BOILED-UP POOL HEAT TRANSFER FOR A HORIZONTAL TUBE BUNDLE

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ABSTRACT

Isolation condensers are effective means of emergency decay heat removal for commercial nuclear power plants when they encounter rapid transients such as a loss of load. Many of these designs use horizontal tube bundles to transport steam to, and through the primary side of the condenser. Steam generated on secondary side causes the water pool to boil-up (level swell) such that the water level is considerably higher than the collapsed level. Consequently, when the collapsed level is below the top of the tube bundles, the boiled-up level is the parameter that determines the extent of heat removal from the condenser.

To determine the functional dependence between the heat removal rate within the bundle and the water level swell, water pool heat transfer experiments have been performed with a horizontal bundle of instrumented electrical heaters. The primary objective was to ascertain the collapsed water level that corresponded to the top row of heater elements no longer being covered by the water level swell (incipient dry-out). To accomplish this, the power was increased in small increments and remained at the new power for several minutes to assure that any possibility for dry-out of the upper elements would be detected. These experimental results show that standard representation of pool boil-up (liquid level swell) conditions also provides a good characterization of the behavior for a horizontal tube/heater bundle.

This paper describes the experiments performed and compares the test results with a well characterized drift flux model. With the expanded use of isolation condensers in the recent, more passively orientated safety system designs for commercial nuclear power plants, this experimental data provides a much needed technical basis to illustrate the influence of the steam generation rate on the "wetted surface" of the horizontal condenser tubes. It is this parameter that determines the maximum heat extraction rate.

KEYWORDS
Isolation Condenser, liquid level swell

1. BACKGROUND

Safety evaluations for the heat transfer rates and the net energy transfer available in the initial fluid inventory for an Isolation Condenser (IC) require a representation of the water level swell on the secondary side that results from large steam generation rates. Specifically, with this representation, the shell inventory could decrease to a collapsed level that is considerably below the mid-plane of the tube bundles, with no penalty in the overall tube bundle heat transfer rate. The basis of this is that the horizontal tubes would remain covered by a two-phase mixture due to two phase thermal hydraulic conditions in the tube bundle. This study experimentally measured the relationship between the two-phase behavior (the water level swell caused by steam generation) and the minimum collapsed water level needed to extract the applied power from the heated bundle.

2. POOL BOILUP IN THE ISOLATION CONDENSER

2.1. Steam Generation in the Isolation Condensers

Several commercial nuclear power plants use ICs to remove heat from the Reactor Coolant System (RCS) following shutdown of the reactor. To accomplish this, the IC receives steam directly from the Reactor Pressure Vessel (RPV), the condensing steam in the tube side transfers energy to the shell side causing boiling in the shell water inventory and venting the steam to the atmosphere with the condensate draining back to the RPV. Therefore, this heat rejection process involves no loss of water inventory from the RCS. Many of the IC designs that have been experimentally tested have vertical tube bundles [1, 2 and 3], but the interest here is for horizontal tube bundles and the relationship between the collapsed water level and the water level swell on the secondary side due to net steam generation. Of particular interest is the influence of the level swell when the collapsed level is below the top of the horizontal tube bundle.

Figure 1 illustrates a typical IC configuration that uses two horizontal U-tube bundles. With continued heat removal and no water addition to the secondary side, the IC collapsed water level would eventually decrease to a level below the top of the tube bundle. Therefore, it is of interest to evaluate the potential for the level swell (also referred to as pool boil-up) as a result of the steam generated within the tube bundle [4 and 5]. A two-phase boil-up condition can sustain the nucleate boiling heat removal rate from the full horizontal U-tube configuration even when the collapsed water level is below the top of the U-tube bundle. Consider that the flow path for steam passing through the bundle has a reference horizontal cross-sectional area for the induced two-phase flow rate that is equal to the product of the bundle diameter and the tube length. Assuming that the secondary side is close to atmospheric pressure, a steam density of 0.86 kg/m^3 [6], would result in a superficial steam velocity through the secondary side of the bundle of several meters per second at rated conditions.

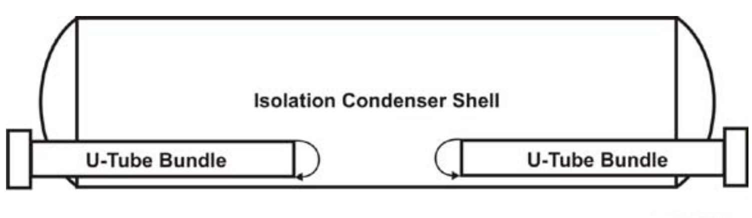

Figure 1. Example of an Isolation Condenser Showing Two U-Tube Bundles Inside of the Shell.

2.2. Experiments and Analysis Relating to Pool Boil-Up

Experimental data has shown that the two phase water level would increase (boil-up) as a result of steam formation beneath the collapsed water level. Specifically, the higher void fractions associated with the "churn turbulent" flow regime, the average void fraction of the associated with the level swell of the pool can be expressed by

$$\frac{j_g}{U_\infty} = \frac{2\,\bar{\alpha}}{1 - C_0\,\bar{\alpha}} \tag{1}$$

where

- C_0 is an experimentally determined parameter for the flow regime of interest,
- j_g is the superficial gas velocity developed within the pool,
- U_∞ is the churn turbulent bubble rise velocity, and
- $\bar{\alpha}$ is the average void fraction within the boiled up region.

The bubble rise velocity for the churn turbulent regime is given by

$$U_\infty = 1.53\sqrt[4]{\frac{g\sigma\left(\rho_\ell - \rho_g\right)}{\rho_\ell^2}} \approx 1.53\sqrt[4]{\frac{g\sigma}{\rho_\ell}} \tag{2}$$

where:

- g is the acceleration of gravity,
- ρ_g is the steam density,
- ρ_ℓ is the water density, and
- σ is the steam-water surface tension.

For the conditions of interest, the churn turbulent bubble rise velocity is approximately 0.23 m/sec and for a boiled up pool with a substantial velocity profile, C_0 has a value 1.5. A non-uniform distribution of the induced water circulation caused by the steam volume generation and also possibly due to a non-uniform steam volume generation rate is represented by the 1.5 value. If the flow distribution is uniform within the pool, a value of unity would be appropriate for C_0 and the pool boil-up level would be even higher. Substituting a value of 1.5 into the above equations and calculating the average void fraction within the pool results in a value of 0.63. This representation indicates a very dynamic pool behavior with a boiled-up pool water level that continues to maintain complete coverage of the top tubes until the water level is decreased such that approximately 1/3 of the tubes are below the collapsed water level.

The results of pool boil-up the experiments have been evaluated by the Design Institute for Emergency Relief Systems (DIERS) by Grolmes et al [5] as shown in Figure 2 as well as the combination of the DIERS data and similar data was reported by Ginsberg [4]. (Note that the two points designated as "Winfrith Tests" and "FAI Bundle Data" are developed in this paper.) As illustrated in this figure, there is a considerable technical basis associated with the boil-up of volumetrically heated pools.

2.3. Winfrith Prototypic Molten Fuel-Water Tests

Another contribution to the technical basis for the level swell produced by steam generation is from the test program at the UK Winfrith Laboratories that examined the response of a water pool when molten uranium thermite was poured into the water [7 and 8]. These experiments measured the dynamic response (level swell) of a water pool when a molten uranium dioxide/molybdenum mixture, in the form of capillary size droplets at a temperature of approximately 3600 K, entered the pool. With respect to the technical basis of interest, the molten debris is the heat/power source responsible for generating steam with a high superficial velocity within the water pool. This data is of interest because the superficial velocity is greater than, but comparable to the velocities of interest for IC behaviors. Also, the influence of this high superficial velocity on the pool can be compared to the information developed in the DIERS experimental program and others.

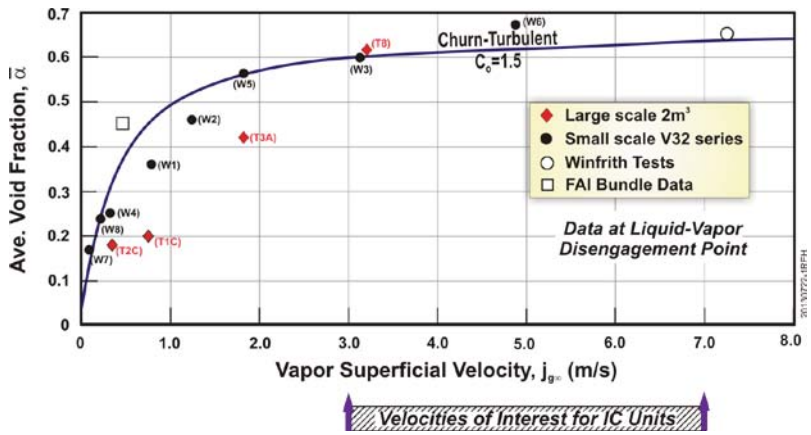

Figure 2. Comparison of Test Data with Churn Turbulent Void Fraction – Superficial Velocity Relation. (Data from 35ℓ vessel compared with data from 2 m vessel.) Test Designations Refer to DIERS Report III-4. as presented by Grolmes et al. [5].

These thermite experiments were performed by having the melt flow through a droplet former, which was an array of 13mm square carbon bars that were spaced 10 mm apart. As a result, the melt was broken-up into 16 melt streams which subsequently disintegrated into molten droplets, of approximately the capillary size, before the melt reached the water surface. The experimental apparatus had the following characteristics:

- a 0.37m x 0.37m x 1.60m high interaction chamber,
- a charge container in which the thermite reaction occurred,
- the droplet former,
- cylinder skirts of different lengths to restrict the cross-sectional flow area of the molten droplets as they fell through the gas space above the water,
- and a vent pipe-vent tank combination with a vortex flow meter in the vent line.

The vortex flow meter in the vent line provided a means to measure the steam flow rate generated during the melt quenching transient. Figure 3 shows the steam flow rate histories for the three tests that were reported. Of these, MIXA01 used a molten mass of 2.84 kg, but did not use a skirt to restrict the lateral dispersion of the droplets, MIXA04 used a skirt that was 210 mm long with a melt mass of 2.75 kg and test MIXA06 delivered a molten mass of 3.00 kg with a skirt length of 480 mm. As illustrated in Figure 3, the steam generation histories are similar between the three tests, with the respective steam volumes generated being 1.286, 1.067 and 0.701 m^3. The latter test had the highest melt stream density entering the water pool and therefore would tend to have the deepest penetration and the shortest penetration time. Consequently, this test would experience the largest transfer of energy to the subcooled water pool, thereby having a lower steam flow to the vent tank.

Relevant to the extent of pool boil-up, the discussion of test MIXA01 [7] identifies the following with respect to the level swell. "…. The water surface rose by 0.05 m in the first 0.1 s following melt arrival at the water, ….. At later times it was observed that the vessel was filled by a two phase mixture….." Ref.8 discuss test MIXA06 in a similar manner. "At 0.18 s after the melt entered the water there was ~0.1 m of level swell. At 0.6 s after melt/water contact the level swell had reached the bottom of the 'skirt'. …… After 1.2 s the level swell had filled the vessel." Consequently, both of these tests, were observed to fill the vessel with a boiled-up two-phase pool. Completely filling the vessel with a two-phase mixture corresponds to a void fraction of 0.6. Taking the steam volumetric flow rate of about 1 m^3/sec and the vessel cross-sectional area of 0.137 m^2, results in a maximum steam superficial velocity of 7.3 m/s. Referring to the experimental data in Figure 2, this combination of superficial velocity and void fraction is on the far right hand side of this figure and is consistent with the available data, as well as the churn-turbulent prediction. Both of these superficial velocities produce a void fraction of approximately 60%.

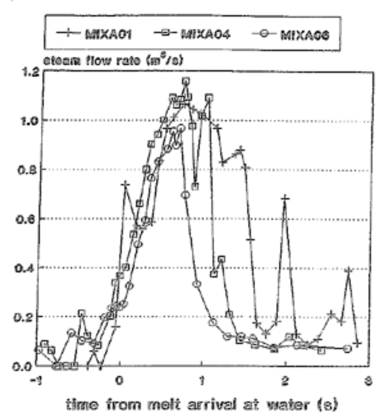

Figure 3. Measured Steam Volumetric Flow Rates for the Winfrith Melt-Water Interaction Tests (from Denham et al., 1992).

3. EXPERIMENT FOR POOL BOIL-UP IN A HEATER BUNDLE

To examine the behavior of pool boil-up within a horizontal heated bundle, an experiment was performed in the FAI laboratory using available equipment that included an electrically heated bundle and a test vessel (Figure 4). The collapsed water level, which was initially above the top element of the heater bundle, was measured by both a pressure transducer (15 psig with an accuracy of 0.25% of span or better) and a sight glass . Water was vaporized by the heat generated in the heater bundle, which produced a measurable decrease in the water level. Thermocouples were located on the top surface of the highest heater element and an element that was essentially at the 90° position on the bundle (see Figure 5). The objective was to monitor the heater bundle for a possible dryout using the thermocouples to determine the conditions that resulted in surface overheating. Sustained heat removal by nucleate boiling with the collapsed water level below the top of the heater bundle, indicates that the swell height is supplying sufficient water to the heater element surfaces to support the heat transfer. Once the measured heater surface temperature demonstrated an increase considerably above the saturation temperature (approximately 100°C), this was indicative of the bundle upper surface no longer being covered by a two-phase mixture. Immediately prior to this point, the water swell height was the difference between the top of the bundle and the collapsed water level. The average void fraction at that time was the swell height divided by the height of the heater bundle (5.5 inches). This measured value can be compared to the DIERS related experiments and analyses discussed in Section 2.

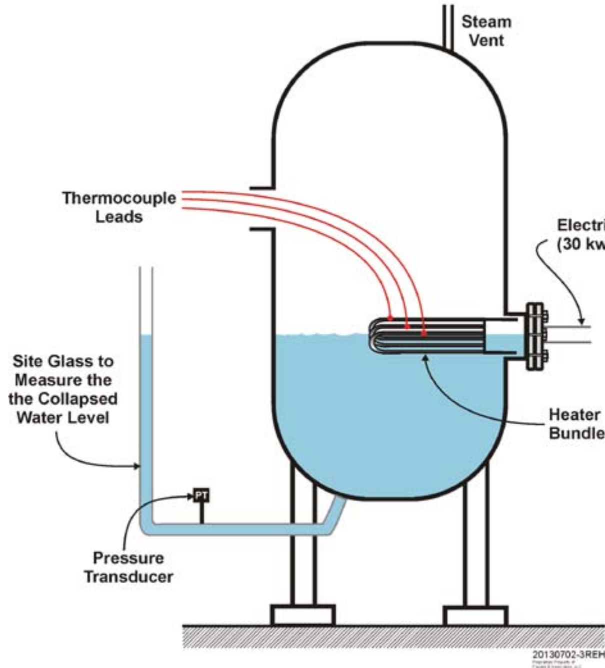

Figure 4. Schematic Representation of the Experiment Measuring the Boil-Up Water Level in a Horizontal Heater Bundle.

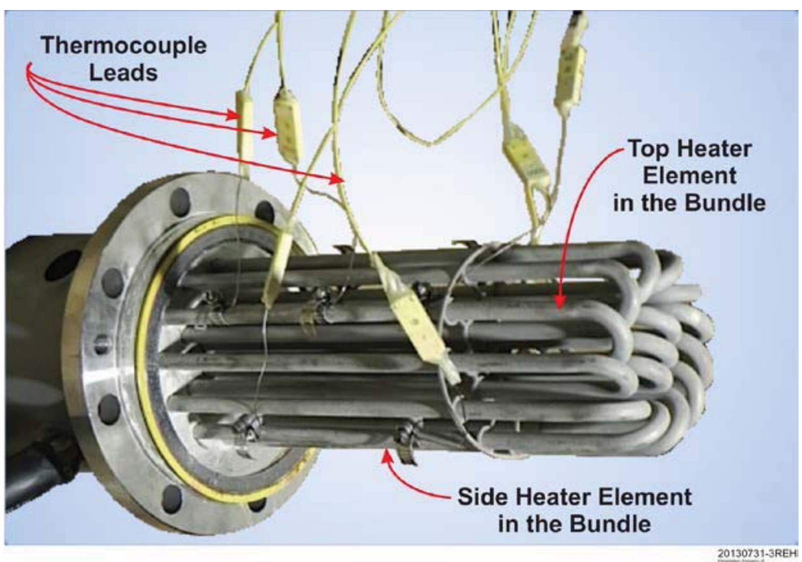

Figure 5. Photograph of the Heater Bundle with the Thermocouples Mounted on the Heater Surfaces.

The electrically heated bundle generates 30 kW at full power and was operated at full power for all of the tests since this is the most relevant condition to the limiting IC performance. The heater bundle is comprised of separate U-tube heater elements with 15 U-tube electrically powered heaters, each having a diameter of 0.5 inches (0.0127 m) and a bundle length of approximately 16 inches (0.406 m). In addition, the outer bundle diameter is approximately 5.5 inches (0.14 m) which, along with the bundle length defines the reference flow area for steam within the bundle (0.057 m^2 or 0.612 ft^2). Since the experiment was operated at 1 atm, the steam density was 0.6 kg/m^3 and the resulting maximum steam velocity in the bundle was 0.39 m/sec. Substituting this into the churn turbulent formulation given above, results in an average void fraction of 0.37 in the tube bundle. The heat transfer surface area in the U-tube bundle can be approximated by $A_{ST} = 15 \times 2 \times \pi DL = 15\,(2\pi)\,(0.0127)\,0.406 = 0.486\ m^2$ (5.23 ft^2). Given the heater bundle power of 30 KW, the average heat flux is 61,729 W/m^2.

These parameters give a power density of 4.8 MW/m^3, which is about one-half of that developed in a typical IC with a horizontal tube bundle (approximately 8.5 MW/m^3 or 125 MBTU/hr) at design basis conditions. As discussed later in this paper, when the collapsed water level in an IC decreases below the top of the bundle, the isolation condenser can redistribute the heat flux such that more heat is transferred in the lower parts of the tube bundle. This increases the steam velocity in the lower regions of the bundle and also increases the average void fraction in this region. An electrically heated test bundle cannot redistribute the energy generation in this manner. Hence, the test configuration provides a conservative representation of the manner in which the IC tube bundle could remove the design basis heat load.

As noted above, the experiments were performed at atmospheric pressure (local pressure is about 14.5 psia or 0.1 MPa), such that the steam density is 0.59 kg/m^3 and the resulting maximum steam velocity in the bundle is 0.39 m/sec with calculated level swell developing an average void fraction of 0.37 within the tube bundle. Of course, since the steam superficial velocity in the experiment is less than that which would be generated in the IC, the level swell is also less in the test apparatus than that which would be typical of the design basis response of an IC. However, it is sufficient to demonstrate the fact that the bundle heat transfer is determined by the extent that the tubes (heaters) are covered by water and this is significant even at this lower superficial velocity. These experiments are also sufficient to compare the measured two-phase (swelled) height for this horizontal bundle configuration to the existing technical basis. Three experiments were performed with the power being the same for each, essentially 30 kW. This was measured by the rate at which the water level decreased in the test vessel (see Figure 6), which resulted in a value of 29 kW and estimates of heat losses by convection and radiation to the environment off the surface of the uninsulated vessel giving values of about 1 kW, the value of 30 kW was used to evaluate each test.

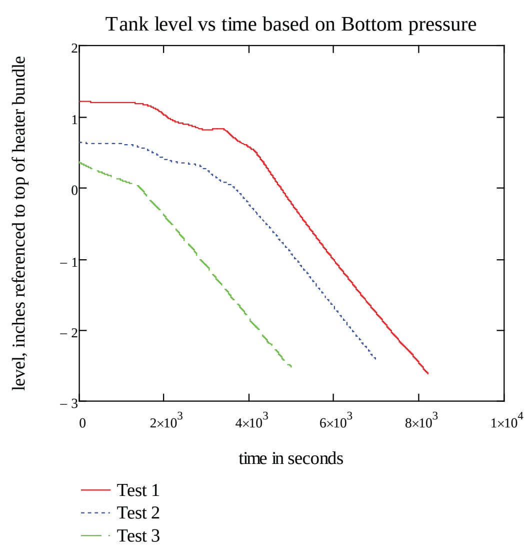

Figure 6. Decreasing Collapsed Water Level in the Test Vessel for Test #1, 2 and 3.

The heater surface thermocouple measurements for the first test are shown below in Figures 7 and 8. As demonstrated by these measurements, all of the surface temperatures were within a few degrees of the water saturation until the collapsed water level was well below the top of the heater bundle. With the decrease of the collapsed water level, eventually the thermocouples on the upper surface of the top element began to oscillate and then began to heatup at a rapid rate. All of the three experiments demonstrated the same behavior. Specifically, when the collapsed level reached 2.5 inches below the top of the bundle, the thermocouples on the top of the upper most heater element demonstrated dryout. Therefore, just prior to dryout, the average void fraction in the heater bundle due to the level swell was 0.45. Referring back to Figure 2, this bundle data is in general agreement with, and somewhat greater than, the predicted behavior calculated by the experimental correlation discussed above.

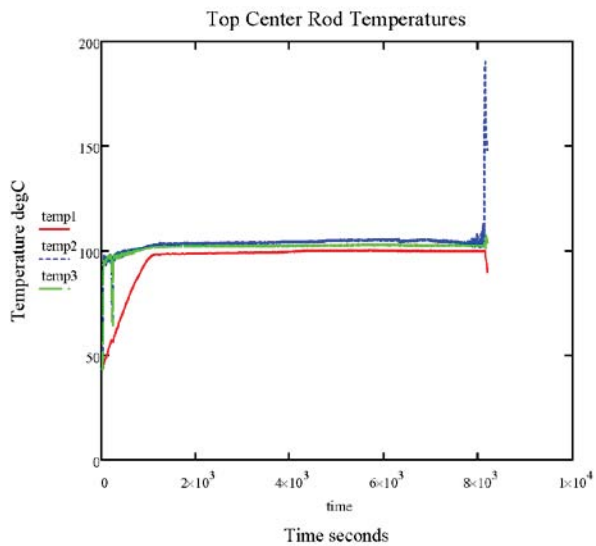

Figure 7. Measured Heat Element Surface Temperatures for the Top Element in the Heater Bundle for Test #1.

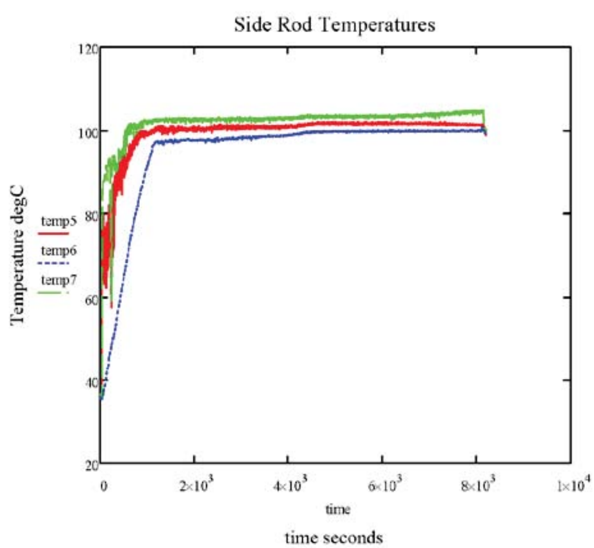

Figure 8. Measured Heater Surface Temperatures for the Heater Element Adjacent to the Top Element for Test #1.

4. INFLUENCE OF REDISTRIBUTION OF THE HEAT FLUX WITHIN AN IC TUBE BUNDLE

It is noted that the manner in which the tubes are implemented within a typical IC tube bundle means that the top tubes in the bundle on the inlet side are the lowest tubes in the bundle on the discharge side. Consequently, should these outer rows of tubes experience degraded heat transfer in the upper portion of the bundle, the lower portion would experience an increase in the average heat flux as long as the surface heat flux on these lower tubes is less than the critical heat flux. This increase in the heat transfer in the bottom of the bundle would increase the average steam void fraction in the bottom of the bundle, and therefore the boiled-up height in the tube bundle. The maximum heat flux that could be removed from the horizontal tubes is the critical heat flux that is given as [9]:

$$q/A)_{CHF} = 0.89\ q/A)_z \tag{3}$$

where $q/A)_Z$ is the critical heat flux recommended in Ref. 10 which can be expressed by:

$$q/A)_Z = (\pi/24)\ h_{fg}\ [g\sigma(\rho_f - \rho_g)/\rho_g^{\,2}]^{1/4} \tag{4}$$

In this expression g is the acceleration of gravity, h_{fg} is the latent heat of vaporization, σ is the steam-water surface tension, ρ_f is the density of saturated water and ρ_g is the density of saturated steam.

For a pressure of 1.5 bars (21.8 psia), this expression results in a critical heat flux of 1.5 MW/m^2. Assuming that a typical IC has 100 tubes in the tube bundle and that the lower horizontal portion of 100 tubes is covered by a two-phase level, the heat transfer area would be 40.7 m^2 such that a design basis heat removal rate of 36.9 MW would produce a surface heat flux of 0.91 MW/m^2 which is well below the critical heat flux.

Therefore, since the average heat transfer rate is about one half of the critical heat flux, if the heat transfer should be degraded in the upper tubes of the bundle, the heat removal could be redistributed (increased) to the lower regions of the tube bundle. Specifically, the steam flow would continue to be imposed on the entire tube bundle but those tubes which are covered would increase their average heat transfer to compensate for the degraded heat transfer in the upper regions. A low collapsed water level is one mechanism that has been considered, perhaps because the water level decreased sufficiently below the top of the bundle to prevent the upper tubes from being covered.

While the heated horizontal bundle experiments were the central component of this investigation, an existing RELAP5 model of an Isolation Condenser with horizontal tube bundles was modified by to examine the relationship between the level swell and the decreasing collapsed water level. These modifications subdivided the IC shell and tube bundles in a manner that enables the study of thermal hydraulic behavior of the tube bundles as the shell collapsed water level approaches and then decreases into the tube bundle (see Figures 9 and 10 below).

The model was used to study the phenomena associated with a decreasing water inventory on the shell-side, particularly the gradual uncovering of the horizontal U-tube bundles. The key phenomena of interest here are:

1) The nominal operating void fractions in the horizontal tube bundles and the effect of water level reduction on these void fractions.

2) The redistribution of heat flux as upper level tubes lose heat transfer capability and steam penetrates further into the lower regions of the tube bundles on the primary side of the tubes.

3) The point at which natural convection driving head is affected by loss of subcooling of the condensate being returned to the reactor.

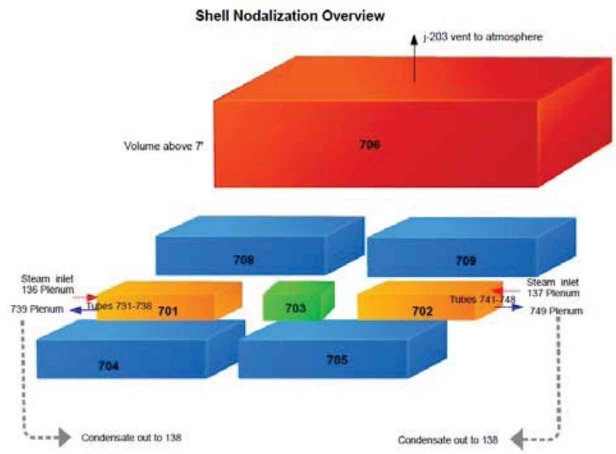

Figure 9. Nodalization of the IC Shell Side.

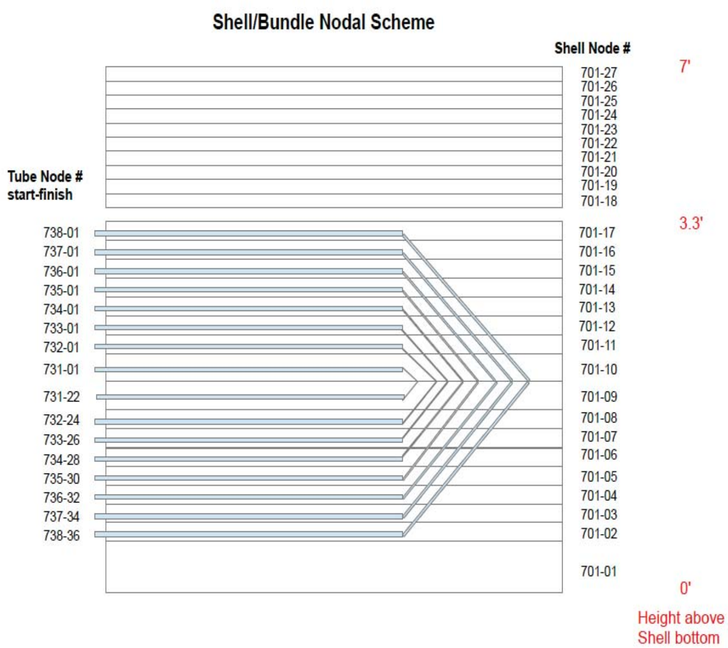

Figure 10. RELAP Nodalization of the Horizontal U-tubes in the IC

It should be noted that while the point at which heat transfer begins to be lost will be identified with this model, and should be relatively consistent with the churn turbulent level swell data presented earlier, some differences are to be expected. The RELAP model developed was not "tuned" to force consistency with churn turbulent data, since the principal use of the results of this study are the phenomena identified, such as the redistribution of the heat transfer within the tubes, and not the specific level at which heat transfer begins to degrade.

Revised Isolation Condenser Model

A modified treatment of the condenser shell and a much more detailed characterization of the heat exchangers were prepared for this study, including a detailed nodalization for the tube bundles and adjacent volumes, with each of the volumes modeled as a pipe volume.

Cross-flow Modeling Considerations

The cross-flow modeling was developed based on the geometry of the tube bundle to ensure that the flow entering and leaving the bundle is appropriately characterized. Horizontal tube bundles have several features that are relevant to the cross-flow modeling:

1) The tube support plates effectively block axial flow along the bundle. To address this, flow along the axis of the bundle is not credited due to these support plates.

2) The angle iron supports for the tube bundles adds blockage to lateral flow. To represent this, the connections between the tube bundles that have the cross-flow areas in the vicinity of the angle iron are set to very small values.

3) Flow from inside the bundle in the lateral direction will experience significant pressure drops traversing the tubes. This is also a factor in vertical flow through the bundle. The cross-flow junctions for the connections between the tube bundles and the adjacent volumes have areas based on the pitch ratio of the tubes. Loss coefficients applied to these junctions include a term for pressure drop from the center of the bundle to the edge plus a sudden expansion/contraction term. The vertical junctions also apply loss coefficients based on pressure drop across a staggered tube array.

Key observations obtained from this RELAP study are summarized in the following points.

1. The void fractions in the bundle remain nearly constant from the start of boiling at high water level conditions to the loss of heat transfer as the collapsed level falls below the mid-plane of the tube bundle. The only change observed is that the void fraction grows slightly with time as the static pressure supplied by the level decreases.

2. The heat transfer from the bundles causes a large steam generation rate that drives large scale circulation of the shell water inventory.

3. Heat transfer rates remain nearly constant until collapsed water level falls below the mid-plane of the bundle. Heat transfer rates decline as the higher elevation tubes enter saturated transition boiling heat transfer modes, but the rate of decline is mitigated by redistribution effects. The normal pattern in the tubes is steam condensation in the upper portion of the U-tube transitioning to single phase heat transfer further along the tube. As heat transfer degrades in the upper portions of the tube, steam condensation occurs in the lower portions of the tube. This has the effect of raising the void fractions in the lower bundle and causing level swell and rewetting of the upper tubes. Heat transfer rates in

this region are estimated to run from about 83% of full capability on falling below the mid-plane to approximately 71% at the 33% bundle height level.

4. Condenser performance does not decline significantly until the condensed steam sub-cooling begins to decline, causing a change in the natural circulation driving head and reducing the flow through the tubes.

As reflected by these observations, the redistribution of the heat transfer along the tubes with a decreasing collapsed water height has been confirmed by this RELAP analysis of a typical IC tube bundle.

5. CONCLUSIONS

The analytical and experimental investigations related to the potential for the water swell within horizontal tube bundles of an Isolation Condenser during a design basis heat load lead to the following conclusions.

1. The experimental technical basis for level swell conditions developed by Design Institute for Emergency Relief Systems (DIERS) show that the extent of level swell can be correlated as a function of the superficial vapor velocity (j_g) divided by the churn-turbulent bubble rise velocity (U_∞).

2. Experiments which poured a molten mixture of uranium dioxide and molybdenum at an estimated initial temperature of 3600 K, demonstrated the water level swell at high steam superficial velocities. This extent of level swell is in agreement with the asymptotic behavior of the correlation at these velocities. While the measured maximum steam superficial velocities for the three tests reported are somewhat higher than the maximum superficial velocities that would be anticipated in the IC horizontal tube bundles, both approach the asymptotic limit for the average pool void fraction, which is greater than 60%.

3. Heated bundle experiments reported in this paper investigated the performance of a horizontal, electrically heated (30 kW) bundle in a water pool. Three tests were conducted at full power and these all demonstrated a water level swell that is consistent with the DIERS experimental data base as well as the correlation that was developed from that data base. The level swell provided a water (surface) submergence that is sufficient to support nucleate boiling on the heater surfaces. If anything, the level swell experienced within the bundle is greater than that predicted by the correlation.

4. RELAP5 analyses of the IC tube bundles illustrate two important features related to the extended heat removal associated with condensing steam within the tubes. The first is that the level swell is predicted due to the fact that the pool must swell for the steam bubbles (void) to exit the water pool and this swell level determines the tube surface area for efficient heat transfer. The second feature is that any degradation of heat removal along the upper horizontal segment of the U tubes causes the redistribution of the heat removal process toward the lower horizontal legs of the condenser tubes. The RELAP5 calculations show that this enables the heat removal process to continue unabated until the collapsed water level decreases considerably below the mid-plane of the bundle.

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