This document was prepared in conjunction with work accomplished under Contract No. DE-DE-AC09-76SR00001with the U.S. Department of Energy.

TECHNICAL DIVISION
SAVANNAH RIVER LABORATORY

DPST-76-241

Acc#94742

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February 18, 1976

TO: G. F. MERZ

FROM: J. R. TAYLOR

COOLING OF PARTIALLY SUBMERGED VERTICAL ASSEMBLIES

INTRODUCTION

During reactor discharge, assemblies are placed vertically into the deposit and exit (D & E) conveyor in the discharge canal for transport to the disassembly basin. One postulated discharge mishap is failure of the automatic lowering mechanism on the D & E conveyor which could leave part of an assembly extended above the liquid level in the discharge canal. Because heat removal from a partially submerged assembly was not well understood, an experimental program was undertaken to determine the potential for melting should the D & E conveyor automatic lowering mechanism fail to operate.

Previous calculations[1] and tests[2] indicated that partially submerged assemblies with typical SRP discharge decay powers would be cooled by chugging flow, a phenomena in which water is pumped upward through the assembly as a result of density differences between the relatively cold bulk canal water and the two-phase steam/water mixture in the heated annulus. More recent data have shown that a threshold power exists below which chugging flow cannot be supported and overheating or melting of heated portions of the assemblies extending above the water level may occur. This memorandum reports details of those tests as well as experimental bases for determining the potential for melting in an assembly partially submerged in the discharge canal.

SUMMARY

Test data show that all current assembly types at SRP, if discharged normally (i.e., without Universal Sleeve Housings), can be cooled indefinitely be either single-phase, natural convection or by two-phase chugging flow. Cooling of assemblies without USH is satisfactory because all heat generating portions are either submerged or protrude no more than one inch above the canal water level. Demonstration tests were conducted to show that these assemblies could be cooled whether chugging occurs or not.

The test data also indicate that, in the absence of prompt operator action, overheating is possible in assemblies discharged inside Universal Sleeve Housings (a rare mode of discharge). A threshold power exists, below which chugging cannot occur, because heat generated in submerged portions of an assembly can be transferred radially without vaporizing water in the assembly annuli. Assemblies discharged inside USH's may have some heat generating material protruding above the canal water level.* Thus, if an assembly discharged inside an USH is operating below the chugging threshold, no mechanism exists for removing heat from the protruding portion (axial conduction and natural convection to air are too small to be of practical significance). The current practice of supplying emergency cooling from the D machine if the D & E conveyor fails will provide adequate cooling for assemblies in USH.

DISCUSSION

Background

An SRP assembly, when discharged from the reactor, is transported to the discharge canal by the discharge machine. The discharge machine deposits the assembly vertically into the D & E conveyor in the discharge canal for transport underwater to the disassembly basin.

* For a Mark 31A assembly in K Area (worst case) discharged inside an intact USH, up to 13.5 inches of core material may protrude above the canal level. For the rarer case of the same assembly discharged inside a sheared USH, up to 33 inches of core material may protrude.

When the assembly is initially placed into the D & E conveyor, part of the assembly may protrude above the canal water level. The length of assembly above the canal water level depends on assembly design as well as reactor area (canal and conveyor designs differ slightly) and mode of discharge (with or without an USH). Once the assembly is seated in the D & E conveyor, the conveyor is automatically lowered to an elevation which completely submerges the assembly. The conveyor then transports the assembly underwater to the disassembly basin.

One postulated discharge mishap is failure of the automatic lowering mechanism on the D & E conveyor which could leave the assembly partially submerged until action could be taken to lower the assembly manually (this could require several minutes). Because normal, natural convection cooling is inhibitted in partially submerged assemblies, a program of tests and analyses was instituted to provided technical bases for analyzing the potential for melting in an assembly should the automatic lowering mechanism on the D & E conveyor fail.

Calculations[1] (which neglected radial heat transfer to the discharge canal) indicated that ~ 50 kW could be removed from an assembly protruding 26 inches above the discharge canal level by chugging within the coolant annuli. An experimental program was undertaken to verify the chugging phenomena and to provide verification of the calculated limit. Tests were conducted,[2] using a two-tube, electrically heated assembly, that demonstrated stable cooling of the test assembly at 250 kW with the overflow point 50 inches above the bulk water level.

Further analysis of worst case conditions by Reactor Technology showed that some assemblies (discharged inside an USH) could have overflow points more than 50 inches above the canal water level. Thus, an additional testing program was undertaken to extend the range of data.

Theory

Partially submerged assemblies inside an immobilized D & E conveyor can be categorized in three classes according to how far the heat generating material and the overflow point are above the level of the water in the discharge canal. These classes are:

1) all heat generating portions submerged-overflow point nearly submerged

2) all heat generating portions submerged - overflow point substantially above canal water level

3) some heat generating portions not submerged - overflow point substantially above canal water level.

Heat removal mechanisms for each category are discussed in detail below.

Class 1

This class consists mainly of target assemblis discharged without Universal Sleeve Housings. The bulk of the heat removal is accomplished by primary, single-phase convection currents which rise through the coolant annuli parallel to the assembly axis and overflows from the assembly.* In addition to this primary flow pattern, a secondary flow pattern exists which is characterized by eddy currents which promote radial heat transfer across the coolant annuli.

Class 2

This class is composed mainly of fuel assemblies discharged without Universal Sleeve Housings for which the assembly overflow point protrudes sufficiently to surpress the primary convection current. (The overflow point for a Mark 16 assembly is ~ 8 inches above the canal water level while for a Mark 22 assembly, the overflow point is 22 inches above the water level.) Calculations show the primary convection current will be completely surpressed when the overflow is 6 inches above the canal. Heat removal from outer annuli for this case is primarily by radial heat transfer as a result of secondary convective (eddy) currents. For inner annuli, which may be effectively insulated by surrounding fuel tubes, heat transfer may be by either secondary convective currents or by chugging flow.

Class 3

This class consists of both fuel and target assemblies discharged inside Universal Sleeve Housings and is the worst case for cooling of the assembly. At powers below the chugging threshold, heat is transferred radially from the submerged portion by secondary convective currents but no mechanism exists for transferring heat from the heat generating portion which protrude above the canal level; melting may occur in the exposed portion. However, if power were increased above the chugging threshold, stable cooling of assemblies in this class would be possible.

Chugging Flow

Chugging flow occurs when bulk boiling in a coolant annulus causes a decrease in coolant density. Because static pressure at the assembly bottom elevation is constant, coolant in the annuli will seek a new level which satisfies:

$$\rho_c H_c = \rho_h H_h + \Delta P_f$$

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* Heat removal for Class 1 is essentially the same as for a fully submerged assembly.

where: ρ = fluid density, lb/ft^3

H = height of fluid above assembly bottom, ft.

ΔP_f = dynamic pressure drop (friction + acceleration) due to the flowing fluid, psfd

subscript c refers to cold (bulk) canal water

subscript h refers to relatively hotter two-phase steam/water in the annuli

Thus, total heat removal by chugging flow from a partially submerged vertical assembly is a function of the length of the assembly which protrudes above the water as well as the heat transfer properties of the two phase fluid in the annulus and the assembly resistance to two-phase flow.

Experimental Program and Results

The experimental program to characterize heat removal from partially submerged assemblies is diveded into four series of tests. Tests were conducted to:

1) Determine the upper limit for heat removal from a chugging assembly.

2) Investigate phenomena at and below the lower chugging threshold.

3) Demonstrate stable cooling of assemblies with all heat generating portions submerged whether chugging occurs or not.

4) Determine the time required to fill a voided annulus.

Each test series is discussed in detail below.

Upper Chugging Limit

Tests to determine the upper limit of heat removal by chugging flow were conducted using the test assembly shown in Figure 1. The test assembly consists of a stainless steel heater tube, 12.5 feet long, inside a transite* outer housing. Spacing between heater tube and housing was provided by 1/8 inch square steel keystock welded to the steel heater tubes at intervals of ~ 1 foot. The top of the transite outer housing extended 59 inches above the top of the heater tube.

* Transite is a Johns-Mansville trade name for an asbestos-concrete laminate. Transite was used to minimize radial heat transfer to the bulk water.

The test assembly was instrumented with a sheathed thermocouple to indicate overheating that would result from inadequate cooling (the thermocouple system was not designed for absolute temperature measurement). The thermocouple was spring loaded through the transite housing onto the heater surface ~ 2 inches below the heater top. Test section power was measured using the normal current and voltage measuring devices in the heat transfer laboratory.

Tests were conducted in "A" tank test station, a stainless steel tank 3 feet in diameter by 22 feet long. A tank level indicator (part of the laboratory operating instrumentation) was used to determine tank water level. This tank level indicator was calibrated against known reference points (taken from "A" tank blueprints) several times during the testing program and was found to vary as much as 4 inches from actual level. Raw data have been adjusted to the most conservative calibration.

Test procedure was to establish a tank water level and a stable test section power. Power was then increased in 5-10 kW increments until the test assembly thermocouple indicated overheating. Several minutes were allowed at each power level to assure steady state conditions. Whenever indicated metal temperature became unstable, the test was either scrammed or stable temperature was re-established by reducing test section power to a level known to be stable.

An independent check on temperature stability was provided by the transite housing which made a loud popping sound at high temperature as thermal stresses caused the housing to crack. These cracks finally destroyed the housing.

Results of these test are shown in Figure 2. Tank water level was adjusted to the most conservative tank level calibration taken during the program. While the power levels achieved are not as great as measured for the two tubed heater[2] (probably because of higher resistance to flow for this test assembly), they are substantially above the highest power at which an assembly can be removed from the reactor.*

When the test section was disassembled, large flakes of transite were found in the channel near the top of the heater. These flakes were of such size and quantity to have substantially restricted chugging flow during the tests. Thus, the data in Figure 2 are conservative.

Lower Chugging Threshold

A cross section for the test assembly used to investigate the lower threshold for chugging flow is also shown in Figure 1. The

* Limits based on emergency discharge machine cooling, prevent discharge of assemblies generating more than 50 kW decay heat.[2]

assembly consisted of a stainless steel heater, 12.5 feet long, of somewhat smaller dimensions than the assembly used to determine the upper heat removal limit. For these tests, a stainless steel outer housing was used to provide more realistic radial heat transfer as well as to avoid problems with material deposition from the flaking transite. Spacing between the heater tube and housing was provided by 1/4 inch diameter fiberglas rods loaded through the outer housing onto the heater tube. The fiberglas rod was held in place with Swagelok tubing fittings welded onto the housing tube. The top of the outer housing also extended 59 inches above the top of the heater tube.

Instrumentation for these tests was the same as for the tests to determine upper heat removal limit (sheathed thermocouple plus existing equipment). In addition, the test assembly was equipped with a resistivity probe located 24 inches below the sheathed thermocouple (~ 26 inches below the top of the heater) to provide information on the chugging mechanism and flow pattern. (This technique has been shown to be effective for differentiating between slug and bubbly flow patterns in the Reactor Hydraulic Test Facility.[3])

Test procedure for the tests to investigate the lower chugging threshold was first to establish a tank water level and stable operating power. Test section power was then lowered in 5-10 kW increments, allowing several minutes at each power level to assure steady state conditions. At all tank water levels, temperature at the top of the heater tube (well above the bulk water level) became unstable when test assembly power was lowered below ~ 50-55 kW. Stable temperature could usually be restored by increasing test section power to between 65 and 80 kW (the increase required appeared to depend more on maximum temperature achieved during the transient than on tank water level). Because of geometric constraints in the test section, tests were not run with the heater tube submerged.

Resistivity probe output indicated steam/air in the channel at powers below the 50-55 kW threshold (except for those tests in which the probe was near the tank water level and single phase liquid was observed throughout the test), but showed bubbly or frothy flow at higher powers. There was no evidence of voiding inside the annulus during the chugging phenomena. In one test, the tank was filled to a level sufficient to submerge the probe and the probe signal showed liquid phase only.

Demonstration Tests-Heat Generating Material Submerged

Demonstration tests were conducted to prove that assemblies with all heat generating portions submerged will be cooled whether chugging occurs or not. The test assembly for these tests consisted of a thin-walled stainless steel heater tube (1 inch OD x 0.047 wall) containing a 3/4 inch OD fiberglas rod 8 feet long to form an annulus of 0.156 inch equivalent diameter (spacing between the heater tube and fiberglas rod was provided by round-head screws fastened to the fiberglas rod).

The steel tube was 14 feet long with the top six feet unheated. Water level for the tests was ~ 3 inches above the heated portion of the tube (nearly 6 feet below the assembly overflow.) Tests were conducted with the heated portion of the tube in intimate contact with bulk tank water and, later, with the heated portion insulated by fiberglas cloth.

Instrumentation for the demonstration tests consisted of a bare thermocouple tack-welded to a steel band clamp which was then electrically insulated from the heater surface. (The thermocouple system was located ~ 2 inches below the top of the heated portion of the tube.) Test assembly power was measured using existing current and voltage measuring devices in the heat transfer laboratory. Water level was determined visually.

The test procedure was to determine the lower threshold for chugging flow by decreasing power in small increments and then to operate the test assembly as close as practical to (but still below) the chugging threshold for an extended time. For the heater tube in intimate contact with the tank water (i.e., uninsulated), the lower chugging threshold was determined to be between 40 and 45 kW. The test section was operated at 40 kW for five minutes during which time no visible chugging occured (after the test, the assembly was returned to 45 kW where visible chugging was observed). For the case of the insulated heater tube, the lower threshold was determined to be between 3 and 5 kW. This assembly was operated at 3 kW for 10 minutes with no visible chugging (after the test the assembly was returned to 5 kW where visible chugging was observed).

During both tests, indicated surface temperature was continuously monitored; there was no evidence of temperature instability. Furthermore, following each test, the test section was disassembled and visually examined for evidence of overheating. There was no evidence of overheating save a small amount of bow associated with heating the tube between the relatively fixed bus connections.

Annular Fill Times

Based on analysis of data from the previous tests, it is highly unlikely that annulus voiding occurs during the chugging phenomenum. However, because this is difficult to substantiate beyond doubt, a series of tests was conducted to determine the time required for a voided annulus to refill. For these tests, two concentric PVC pipes were used. Spacing between the pipes was maintained with plastic (ABS) ribs chemically welded onto the inner pipe to form an annulus with 0.259 inch equivalent diameter.

The test assembly was provided with a small tubing line connected to the building air supply and with a 1½ inch quick opening valve vented to atmosphere.

The assembly was instrumented with resistivity probes at 2 foot intervals along the assembly axis (the bottom probe was 3 inches above the bottom of the assembly). Output from selected probes was recorded on a high speed (1 inch/second) strip chart. Tests were run with no restriction to flow at the bottom of the assembly and with a bottom flow restrictor consisting of a single hole drilled into a flat plate which was chemically welded to the assembly bottom.

The test procedure was first to establish a tank water level (determined visually) at the level of a selected resisitivity probe. The assembly was then voided using building air at ~ 10 psi pressure and quickly vented to atmosphere. The time required for water level in the annulus to rise from the bottom probe to bulk tank level was measured on the high speed strip chart.

The increase in annular fill time with assembly submersion for an assembly with no bottom flow restrictor is shown in Figure 3. For an assembly submerged to a depth of 150 inches (typical for SRP assemblies discharged without USH), the annulus fill time is 2.5 seconds.

For large restrictions to assembly flow (i.e., small orifice holes), there is a large increase in annular fill time (Figure 4). However, the increase in fill time drops sharply with increasing orifice size to a value near that for no bottom flow restrictors. For assemblies without USH, the worst bottom restriction to flow occurs in target assemblies with an equivalent area of the bottom restriction to flow of 0.60 square inches. Thus the increase in annular fill time due to bottom flow restriction can be no more than 0.5 sec (total annular fill time of 3.0 sec).

Calculations of the rate of temperature increase during adiabadic heating were done for an aluminum tube, 2 inches OD by 0.100 inch wall by 12.5 ft long generating 20 kW decay power.* Temperature rise for this tube is 5°C/sec. At this rate of temperature rise, twenty seconds of adiabatic heating would be required to increase surface temperatures from 150°C to 250°C (near the Liedenfrost point).

Film Boiling Burnout

The potential for film boiling burnout in a chugging assembly is vanishingly small. Burnout heat flux for a partially submerged assembly during chugging is conservatively estimated to be 204,000 pcu/ft^2-hr based on an existing pool boiling burnout correlation[4] evaluated at zero subcooling. For a typical fuel tube (2 inch OD by 12.5 feet long) generating 20 kW and insulated on the inside, maximum operating heat flux is < 6000 pcu/ft^2-hr. Thus the burnout safety factor for this tube is ~ 34.

* These dimensions and power are typical for heater tubes at SRP but were deliberately chosen from the conservative end of the spectrum.

Application to SRP Assemblies

Should the automatic lowering mechanism or the D & E conveyor fail, all heat generating portions of assemblies discharged with no USH would either be completely submerged or would protrude no more than one inch above the discharge canal water level. Heat removal capability for such assemblies is greater than the heat generation rates permitted for assembly discharge. Figure 2 shows the maximum heat removal rates for chugging flow without conection for axial heat flux variation.

For the case of an assembly discharged inside an USH, all heat generating portions may not be submerged should the D & E conveyor fail to lower. For these assemblies, cooling by chugging flow cannot be guaranteed so emergency cooling must be provided when the D & E conveyor fails (present practice).

REFERENCES

1. J. P. Morin, Percolation Cooling in Partially Submerged Assemblies, DPST-75-302 (Unclassified)

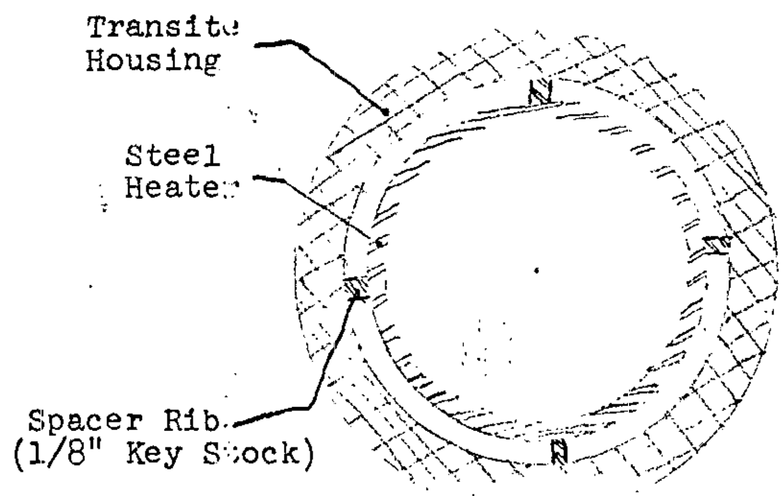
2. J. R. Taylor, Convective Chugging in Partially Submerged Assemblies, DPST-74-534.

3. D. J. Orliff, Steam Void Behavior and Postulated Mathematical Model for RHTF Studies, to be issued.

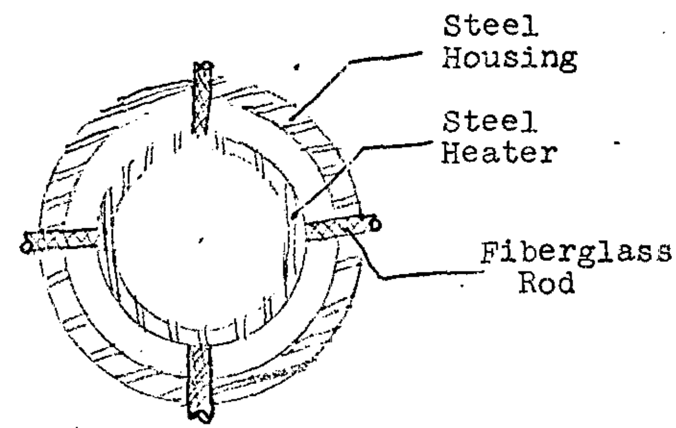
4. Technical Manual, Effluent Temperature and $BOSF_N$ Limits For Fuel and Target Assemblies and Reactor Effluent Temperature Limits, DPSTM-110.

JRT:sbc

Figure 1. Cross Section View of Test Assemblies



Assembly for Upper Heat Removal Limit



Assembly for lower chugging threshold

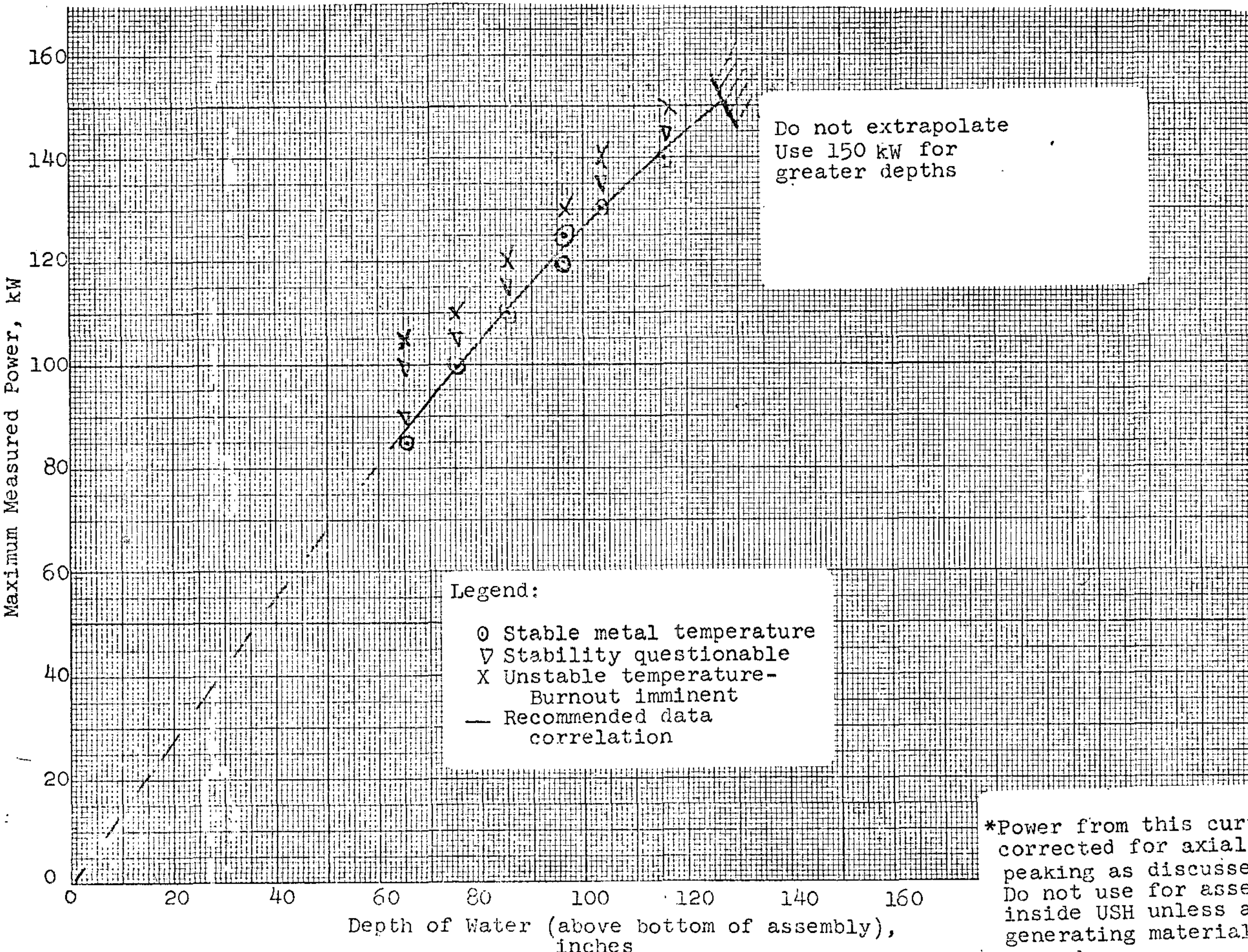
Dimensions

Transite Housing*	Steel Housing
OD 4.740	OD 3.500
ID 4.000	ID 2.900

Steel Heater	Steel Heater
OD 3.700	OD 2.375
ID 2.434	ID 2.000

*Dimensions approximate

Figure 2. Maximum Safe Operating Power* for a Partially Submerged Assembly with all Heat Generating Portions Immersed.



*Power from this curve to be corrected for axial flux peaking as discussed in text. Do not use for assemblies inside USH unless all heat generating material is immersed.

Figure 3. Measured Time for Annulus to Fill in the Unlikely Event the Annulus Voids

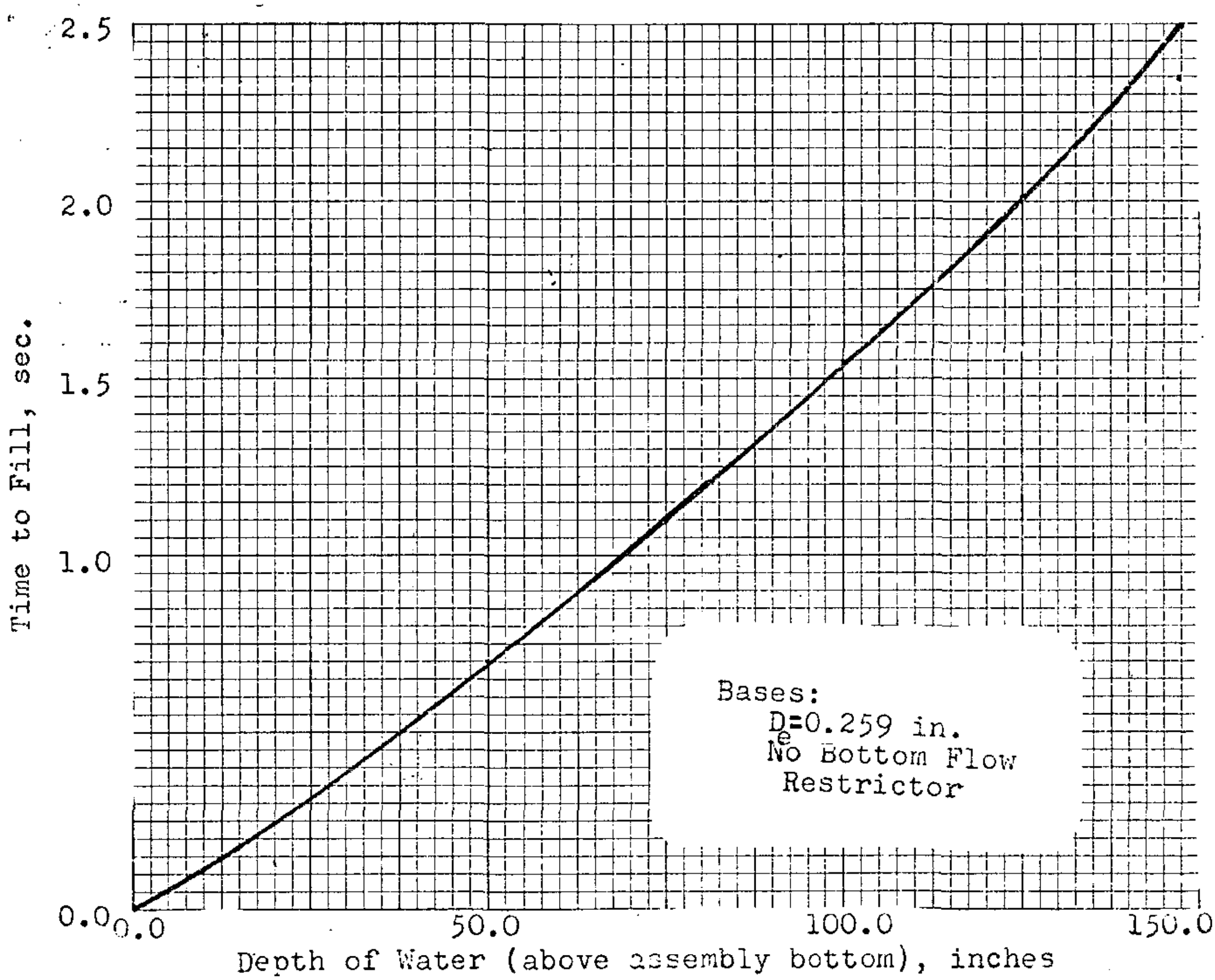


Figure 4. Effect of Bottom Flow Restrictor on Measured Fill Time
(Imersion Depth of 12 ft, 3 in.)