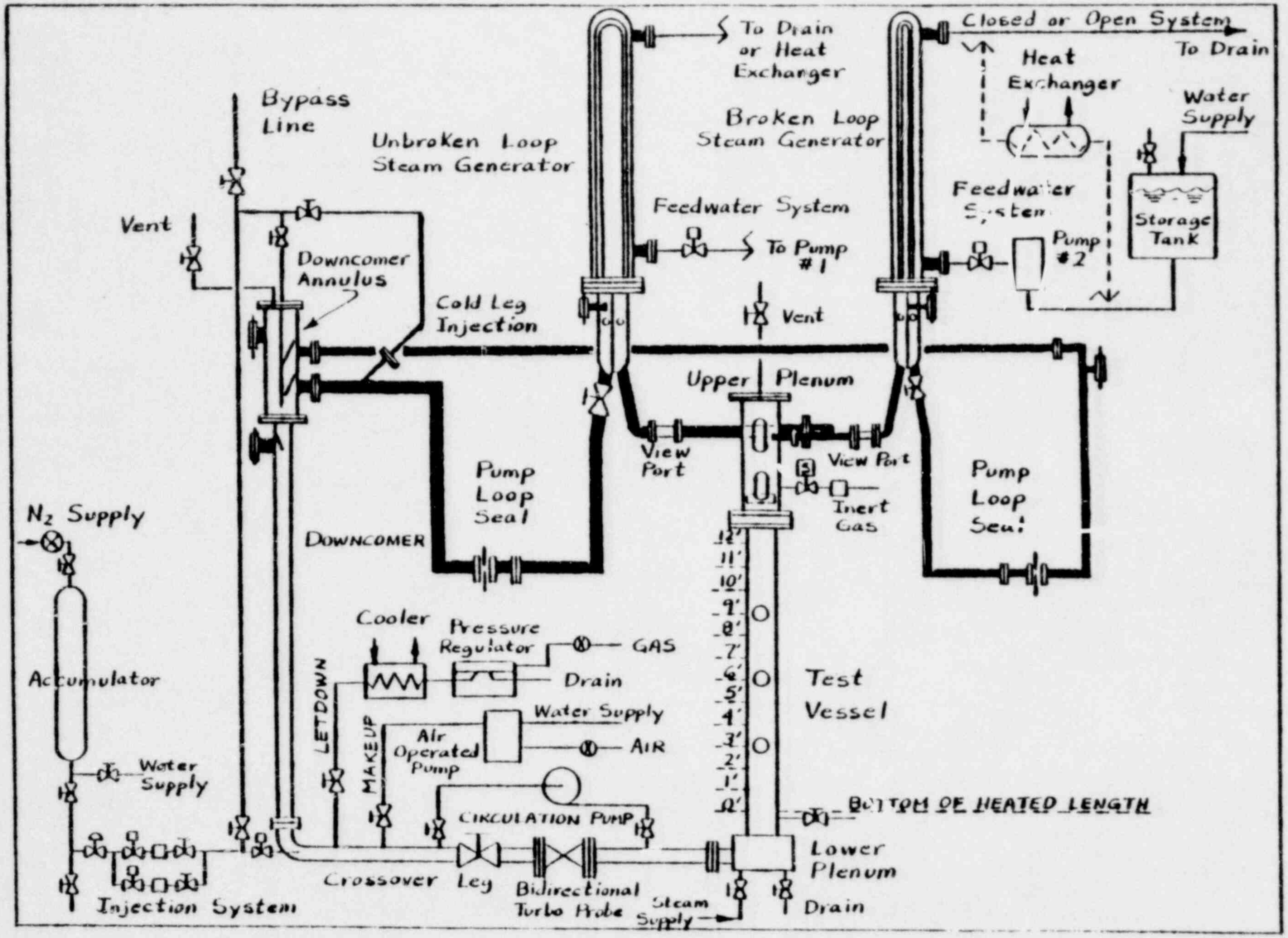

Figure 2. FLECHT-SEASET alternate mode facility schematic.

POOR ORIGINAL

recirculation pumps are not provided in the test facility because the alternate modes of operation presume inactive pumps in the reference reactor. The pumps' flow resistances will be simulated. Other systems and components shown in Figure 2 are used to simulate subsystems in the full scale design or to provide measurement capability. Typical test operations significant to this study are not defined in detail yet, but will be appropriate to the potential operating modes described in the next section.

2. OPERATING MODES

Three potentially interesting operating modes have been identified for the subject facility: a). single phase natural circulation, b). two phase natural circulation and c). reflux condensation. These modes are generally described in the following paragraphs (2.1 through 2.3). Currently all three of these modes are assumed to potentially occur in the reactor not earlier than one to two hours after SCRAM (i.e., core decay power initially at one to two percent of rated power) and at system pressures in the range of 4.137 MPa (600 psia) to 8.273 MPa (1200 psia). Because of limitations on existing equipment for the proposed test facility, that system cannot operate at pressures higher than 0.517 MPa (75 psia). It is presumed the subject operating modes can be affected in the experiment at a significantly reduced pressure relative to the reference reactor. Possible effects of this reduction are evaluated in Sections III and V.

2.1 Single Phase Natural Circulation Mode

In this mode it is assumed the total primary system is occupied with saturated and/or subcooled liquid (i.e., zero quality-water solid). Starting with the core: the core decay heat produces a less dense liquid relative to the liquid upstream of the core. Because of the elevation difference upstream of the core (lower plenum, downcomer, cold legs) flow from the core through the upper plenum to the steam generator downhill U-tube is promoted. With the steam generator secondary acting as a heat sink, the liquid in the downhill side of the U-tubes undergoes a density reduction which also promotes primary liquid circulation. Providing the circulation potential in the core and downhill side of the U-tubes is larger than the potential for opposite flow direction because of hot leg ambient and uphill side of U-tube heat loss and system flow resistance, the system will naturally circulate fluid in the normal direction. The system will probably operate in this mode even if the steam generator secondary side did not provide a heat sink. However, the steam generator is expected to promote normal direction flow to varying degrees.

2.2 Two Phase Natural Circulation Mode

This mode is similar to the single phase mode, except that the system is assumed to be low quality fluid solid. Other potential differences in the two flow modes are associated with slip between the vapor and liquid, two phase versus single phase system flow resistance, vapor/liquid versus liquid heat transfer, etc. The phenomenalogical complexities associated with these items make analysis of the two phase mode significantly more difficult than the single phase or reflux condensation modes.

2.3 Reflux Condensation Mode

This mode assumes the core is nearly or completely full of low quality fluid. Other parts of the system, such as the lower plenum and downcomer, are assumed to contain low or zero quality fluid up to the same elevation as the liquid level in the core. It is further postulated all of the decay heat in the core is producing vapor which rises to and through the liquid surface in the core. It is probable little or no liquid is entrained in the vapor passing into the upper plenum, thus the vapor is considered to be of high quality. The high quality vapor exiting the top of the core passes through the upper plenum and into the steam generators where it may be partially or totally condensed. Vapor condensed on the uphill side of the steam generator U-tubes is assumed to flow back into the steam generator inlet plenum. Consistent with the facility design and the amount of mass condensed, the liquid may in turn flow from the steam generator inlet plenum back to the upper plenum. It is assumed that the liquid and vapor through out the system are very close to saturation conditions at the system average pressure. Thus the volume of the liquid flowing back to the upper plenum is small relative to the volume of vapor flowing in the opposite direction (except for possible pooling at local low points in the system). Vapor condensed in the downhill side of the steam generator U-tubes will flow concurrently with any uncondensed vapor into the steam generator outlet plenum. Again, consistent with the facility design and amount of mass condensed, the liquid may flow through the steam generator outlet plenum to the pump loop seals and possibly to the downcomer. It is postulated the reflux condensation mode can operate with or without steam generator secondary feedwater flow. However, because the primary side condensation requires a heat sink from the secondary side, a non flowing feedwater condition would be self limiting in time.

III. RESULTS FROM SINGLE PHASE NATURAL CIRCULATION MODE OF OPERATION

Scaling, ambient heat losses and estimated system performance are discussed in Sections 1, 2 and 3, respectively.

1. SCALING CONSIDERATIONS

It has been our experience that in most operating modes of interest, tubulent natural circulation will exist. Therefore, we have examined the conservation equations for turbulent flow making the normal assumptions that:

(a) Turbulent transport of momentum or energy is much larger than molecular transport.

(b) The energy dissipation terms are insignificant relative to the heat added to the system and can be neglected.

Within these conditions it can be demonstrated that:

(a) For steady state flow there will be similarity in the continuity equations for FLECHT-SEASET and the reference reactor.

(b) Similarity in the momentum equations will exist for the two systems providing:

$$\left(\frac{P_{FS}}{P_{PWR}}\right)\left(\frac{\rho_{PWR}}{\rho_{FS}}\right)\left(\frac{L_{PWR}}{L_{FS}}\right)^2 = 1 \qquad (1)$$

(c) Similarily in the energy equation will exist for the two systems providing:

$$\left(\frac{q'_{FS}}{q'_{PWR}}\right)\left(\frac{\rho_{PWR}}{\rho_{FS}}\right)\left(\frac{c_{p_{PWR}}}{c_{p_{FS}}}\right)\left(\frac{T_{PWR}}{T_{FS}}\right) = 1 \qquad (2)$$

where:

P = Pressure   FS = FLECHT-SEASET

ρ = Density   PWR = Reference Reactor

L = Length

q' = Heat to volume ratio

c_p = Specific heat

T = Temperature

From Equation 1, assuming FLECHT-SEASET preserves prototypical lengths and elevations then:

$$\frac{P_{FS}}{P_{PWR}} = \frac{\rho_{FS}}{\rho_{PWR}}$$

This result indicates that for both systems operating with liquid phase water, but at significantly different pressures, momentum similarity will not be achieved.

Rewriting Equation 2, assuming:

(a) The two systems operate at significantly different pressures; for example 0.517 MPa (75 psia) for FLECHT-SEASET and 6.205 MPa (900 psia) for the reference reactor.

(b) The fluids are subcooled up to 39 K (70°F)

Then:

$$\frac{q'_{FS}}{q'_{PWR}} = \left(\frac{\rho_{FS}}{\rho_{PWR}}\right)\left(\frac{cp_{FS}}{cp_{PWR}}\right)\left(\frac{T_{FS}}{T_{PWR}}\right) \cong 0.5$$

This result indicates that energy similarity can be achieved by the proper attention to system ambient heat loss and bundle applied power.

Based on the above scaling considerations, we conclude that with the proper attention to bundle power and heat losses, similarity of the coninuity and energy equations can probably be achieved. However, similarity in the continuity, momentum and energy equations can not be achieved similtaneously for the low operating pressures of the FLECHT-SEASET system. The implications of this are that by adjusting the bundle power, similarity in specific parameters can be achieved, while at the same time compromising similarity in other parameters. This was born out by calculations made with a model which is described in Section III-3. We found that by increasing bundle power we could achieved similarity in the mass flow while compromising similarity in the bundle ΔT. Conversely, by decreasing the bundle power we achieved similarity in the bundle ΔT, at the same time sacrificing similarity in the mass flow.

An additional consideration is pressure scaling. If we assume a Darcy Weisbach equation for friction losses, similarity in loop resistance requires that

$$R' = \frac{\dot{m}^2_{PWR}}{\dot{m}^2_{FS}} \frac{\rho_{FS}}{\rho_{PWR}} R'_{PWR}$$

where

$R' = \frac{K}{2A^2}$

K = resistance coefficient

A = flow area

$\dot{m}$ = mass flow rate

ρ = density

If FLECHT-SEASET was volumetrically scaled and operated at typical PWR pressures, then

$$\rho_{FS} = \rho_{PWR}$$

and

$$\frac{\dot{m}_{PWR}}{\dot{m}_{FS}} = 327$$

Because the FLECHT-SEASET system operates at low pressures, the loop resistance will have to be adjusted to account for different mass flow and density ratios.

2. AMBIENT HEAT LOSS IN HOT LEG

We have performed an analysis similar in many respects to that given in Section IV-2, but also using the information contained in Equation 2. Based on the results of that analysis it is our opinion that an effective insulation thickness of 0.0635 m (2.5 inch) to 0.076 m (3 inch) will provide the desired maximum ambient hot leg heat loss. This amount of insulation does not seem unreasonable in terms of construction considerations; however we recommend that the experimenter perform an independent assessment of the insulation requirements to provide further assurance of an adequate test facility.

3. ESTIMATED SYSTEM PERFORMANCE

Two scoping type studies of system performance have been accomplished. These analyses had as their objective the development of probable system temperature profiles in order to make judgements as to accuracy required in the system instrumentation. Section 3.1 describes a study to define typical values of the difference in the heater rod surface temperature and the bulk liquid temperature as a function of elevation. Section 3.2 describes a study to define typical values of the difference between the primary and secondary fluids in the steam generator as a function of elevation.

3.1 Bundle Performance

Kays[3] indicates the desired turbulent flow relation for the difference between the rod surface and bulk liquid temperatures as a function of an axial varing heat flux is of the form:

$$(T_w - T_m)(X^+) = \frac{D}{4k} \int_0^{X^+} \left[q(z)\ g(X^+ - z) - 4 \right] dz \qquad (3)$$

where:

T_w = Rod surface temperature

T_m = Bulk liquid temperature

D = Hydraulic diameter

q = Heat flux = $q_T\ (a + b\cos(cz))$

q_T = Total heat flux

g = Greens function

X^+ = $2\,(X/D)/\mathrm{Re}\,\mathrm{Pr}$

X = Distance from core inlet

z = Distance from mid plane

Re = Reynolds number

Pr = Prandel number

Using the appropriate system parameters, trapizoidal integration and assuming $\mathrm{Pr} \cdot \mathrm{Re} = 2000$ (i.e. minimum turbulent conditions) solutions to equation 3 are shown on Figure 3 for bundle power levels of 1 percent and 0.2 percent of scaled rated power. In our opinion, Figure 3 implies that to operate successfully at the lower bundle power levels (0.2 percent minimum) proposed for this task, requires instrumentation with uncertainties in the subject parameter in the order of ± 1.1 K ($\pm 2^{\circ}$F).

3.2 Steam Generator U-Tube Performance

By assuming density changes linearly with length, the ambient heat loss in the hot and cold legs are similar, and the fluid specific heat is constant, the following one-dimensional, transcendental equation relating mass flow, heat transfer, density, elevation and loop flow resistance was developed for the single phase natural circulation mode.

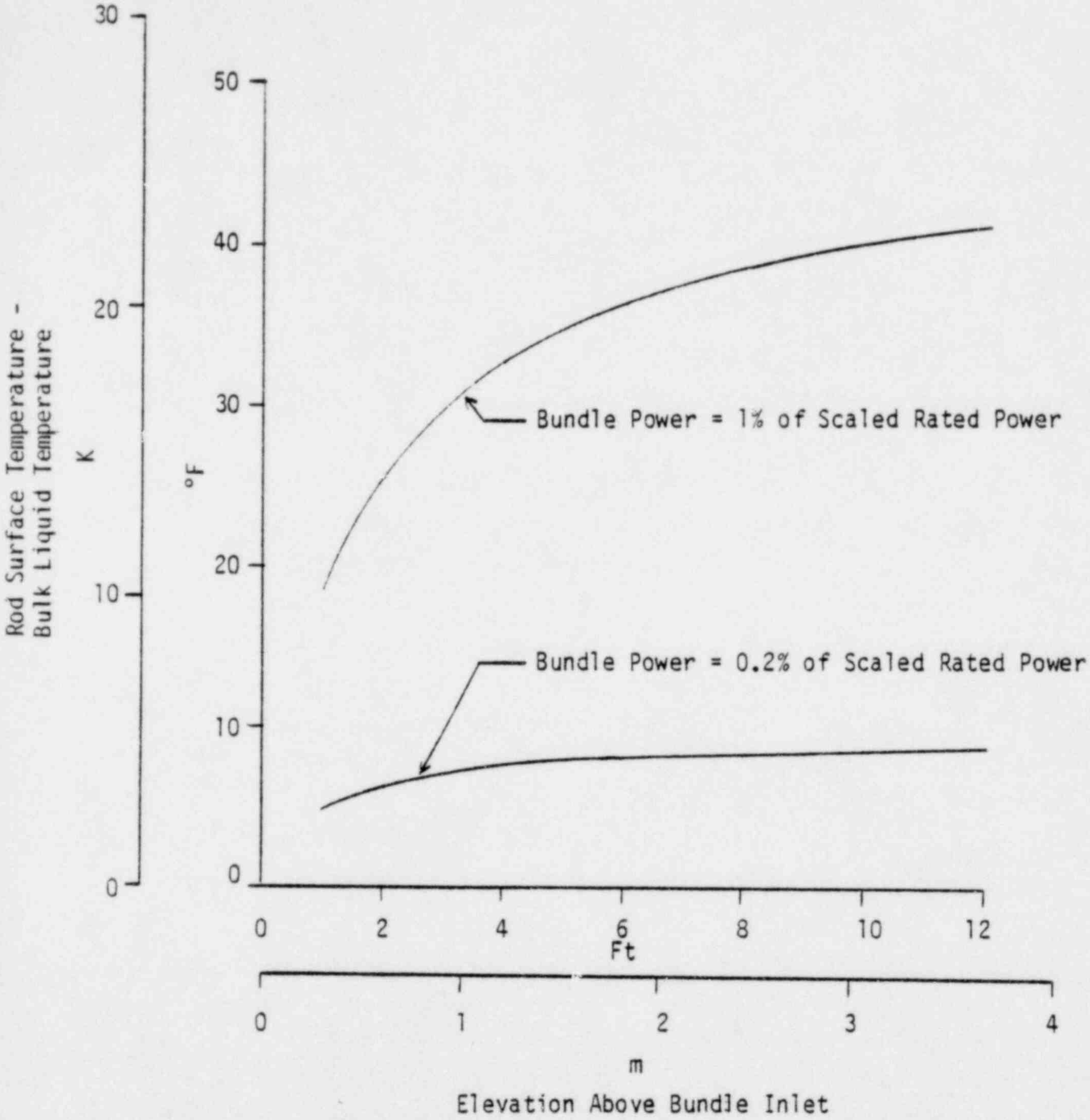

Fig. 3 Estimated FLECHT-SEASET bundle performance for natural circulation - single phase operation mode.

$$Z_B \left[e^{-\phi q_{HL}} - e^{-\phi q_B}\right] + Z_{HL} \left[e^{-\phi q_{HL}} - e^{-\phi q_B} - e^{-\phi(q_{HL}-q_B)} + 1\right]$$

$$+ Z_{SG} \left[e^{-\phi q_{HL}} - e^{\phi(q_{HL} - q_B)}\right] = \frac{4\, \dot{m}^2 R'}{\rho^2 \left[1 + e^{-\phi q_B}\right]} \qquad (4)$$

where:

ϕ = $\bar{\beta}/\dot{m}c_p$; $\beta = -\frac{1}{\rho}\frac{d\rho}{dT}$

β = Average β

ρ = Density

$\dot{m}$ = Mass flow rate

c_p = Specific heat

T = Temperature

Z = Elevation

q = Heat addition or loss

R' = Loop resistance = $\frac{\rho \Delta P}{\dot{m}^2}$

Subscripts:

B = Bundle

HL = Hot leg

SG = Steam generator

The assumption of a linear change of density with length makes the solution independent of the details of the steam generator heat transfer. This assumption is marginal in concept; however our calculations indicate the results are relatively insensitive to the assumption, therefore the simplification achieved is considered well worth any small inaccuracy.

Equation 4 was applied to the Zion Plant and the results compared to an existing RELAP4 simulation of the same plant in the same operating mode. That comparison indicates the system mass flows and fluid temperature change across the core developed from Equation 4 are within 5 percent and 1 percent, respectively, of the RELAP4 solution. In our opinion, these results indicate Equation 4 is a reasonable scoping tool for the FLECHT-SEASET facility. Such an application combined with a steam generator heat transfer model for single phase liquid (similar to that developed in Section V-3.3) results in the performance shown in Figure 4. The two curves for two percent scale rated power are considered bounding type performance. There will certainly be some ambient heat loss in the system so the curve assuming no heat loss forms one limit. The second curve assumes a heat loss calculated to be representative of the semicsale facility under similar conditions. We feel this order of heat loss to be representative of the other (upper) limit for FLECHT-SEASET.

Figure 4 again indicates a need for small instrumentation uncertainties in the steam generators. It also implies that ambient heat loss may be all or a large part of the system heat transfer when the bundle is operated at the minimum proposed power level (0.2 percent). This has large implications concerning the steam generator instrumentation specifically and the other system insturmentation generally.

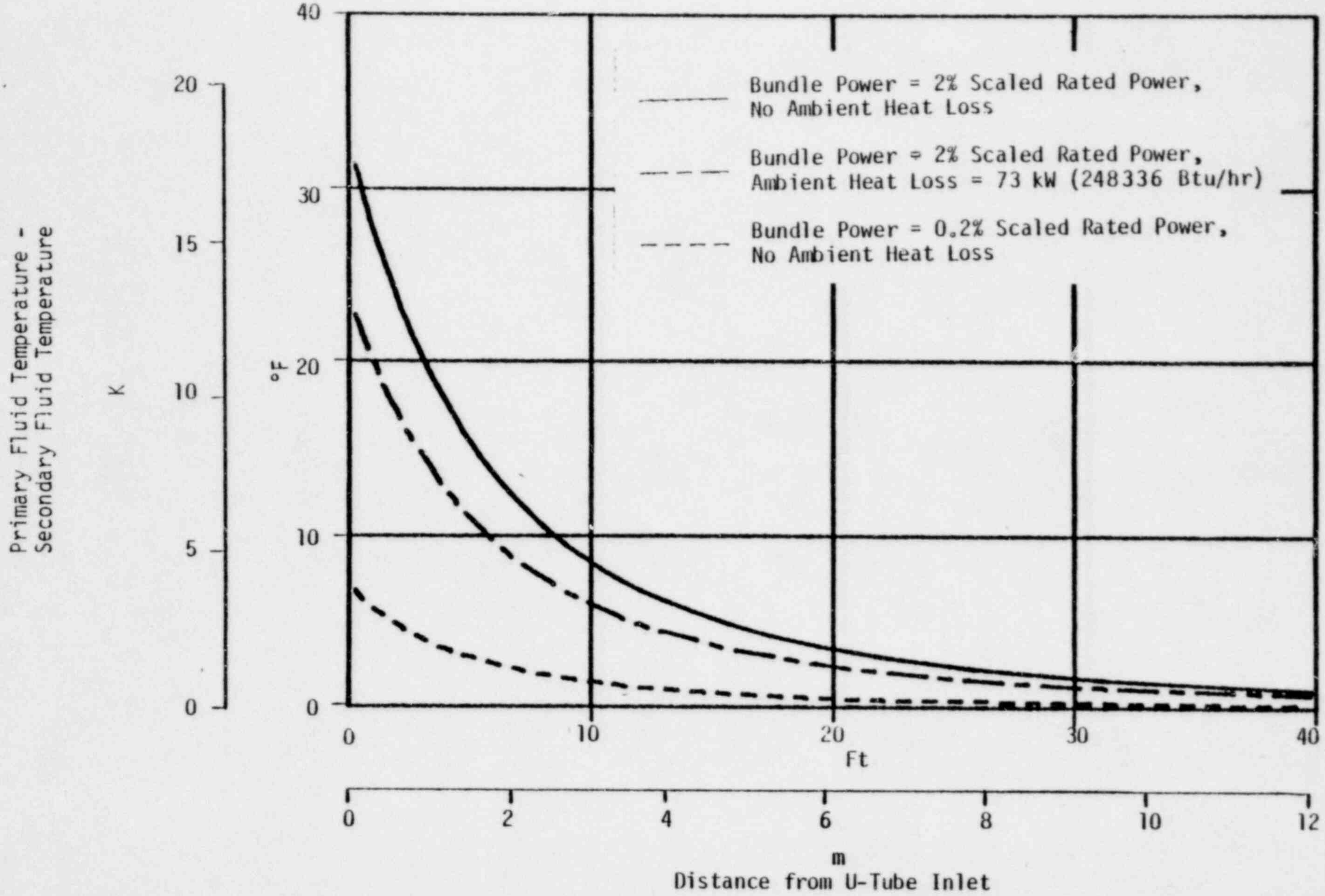

Fig. 4 Estimated FLECHT-SEASET steam generator performance for single phase liquid, natural recirculation operation at 0.52 MPa (75 psia).

IV. RESULTS FOR TWO PHASE NATURAL CIRCULATION MODE OF OPERATION

We attempted to develop a simple model for this operating mode similar to that described in Section III-3.2. It quickly became evident that the complex relations between mass flow, loop flow resistance and steam generation prohibit such a simple treatment. It is our opinion that study of this flow mode will require more sophisticated computer modeling which we have not been able to schedule to date. This condition should not be interpreted to mean study of this mode is of lesser importance. On the contrary, it is our feeling that there are uncertainties associated with a successful operation in this mode and although we have not examined these uncertainties in depth, we recommend the experimenter perform the necessary scoping type analyses required to establish the probability of successful operation in this mode. Particular attention should be given to the effect of the increased FLECHT-SEASET heat of evaporation (h_{fg}) on prototypicality questions.

V. RESULTS FOR REFLUX MODE OF OPERATION

Scaling, ambient heat losses and estimated steam generator condensation performance are addressed in Sections 1, 2, and 3, respectively.

1. SCALING CONSIDERATIONS

Ideally, testing in the subject facility would maintain the following criteria in the bundle, hot legs and steam generator between a PWR and the test loop:

(a) Equal superficial vapor velocites

(b) Equal heat transfer simulation

(c) Equal mass flux ratios

(d) Equal power to volume ratios

(e) Equal momentum flux

It is clear at the on-set that all of these items cannot be maintained. Thus it becomes necessary to prioritize the above criteria in order of importance to the subject phenomena. This ranking process is, to some degree, a matter of judgement and therefore open to debate. In our opinion the hydraulic phenomena in the bundle, hot legs and steam geneator are influenced, significantly, by superficial vapor velcoity. This parameter is not only a resonable indicator of the flow patterns it is also important to descriptions of the counter current flow in the uphill side of the steam generator U-tubes.

On the other hand, if the steam generators are capable of condensing all of the entering steam, equivalent condenstation rates and the resulting liquid film down flows in the inlet U-tubes may be more important. If this is so, equal mass flux may be the more desirable criteria.

Equal superficial vapor velocity and equal mass flux are not mutually achievable unless geometric changes to the experimental system are made. Because the system will also be used for the reflood test, design changes were not considered. It would be particularly expensive to rework the steam generators either before or between testing of the two flow modes. Which of the two competing criteria is most important to developing a sound data base is unclear to us at this time. Therefore we have examined the effect of enforcing one or the other schemes on other desirable scaling factors with the following assumptions.

(a) The volume ratio between FLECHT-SEASET and the reference PWR in the core, hot leg and steam generator U-tubes is 1/327.

(b) FLECHT-SEASET operates at 0.517 MPa (75 psia)

(c) The average reflux mode pressure in the reference reator is 6.205 MPa (900 psia)

(d) All core power is used to produce saturated steam.

Based on these assumptions our calculations show the scaling results given in Table 1. Note these results ignore the effect of any condensed liquid return from the uphill side of the steam generator through the hot leg to the core. Assuming complete condensation return, the volume of liquid in the hot leg would be approximately 0.003 of the steam volume providing there is no local pooling. In the steam generator U-tubes, CCFL may also be important and is addressed in Section 3.2.

TABLE 1. FLECHT-SEASET REFLUX MODE SCALING RESULTS

Enforced Scaling Factor	RESULTING VALUES OF OTHER SCALING FACTORS*			
	Superficial Vapor Velocity Ratio	Mass Flux Ratio	Momentum Flux Ratio	Ratio of Power To Volume Ratio
Equal Superficial Vapor Velocity	1.000	0.086	0.086	0.116
Equal Mass Flux	11.620	1.000	11.62	1.350

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* In all cases a value of 1.0 indicates perfect scaling.

In our opinion the information in Table 1 implies the following. By maintaining equal superficial vapor velocity, similar flow patterns are probably produced in the bundle and hot leg although one can't discount the potential effect of the much reduced momentum flux. It is evident from the small mass flux ratio, equal superficial velocity will result in a much reduced potential for condensation in the steam generator U-tubes. Equal superficial vapor velocities will also require low bundle power settings. This in turn will require assurance that the bundle power can be accurately controlled and measured at these levels.

On the other hand, equal mass flux probably produces the desired condensation potential in the U-tubes; however may result in atypical flow patterns as evidenced by the much increased superficial vapor velocity and momentum flux. The required bundle power for equal mass flux is also increased, but is probably within the capability of the test facility.

It is evident from Table 1 that enforcing either scaling criteria produces uncertainties in the hot leg and steam generator performance; therefore, further analyses were performed and are reported in Sections 2 and 3.

2. AMBIENT HEAT LOSS IN HOT LEG

In our opinion, the desired scaling of ambient heat loss can be achieved if the fluid temperature loss, as it passes through the FLECHT-SEASET hot leg is equal to or less than the reference reactor. For this condition one can write:

$$(T_{\text{hot leg in}} - T_{\text{hot leg out}})_{FS} \leq (T_{\text{hot leg in}} - T_{\text{hot leg out}})_{PWR}$$

$$\left(\frac{q}{\dot{m}c_p}\right)_{FS} \leq \left(\frac{q}{\dot{m}c_p}\right)_{PWR}$$

$$\frac{q_{FS}}{q_{PWR}} \leq \frac{(\dot{m}c_p)_{FS}}{(\dot{m}c_p)_{PWR}} \tag{5}$$

where:

T = Temperature of fluid

q = Heat transfer from the fluid

m = Mass flow rate

c_p = Specific heat of fluid

FS = FLECHT-SEASET

PWR = Reference reactor

Noting that the heat lost from the fluid is also the heat transferred through the hot leg walls one can also write:

$$\frac{q_{FS}}{q_{PWR}} = \frac{\left[UA\ (T_{fluid} - T_{ambient})\right]_{FS}}{q_{PWR}} = \frac{(UA\Delta T)_{FS}}{q_{PWR}} \tag{6}$$

U is the overall heat transfer coefficient and depends on geometry, the heat transfer coefficient at the hot leg fluid/wall interface, the wall and insulation thermal conductivity, the heat transfer coefficient at the insulation/ambient air interface and radiation from the insulation. If one assumes the insulation thermal resistance is large compared to other resistance then:

$$UA \cong \frac{2\pi kL}{\ln(r_2/r_1)} \tag{7}$$

where:

k = Insulation thermal conductivity

L = Length of hot leg

r_1 = I.D. of insulation = O.D. of hot leg wall

r_2 = O.D. of insulation

Combining and rewriting equations 5, 6, and 7:

$$r_{2_{FS}} \geq r_{1_{FS}} e^{a} \qquad (8)$$

where:

$$a = \frac{(2\pi k L \Delta T)_{FS}}{q_{PWR}} \; \frac{(\dot{m}\, c_p)_{PWR}}{(\dot{m}\, c_p)_{FS}}$$

If we assume the FLECHT-SEASET hot leg fluid is saturated at 0.517 MPa (75 psia) and the ambient temperature is never less than 273 K (32^{o}F) then:

$$\Delta T \leq 153 \text{ K } (276^{o}\text{F}) \text{ and } c_{p_{FS}} = 2.326 \, \frac{\text{kJ}}{\text{kgK}} \; (0.556 \text{ Btu/lb-}^{o}\text{F})$$

Also assuming the hot leg fluid in the reference reactor during reflux is saturated at 6.205 MPa (900 psia) then $c_{p_{PWR}} = 4.704 \, \frac{\text{kJ}}{\text{kgJ}}$ (1.124 Btu/lb-^{o}F).

For equal superficial vapor velocity: $\dot{m}_{FS}/\dot{m}_{PWR} = 0.086/327 = 2.63 \times 10^{-4}$

and for equal mass flux: $\dot{m}_{FS}/\dot{m}_{PWR} = 1/327 = 3.06 \times 10^{-4}$.

Based on data from a U.S. 2 x 4 reactor and LOFT we estimate the ambient heat loss in a typical reactor hot leg during reflux is in the order of 0.004 percent of rated power. The rated power of the reference reactor is 3425 MW thus in equation 8, $q_{PWR} \cong 137$ kW (4.675×10^6 Btu/hr). Assuming the FLECHT-SEASET hot leg is 3" standard pipe then $r_1 = 0.0889$ m (3.5 inch). Further assuming the hot leg length is in the order of 4 m (13.1 ft) and fiber glass insulation is used $k \cong 0.0692$ W/mK (0.04 Btu/hr-ft-^{o}F) then for equal superficial velocity, $r_2 \geq 0.0893$ m (3.516 inch). These results indicate that any reasonable thickness of insulation will result in the desired scaling of hot leg ambient heat loss. In fact one could probably demonstrate that the inside and outside film coefficients provide sufficient thermal resistance when the hot leg fluid is primarily vapor.

3. STEAM GENERATOR CONDENSATION PERFORMANCE

The results given in Section V-1 indicate the steam generator performance is influenced by what ever scaling criteria is enforced, thus the steam generator behavior required further study. In this section we report our conclusions regarding bundle power (3.1), counter-current flow (3.2) and the primary to secondary heat transfer across the U-tubes (3.3).

3.1 Bundle Power

Concering the bundle power (and resulting mass flow) we have assumed all bundle power produces saturated steam at an operating pressure of 0.517 MPa (75 psia). We also assume that the reflux mode cannot be established in a reactor prior to two hours after SCRAM. For this assumption the standard ANS decay curve indicates the core power would be in the order of 1 percent of rated power, to which we have added another 1 percent to cover residual structure heat and power uncertainties. Thus the probable maximum reactor core power during reflux is in the order of 2 percent of rated power or 68.5 MW (2.34×10^8 Btu/hr).

From Table 1:

For equal vapor velocity:

$$P_{FS} = \frac{(P/V)_{FS}}{(P/V)_{PWR}} \cdot \left(\frac{V_{FS}}{V_{PWR}}\right) \cdot P_{PWR} = \frac{(0.116)(68.5\text{MW})}{327} = 24.3 \text{ kW } (83214 \text{ Btu/hr})$$

$$\underset{\substack{\text{per}\\ \text{U-tube}}}{\dot{m}_{FS}} = \frac{P_{FS}}{(h_{fg})\, N_{\text{U-tube}}} = \frac{24.3 \text{ kW}}{(2.104 \times 10^3 \, \frac{\text{kJ}}{\text{kg}})(43)} = 0.953\frac{\text{kg}}{\text{hr}} \ (2.14 \text{ lb/hr})$$

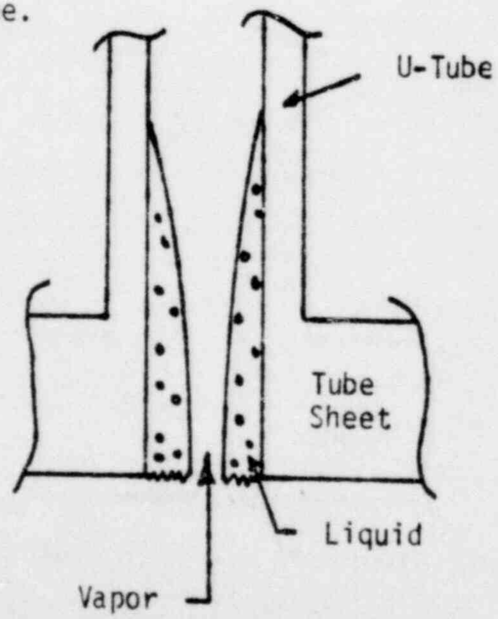
And for equal mass flux:

$$P_{FS} = 282.8 \text{ kW } (964950 \text{ Btu/hr})$$

$$\underset{\substack{\text{per}\\ \text{U-tube}}}{\dot{m}_{FS}} = 11.254 \ \frac{\text{kg}}{\text{hr}} \ (24.8 \text{ lb/hr})$$

3.2 Counter-current Flow In U-tubes

The following figure is considered a reasonable model of the condensation process in the U-tube.



For this model Wallis[4] indicates that as long as

$$(j_g^\star)^{1/2} + m\,(j_f^\star)^{1/2} \leq C$$

then the liquid film flows unimpeded down the U-tube where:

$$j_x = \frac{\dot{m}_x}{A_{\rho_x}} \;; \qquad j_x^\star = \frac{j_x(\rho_x)^{1/2}}{gD(\rho_f - \rho_g)^{1/2}}$$

and

m = Mass flowrate

A = Cross sectional area of U-tube

ρ = Density

j = Volumetric flux

g = Gravitational acceleration

D = I.D. of U-tube

x = g for vapor phase

= f for liquid phase

m and C are functions of the dimensionless group

$$N_f = \frac{\left[g(\rho_f - \rho_g)\right]^{1/2} D^{3/2} \rho_f^{1/2}}{\mu_f}$$

For the steam generator U-tubes operating at assumed pressure, $N_f \cong 9.5 \times 10^5$ thus: $m = 1.0$ and $C = 0.88$.

Noting that over the length of the liquid film, $m_g \cong m_f$ (i.e. vapor condensed is added to liquid film at the same elevation) then the maximum mass flow for both phases is at the U-tube inlet. Therefore, because the densities and the geometry are constant over the liquid film we need check CCFL only at the U-tube inlet. For the assumed flow conditions and:

Equal superficial vapor velocity:

$$j_g^\star = 0.039 \qquad\qquad j_f^\star = 0.002$$

$$(j_g^\star)^{1/2} + (j_f^\star)^{1/2} = 0.24 < 0.88$$

For equal mass flux:

$$j_g^\star = 0.449 \qquad\qquad j_f^\star = 0.023$$

$$(j_g^\star)^{1/2} + (j_f^\star)^{1/2} = 0.82 < 0.88$$

Thus it appears that CCFL will not occur for either enforced scaling criteria for bundle powers less than 2 percent of scaled rated power, although the equal mass flux case is approaching the point of concern.

3.3 Primary to Secondary Heat Transfer Behavior.

If we are to control the condensation process in the steam generator U-tubes we can do so by control of the temperature difference between the primary vapor and the secondary liquid temperatures. As will be seen we need some idea of the uncertainty of this control. That uncertainty will be developed as follows.

In the recent issue of the Steam Generator Data Report5 the errors associated with the large steam generator T/C's are given as.

Sensor Error = ±2.2 K (±4°F)

Conditioning Error = 0 (i.e. no conditioning required)

Read out (or recording) Error = ± 0.89 (± 1.6oF)

Although not stated, we assume that what is being reported is that the sensed error is equally likely to be any value from -2.2 K (-4°F) to +2.2 K (+4°F) and likewise -0.89 K (-1.6°F) to +0.89 K (1.6°F) for the readout. In essence both of these are uniform distributions with ranges (R_x) of 4.4 K (8°F) and 1.8 K (3.2°F) resp. Thus the standard deviation for each temperature path is

$$\sigma_{T/C} = \left|\mathrm{VAR}\ (\alpha+\beta)\right|^{1/2} = \left|\sigma^2_{\mathrm{sensor}} + \sigma^2_{\substack{\mathrm{read}\\ \mathrm{out}}}\right|^{1/2} = \left\{\frac{R_s^2}{12} + \frac{R_{ro}^2}{12}\right\}^{1/2}$$

Assuming both temperatures are detected separately:

$$\mathrm{VAR}\ \left[T_{\mathrm{vapor}} - T_{\substack{\mathrm{2ndary}\\ \mathrm{liquid}}}\right] = \mathrm{VAR}\ \left[T_{\mathrm{vapor}}\right] + \mathrm{VAR}\ \left[T_{\substack{\mathrm{2ndary}\\ \mathrm{liquid}}}\right]$$

$$= \sigma^2_{\substack{T/C\\ \mathrm{vapor}}} + \sigma^2_{\substack{T/C\\ \mathrm{2ndary}}} = 2\sigma^2_{T/C}$$

or $\sigma_{\Delta T} = \sqrt{\mathrm{VAR}\ \Delta T} = \sqrt{2}\ \sigma^2_{T/C} = 1.9$ K (3.5°F)

We can now say that approx. 95 percent of the time the uncertainty in the detected (controlled) ΔT will be in the order of $\pm 2\sigma_{\Delta T} \cong \pm$ 3.9 K ($\pm 7^{\circ}$F) for the large steam generator providing the primary and secondary temperatures are detected separately. This uncertainty range is considered an upper limit in that reduced uncertainty can be achieved by ganging the T/C's and detecting a difference signal or by performing periodic calabrations on the T/C's or both. A lower limit estimate on the uncertainty might be that resulting from the use of RTD's which can be done in the small steam generator. An analysis similar to that above for typical FLECHT-SEASET RTD's indicates an uncertainty of ± 1.1 K ($\pm 2^{\circ}$F) at the 95 percent confidence limit. The meaning of these uncertainty limits in terms of the condensation process is developed next.

In our opinion, it is reasonable to assume that both the primary vapor and secondary liquid temperatures will be constant over the length of condensation for this scoping type analysis. Further we think it reasonable to ignore any radial temperature variation in the U-tube. Thus we can write:

$$q = \frac{(T_{vapor} - T_{2nd})}{\frac{1}{(A\ h_m)_c} + \frac{1}{(A\ h_m)_{2nd}}}$$

where:

q = Heat released by total condensation

A_c = Area wetted by condensate on the inside of the U-tube

A_{2nd} = Area wetted by the 2ndary liquid on the outside of the U-tube along the length of the condensate liquid

h_{m_c} = Mean condensate heat transfer coefficient

$h_{m_{2nd}}$ = Mean heat transfer coefficient between the U-tube and secondary liquid

T_{vapor} = Primary free stream vapor temperature

T_{2nd} = Secondary bulk liquid temperature

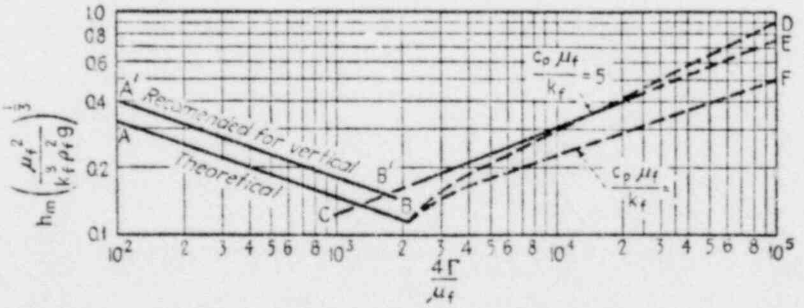
Writing the previous equation as:

$$\Delta T = q\left[\frac{1}{(Ah_m)_c} + \frac{1}{(Ah_m)_{2nd}}\right]$$

$$= q\left[\frac{1}{(\pi DLh_m)_c} + \frac{1}{(\pi DLh_m)_{2nd}}\right]$$

$$= \frac{q}{\pi L}\left[\frac{1}{(Dh_m)_c} + \frac{1}{(Dh_m)_{2nd}}\right]$$

We note that providing we can establish probable lower bounds on h_{m_c} and $h_{m_{2nd}}$ we can also establish the probable upper bound on ΔT. As we will see ΔT will be in terms of the condensation length (L). We can then relate ΔT, L, the uncertainty in ΔT and the instrumentation in the steam generators to make judgements as to the risk of bad test data for the reflux mode. We have not yet found a good treatment of h_{m_c} for counter current flow thus we will need to make some judgement as to its probable value. McAdams[6] gives the following data for condensation on vertical tubes and plates where the vapor/liquid interface shear is insignificant.



Recommended curves *A'B'* and *CE* for film-type condensation of single vapors on vertical tubes or plates.

For this data:

(a) $\Gamma = \frac{\dot{m}_f}{\pi D}$ therefore $\frac{4\Gamma}{\mu_f} = \frac{4\dot{m}_f}{\mu_f \pi D}$

(b) The curves to the left of $\frac{4\Gamma}{\mu_f} = 2000$ assume laminar flow over the total length of the condensing liquid film. The curves to the right introduce corrections to account for the transition to turbulent flow in the condensate film on the lower portions of the tube.

(c) The curve AB represents the classical Nusselt theory for condensing pure vapors. The curve A'B' introduces a 28 percent increase over curve AB to account for observed performance. This increase can be attributed to rippling of the liquid film, deviations from constant liquid temperature, etc. that actually occur in nature.

McAdams implies that in counter current flow the shear at the vapor/liquid interface tends to make the liquid film thicker and thus reduce h_{m_c}. However he also states that as the shear force increases the liquid film tends to ripple and h_{m_c} increases. Unfortunately he nor anyone else found so far defines which of these phenomena predominates nor where the effects of counter-current flow become important. Based on our counter-current flow analysis in Section 3.2 we tend to believe that in this case the reduction in h_{m_c} because of the shear forces will be mostly offset by the observed increase in h_{m_c} (Curve A'B') relative to the Nusselt theory (Curve AB). Thus we estimate that h_{m_c} based on curve AB should be adequate for this study. Therefore per our previous analyses:

$$\left(\frac{4\Gamma}{\mu_f}\right)_{\text{equal } j} = 1918$$

$$\left(\frac{4\Gamma}{\mu_f}\right)_{\substack{\text{equal}\\ \text{mass}\\ \text{flux}}} = 22230$$

The smaller of these values lies close to the minimum point on Curve AB, therefore, we think the following is a reasonable assumption for the probable lower bound on h_{m_c}.

$$h_{m_c} \cong 0.12 \div \left[\frac{\mu_f^{2}}{k_f^{3}\rho_f^{2} g}\right]^{1/3}$$

$= 35642\ \text{W/m}^2 - \text{K}\ (6277\ \text{Btu/hr-ft}^2\text{-}^\circ\text{F})$

Concerning the evaluation of the mean heat transfer on the outside of the U-tubes we can generally state:

$$NU_{2nd} \cong C\ (GR \cdot PR)^n$$

For $GR < 10^9$ $C \cong 0.59$ and $n = 1/4$

$GR \geq 10^9$ $C \cong 0.13$ and $n = 1/3$

To evaluate GR as a function of condensing length:

$$GR = \frac{\rho^2 \beta\ (T_{U\text{-}tube} - T_{2nd}) g L_c^{3}}{\mu^2}$$

$= 2.9 \times 10^3\ \Delta T' L_c^{\ 3}$ for SI units

$= 4.5 \times 10^{11}\ \Delta T' L_c^{\ 3}$ for English units

We note from the above, that for $\Delta T' > 0.56$ K (1°F) and $L_c > 0.04$ m (1.6 inch) that $GR \geq 10^9$. That is to say; for all practical purposes turbulent natural convection will exist on the outside of the U-tubes thus:

$$h_{2nd} = 0.13 \left[\frac{(\rho k)^2 g\beta \; c_p \; \Delta T'}{\mu}\right]^{1/3}$$

Note that the dependence of h on L_c has vanished in the above equation which is another way of saying that h is generally constant over the condensing length. Thus for this study

$$h_{m_{2nd}} \cong 953 \; (\Delta T')^{1/3} \text{ for SI units}$$

$$\cong 138 \; (\Delta T')^{1/3} \text{ for English units}$$

The original formulation of the heat transfer model was based on

$$\Delta T = T_{\substack{\text{primary}\\\text{vapor}}} - T_{\substack{\text{2ndary}\\\text{liquid}}}$$

rather than $\Delta T' = T_{\text{U-tube}} - T_{\substack{\text{2ndary}\\\text{liquid}}}$ used to evaluate $h_{m_{2nd}}$.

To resolve this we proceed as follows:

$$Q_{\substack{\text{primary}\\\text{to U-tube}}} = Q_{\substack{\text{U-tube}\\\text{to 2ndary}}}$$

$$h_{m_c} \; A_i \; (T_{\text{vapor}} - T_{\text{U-tube}}) = h_{m_{2nd}} \; A_o (T_{\text{U-tube}} - T_{2nd})$$

or $(T_{\text{vapor}} - T_{\text{U-tube}}) = \dfrac{h_{m_{2nd}}}{h_{m_c}} \; \Delta T' = B(\Delta T')^{1\frac{1}{3}}$

where

$B \; = \; 0.030$ for SI units

$= \; 0.025$ for English units

we can also write:

$$\Delta T = T_{vapor} - T_{U\text{-}tube} + \Delta T'$$

$$= B\,(\Delta T')^{1\frac{1}{3}} + \Delta T'$$

From the original problem formulation:

$$L = \frac{q}{\pi \Delta T}\left[\frac{1}{(Dh_m)_c} + \frac{1}{(Dh_m)_{2nd}}\right] \qquad (9)$$

where:

L = Condensing length downstream from U-tube inlet

q = Heat transfer required to condense saturated vapor to saturated liquid

= 24.3 kW (83214 Btu/hr) for equal superficial vapor velocity

= 282.8 kW (964950 Btu/hr) for equal mass flux

ΔT = $\underset{primary}{T_{vapor}} - \underset{secondary}{T_{liquid}} = B\,(\Delta T')^{1\frac{1}{3}} + \Delta T'$

$\Delta T'$ = $T_{U\text{-}tube} - T_{secondary}$

D_c = I.D. of U-tube = 0.0197 m (0.775 inch)

D_{2nd} = O.D. of U-tube = 0.0222 m (0.875 inch)

h_{m_c} = Primary side heat transfer coefficient

$\cong$ 35642 $W/m^2\ K$ (6277 $Btu/hr\text{-}ft^2\text{-}{}^oF$) minimum

$h_{m_{2nd}}$ = Secondary side heat transfer coefficient

= $C\ (\Delta T')^{1/3}$; C = 953 for SI units

= 138 for English units

With Equation 9 we can now predict the probable condensation performance of the steam generator U-tubes with the results shown in Figures 5 and 6 for equal superficial vapor velocity and equal mass flux, respectively.

Figures 5 and 6 imply that to use a poorer instrumentation scheme [i.e. uncertainty = ±3.9K (±7°F)] requires the use of large temperature differentials to reduce the influence of the uncertainty on condensing length. This in turn results in short condensing lengths and reduces the number of available instrumentation stations along the U-tube thereby reducing the quality of the developed data base. Only with the use of more precise instrumentation [i.e. uncertainty = ±1.1 K (±2°F)] can longer condensing lengths be used with acceptable uncertainty in that parameter. Figure 6 indicates that the required uncertainty is less restrictive for the equal mass flux mode than for the equal superficial vapor velocity mode. However, if one postulates that as bundle power is reduced, condensing length and ΔT are also reduced it becomes apparent that for either case successful operation of the facility will depend on low uncertainties in the instrumentation scheme. It is our opinion that uncertainties much larger than ±1.1K (±2°F) will prove significantly detrimental to the quality of the generated data base.

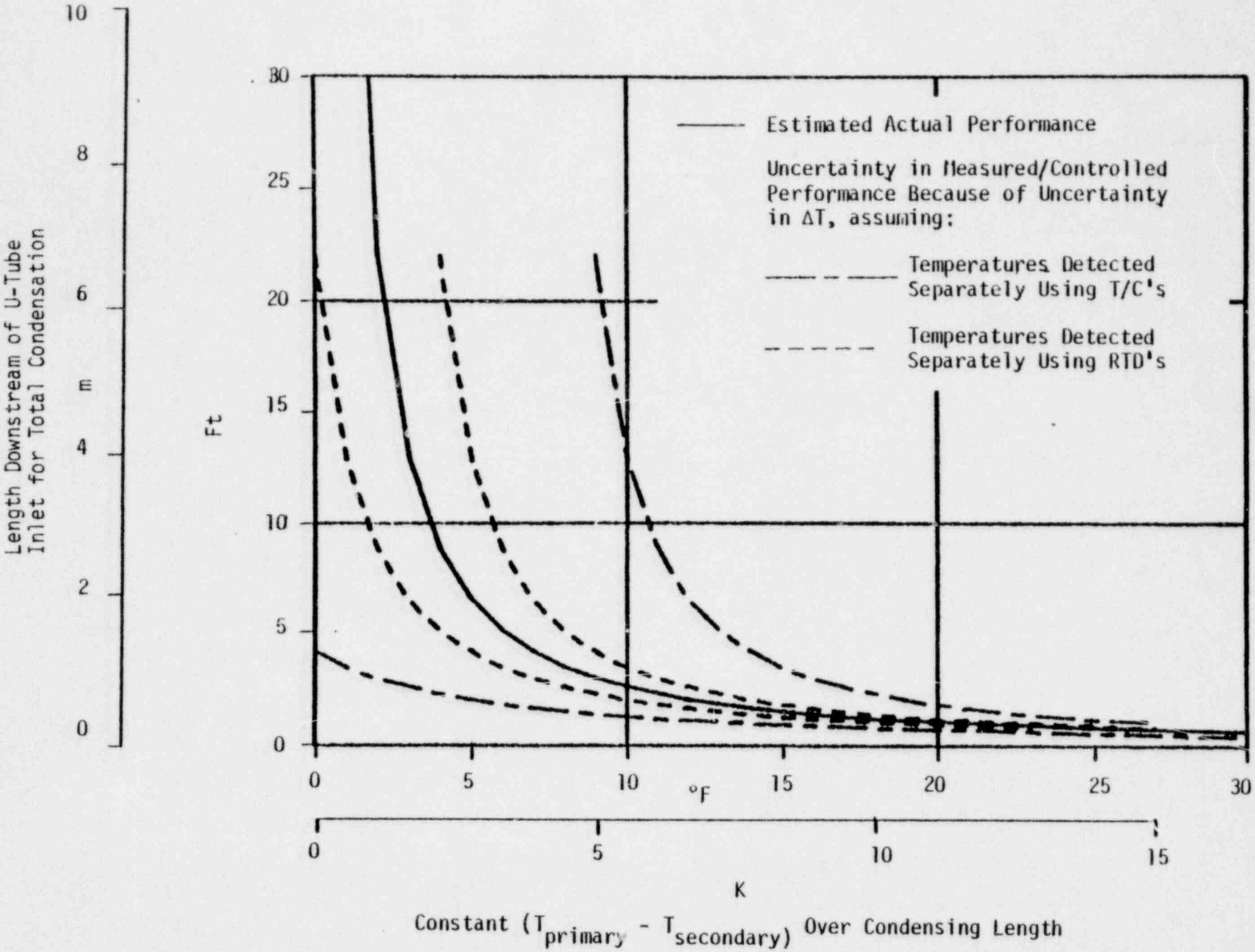


Fig. 5 FLECHT-SEASET steam generator U-tube performance for equal superficial vapor velocity with 2% scaled bundle power.

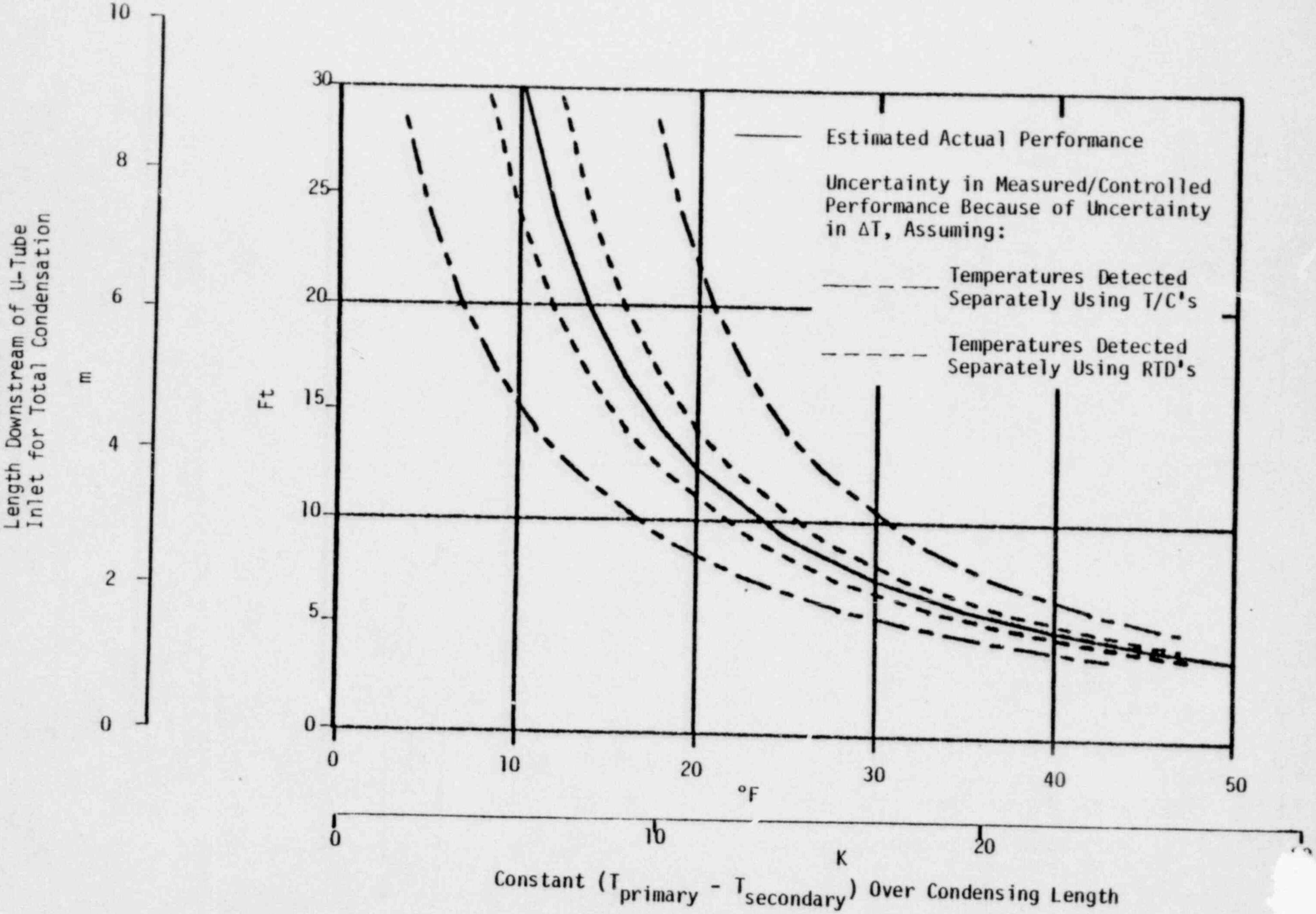


Fig. 6 FLECHT-SEASET steam generator U-tube performance for equal mass flux with 2% scaled bundle power.

VI. CONCLUSIONS AND RECOMMENDATIONS

1. CONCLUSIONS

The following conclusions (1 through 5) are supported by the analytical results described in Section III and pertain to the single phase natural circulation mode of operation.

1. A scaling review indicates it will not be possible to achieve similarity in the conservation of mass, momentum and energy simultaneously. Similarity in individual parameters can probably be achieved only by compromising other parameters. The analyses in Section III-1 also indicate the experimental loop resistance may need to be adjusted to compensate for the low density in the test loop relative to the full scale design.

2. Calculations indicate that a fiberglass mat (or equivalent) 0.0635, (2.5 inch) to 0.762 m (3 inch) thick will provide the required limitation on ambient hot leg heat loss at maximum bundle power. Reduced bundle power may require further insulation.

3. A theoretical model suggested by Kays indicates that uncertainties in the order of ±1.1 K (±2^{o}F) are desirable for the detected temperature difference between the bundle heater rod surface and the bulk liquid at the minimum proposed bundle power levels.

4. The instrumentation in the steam generator must have low uncertainties. Even so the ambient heat loss in the hot leg at the proposed minimum power may significantly affect the quality of the developed data base at those powers. These conclusions are based on the results from the transcendental system model described in Section III-3.2.

5. The model mentioned in 4 above indicates the frictional pressure drops in the test loop will be quite small. This has implications regarding the uncertainty of the loop instrumentation.

6. We were unable to develop a simple system model for the two phase natural circulation mode of operation because of the complexity of the phenomenalogical behavior.

The following conclusions (7 through 10) are supported by the analytical results desceibed in Section V and pertain to the reflux condensation mode of operation.

7. Perfect scaling of the experimental facility relative to the reference reactor will not be achieved. This is demonstrated by the information given in Table 1 which compares the influence of equal superficial vapor velocity and equal mass flux scaling on each other and on other desirable scaling criteria.

8. Ambient heat loss calculations indicate that the hot leg can be easily insulated to the desired level with the maximum expected bundle power (i.e., 2 percent of scaled rated power). This conclusion is based on the assumption that the experimental primary fluid temperature change as it passes through the hot leg is equal to or less than the same change in the reference reactor as described in Section V-2. It should also be noted that as the bundle power is decreased (test to test) we expect the ambient hot leg heat loss to become an increasingly larger percentage of the bundle power.

9. CCFL calculations, at the expected maximum bundle power level, indicate the highest potential for CCFL occurs at the steam generator U-tube inlet. The calculations in Section V-3.2 show

that CCFL will not occur at these locations for either equal superficial vapor velosity or equal mass flux operating conditions. However, the equal mass flux mode is approaching the point of concern. Should higher bundle power levels be used, CCFL is likely at the U-tube inlets for equal mass flux conditions.

10. The desirable maximum uncertainty in the detected/controlled temperature difference between the steam generator U-tube primary vapor and secondary liquid is in the order of ±1.1 K (±2°F). As described in Section V-3.3 smaller uncertainties may be required for low bundle power tests.

2. RECOMMENDATIONS

1. We have not addressed insulation requirements for the core and steam generator for any of the proposed operating modes. We recommend the experimenter do so. We also recommend the experimenter determine the minimum bundle power level for which the achievable ambient heat loss is an acceptable percent of the bundle power and for which the achievable instrumentation uncertainties do not introduce significant reductions in the quality of the developed data base.

2. We recommend the experimenter analytically establish a high probability of successful operation in the two phase natural circulation mode. That study is expected to employ analytical techniques more sophisticated than those used in this report, but should address many of the areas examined herein such as instrumentation uncertainty, ambient heat loss effects, and potential scaling compromises relative to the reference reactor.

3. Should an equal superficial vapor velocity scaling criterion be used in the reflux mode test operations, the experimenter should demonstrate the power control system will accurately provide the reduced power levels required.

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