Attachment

Downcomer Boiling

Introduction

Downcomer boiling is caused by metal heat release from vessel and core barrels walls to fluid in the downcomer gap. Metal heat from the vessel lower head and structures in the lower plenum also contribute to downcomer boiling. As heat is released to the downcomer fluid, its temperature is gradually increased and eventually subcooled and saturated boiling takes place. Voids generated by these processes displace water in the downcomer and reduce the driving head that forces water into the core during the reflood phase of a large break LOCA. This loss in head can significantly reduce the core flooding rate, and increase the peak cladding temperature.

Evaluation Models (EMs) based on Appendix K do not necessarily capture this phenomenon, since nodalization of the downcomer and modeling of subcooled boiling is simplified in those types of EMs. In some EMs, the downcomer is represented by one large volume node. This prohibits the code from calculating thermal stratification, which would allow the upper regions of the downcomer to reach saturation temperature much earlier in the transient than would occur if the entire volume had to be heated to that temperature. Likewise, subcooled boiling is also overly simplified or neglected in Appendix K based EMs. During subcooled boiling, bubbles can be generated along hot surfaces even though the bulk water temperature is below saturation temperature. Neglecting these voids during reflood overestimates the gravitational head in the downcomer, and underestimates clad temperatures.

Downcomer boiling was recognized as a process of moderate importance in the large break Phenomena Identification and Ranking Table (PIRT) produced as part of the Code Scaling, Applicability, and Uncertainty (CSAU) study performed for the NRC [1]. This was established before experimental information from the 2D/3D test programs was available and well before realistic code simulations were performed. Thus, it is not clear that this process would be assigned the same relative ranking given more recent information.

This report provides additional details on downcomer boiling phenomena. In the sections that follow, downcomer boiling is considered in three different ways. First, an analytical basis is presented that suggests that downcomer boiling will indeed occur along a time frame consistent with the duration typical of reflood for a large break LOCA. Second, calculations using so-called "Best Estimate" thermal-hydraulics codes are discussed and results demonstrating the downcomer boiling effect are presented. Finally, experimental findings from major test programs are reviewed and discussed.

Analytical Estimates

Since experimental data from large scale test facilities is limited, and realistic thermal-hydraulic codes such as TRAC, RELAP and COBRA/TRAC may not accurately model all processes important to downcomer boiling, it is useful to estimate when downcomer boiling might affect reflood based on a simple first principles calculation. Therefore, consider the conditions that occur in the downcomer for a hypothetical large break LOCA with the break located on one of the cold legs of a typical Westinghouse or CE/ABB PWR. During blowdown, the downcomer voids and remains empty until the end of ECC bypass. At the end of bypass and after a short refill period, the downcomer rapidly refills to the level of the cold legs with water from the accumulators. The bottom of the core quenches at this time (BOC), and the reflood period begins.

Stored heat in thick metal structures is released slowly due to the thickness of the structures, and wall-to-fluid heat transfer coefficients. The time necessary to raise a volume of fluid to saturation can be estimated by considering transient conduction from a thick metal slab representing the reactor vessel wall. Figure 1 shows the simplified geometry. The outer surface of the vessel is represented as a slab, and is assumed to be well insulated. Heat transfer from the core barrel is ignored. Nominal dimensions assumed for the downcomer gap L_{gap} and wall thickness L_w are $L_{gap} = L_w = 0.254$ m (10 inches).

To simplify the calculation assume that the vessel wall temperature does not change significantly during blowdown and refill, and that the initial downcomer water temperature is equal to the accumulator temperature. Thus, at the start of reflood the vessel wall and downcomer water temperatures are approximately $T_{W,i} = T_{cold} = 566$ K (559 F), and $T_{f,i} = T_{SI} = 322$ K (120 F). At 0.138 MPa (20 psia), the saturation temperature is 382 K (228 F).

For a slab of thickness $2L_w$, exposed to a sudden change in surface temperature on both surfaces the Biot number is,

$$Bi = \frac{hL_w}{k_w}$$

where k_w is the thermal conductivity of the slab. (Note that this is the same as one should use for a slab of thickness L_w with one of the surfaces insulated.) Assuming a thermal conductivity $k_w = 40$ W/m-K for carbon steel [2] and a wall to fluid heat transfer coefficient of $h = 1200$ W/m2-K, the Biot number for the vessel wall is $Bi = 7.6$. (The heat transfer coefficient corresponds to forced convection to liquid with a mean velocity of just under 0.2 m/s.) The high value of Bi indicates that the process is conduction limited.

The internal energy change of the vessel wall necessary to raise the entire downcomer volume of water to saturation can be estimated to be,

$$\frac{Q}{Q_0} = \frac{M_f c_{p,f}(T_{sat} - T_{SI})}{M_w c_{p,w}(T_i - T_{sat})} = \frac{\rho_f \pi (D_v - L_{gap}) L_{gap} H}{\rho_w \pi (D_v - L_w) L_w H} = 0.34$$

for a vessel with an internal diameter of 3.99 m (157 inches). In this expression M_f represents the downcomer fluid mass, and M_w the vessel wall metal mass.

Using Heisler charts such as Figure D.3 in Reference [2], the Fourier number, $Fo = \alpha_w t / L_w$, for this energy change is approximately, $Fo = 0.16$. The term α_w represents the wall thermal diffusivity. From these values of Bi and Fo, it can be shown that the temperature of the entire volume of initially cold downcomer water can be raised to saturation in approximately 575 seconds from vessel wall stored heat alone.

This estimate represents a crude upper bound on the time it should take for downcomer boiling to begin. Metal heat release from the core barrel wall and from structures in the lower plenum are ignored, and the estimation assumes that all of the downcomer fluid must be brought to saturation before boiling begins. In actuality, thermal stratification of downcomer fluid will occur allowing boiling to begin in the upper regions of the downcomer before the entire mass reaches saturation. Stored heat in the core barrel wall, neutron pads increase the rate at which the downcomer fluid is heated. Thus, it is reasonable to expect that downcomer boiling effects will be apparent in a transient within the first few hundred seconds.

Realistic Code Calculations

The issue of downcomer boiling was reported to the staff in by Westinghouse in two meetings, on June 28, 2000 [3] and March 27, 2001 [4]. Westinghouse that noted in their large break LOCA calculations using a realistic thermal-hydraulics code that a second reflood clad temperature maximum and the PCT frequently occurred after several hundred seconds. This second reflood peak was caused by voiding in the downcomer that occurred as fluid in the downcomer thermally stratified and approached saturation.

Examples of downcomer boiling and their impact of large break LOCA calculations using Best Estimate thermal-hydraulic codes are available in the public domain. Reference [5] documents a calculation for a 4-loop Westinghouse PWR where downcomer boiling initiates a secondary reflood temperature excursion and an increase in the peak cladding temperature. Figure 2 shows the peak cladding temperatures on the hot rod, and other representative rods in the core. Each rod shows three distinct peaks; a blowdown PCT which occurs a few seconds following the break (which occurs at 20 seconds in the figure), a first reflood PCT which occurs between 95 and 110 seconds for all but the rods on the core periphery, and a second reflood PCT which occurs at 288 seconds.

Figure 3 shows liquid and saturation temperatures at a location near the bottom of the downcomer. The liquid becomes saturated at approximately 180 seconds. Just before fluid near the bottom of the downcomer becomes saturated, the peak cladding temperature is seen to increase. This increase continues and the PCT for this case is reached at 288 seconds. Thus, this second reflood PCT, is a direct result of downcomer boiling and the loss in hydraulic head to force liquid into the core. Comparing the first and second reflood PCTs, from Figure 2 shows the increase in PCT as a result of downcomer boiling to be approximately 222 K (400 F). If downcomer boiling had not been accounted for, the PCT for this transient would have been the first reflood PCT. The PCT "penalty" due to downcomer boiling therefore is ΔPCT=+400 F.

The Watts Bar example is not unique to that particular unit or thermal-hydraulic code. Similar effects can be seen for a CE/ABB System 80+ unit in References [5] and [6]. In Reference 5, a recent version of RELAP5/MOD3 was used to make the simulations. Particularly significant in the sensitivity studies performed in Reference 5 was the PCT response following downcomer boiling. Figure 4 shows the average liquid level in the downcomer. (The three curves show in the figure are for different time step size limits. For discussion, the study using a maximum time step size to 0.002 seconds is used as the reference.) Downcomer boiling began at 150 seconds, and immediately afterward there was a significant decrease in the downcomer water level. The PCT response, shown in Figure 5, resulted an increase of approximately 450 K (810 F). Thus, for this case the downcomer boiling "penalty" is ΔPCT=+810 F. With regards to downcomer boiling, the study reached the following conclusions:

(a) To capture downcomer boiling, a two-dimensional representation of the downcomer is required. Conventional industry ECCS licensing models employing a single downcomer volume are considered inadequate since they preclude the potential for downcomer boiling.

(b) Results of the calculations show that considerable downcomer boiling takes place at about 200 seconds when the accumulators empty. This boiling persists, with decreasing intensity, until the core is eventually quenched by pumped flow injection. Quench times due to downcomer boiling are greatly extended, for example, to 1500 seconds into the event compared to 350 to 500 seconds for plants without downcomer boiling.

(c) PCTs may occur during very late reflood, exceeding the blowdown and early reflood peaks currently computed by industry. PCTs may even exceed the 10 CFR 50.46 limit of 2200 F, while the peak local oxidation is expected to also increase significantly due to the lengthy time periods when the top of the core remains at elevated temperatures.

It should be noted that the study specifically applies to a CE/ABB System 80+ PWR, none of which are in operation in the U.S. Thus, conclusion (c) should not be considered appropriate to other reactor designs. Overall however, the study in Reference 3 indicates that downcomer boiling has a significant impact on a large break LOCA transient and ignoring the process will result in an underprediction of the peak cladding temperature.

Reference 6 also simulated a CE System 80+ PWR. In that investigation, the WCOBRA/TRAC thermal-hydraulic code was used to make the simulations. Figures 6 and 7 are from that study. Downcomer boiling was predicted to begin before 200 seconds. After downcomer boiling began, a second reflood PCT was reached at 420 seconds. The net loss of downcomer inventory due to downcomer boiling is seen in Figure 7. From 150 to 250 seconds the collapsed liquid level decreases reaching a minimum slightly before the PCT occurs. In this case, the first reflood PCT at 82 seconds was 972 K (1290 F) and the second reflood PCT was 1007 K (1353 F). Thus, the downcomer boiling "penalty" was ΔPCT= 1007 - 972 = +35 K (+63 F). Compete core quench did not occur until 950 seconds.

The magnitude of the increase in PCT in Reference 6 is much smaller than that in Reference 7 because of the decay heat models used in the analysis. In Reference 6 the 1971 ANS decay heat standard with a 1.2 multiplier was used, while in Reference 7 the 1979 ANS decay heat standard was used. As a result, the overall temperatures were much higher in the Reference 6 simulations and the results were sensitive to metal-water reaction and other non-linearities that occur at temperatures above 1900 F.

Each of the calculations cited in this section demonstrate that downcomer boiling results in a second reflood PCT. The hydraulic head in the downcomer is significantly reduced when boiling occurs, and the second PCT is direct result of the reduction in core flooding rate. In each case discussed here, the second reflood PCT exceeded the first PCT. The magnitude of this difference can be significant, and will depend on the specific plant; its power and safety system, and on the code used to simulate the LOCA. The three cases cited show that prediction of downcomer boiling is not restricted to one particular thermal-hydraulic code, nor any one particular type of PWR.

Experimental Verification

Experimental verification of downcomer boiling is limited. Most reflood test facilities have been designed for low pressure operation. As a result, downcomer metal heat is non-conservatively scaled in most facilities. In facilities with sufficient downcomer metal heat, an increase in cladding temperatures and reduction in reflood rate is apparent. This section discusses experimental results in which the effects of downcomer boiling has been observed.

The effect of downcomer wall temperature on reflood was investigated in the Cylindrical Core Test Facility (CCTF). The CCTF is a 1/21.4 scale experimental facility representing a 1000 MWe pressurized water reactor (PWR). It has a full height core, with four primary loops and their components. Two experiments were conducted which provide a sensitivity relevant to downcomer boiling; Test C1-2 and C1-3. Test C1-2 was performed with the downcomer wall initially superheated. The initial temperature was 460 K to provide approximately 70 K initial superheating. Test C1-3 was performed with the downcomer wall initially at the saturation temperature of 388 K.

Figure 8 compares the downcomer void fractions, as evaluated from measured differential pressures at several elevations for these two tests. Since the flow rates in the downcomer are relatively low, the differential pressures are due to the static water head only. The test begins with the downcomer empty, and the void fraction is high everywhere. After emergency core cooling (ECC) injection the void fractions decrease, starting with the elevations near the bottom of the downcomer. Of most interest, are the void fraction comparisons higher in the downcomer. After 100 seconds, the void fractions for the saturated wall test decrease to lower values than those in the superheated wall test. This penalizes the core in two ways. First, as shown in Figure 9, the total static head in the downcomer is lower in the superheated wall test than in the saturated wall test, which reduced the core flooding rate. Second, as seen in Figure 10, the core inlet subcooling is less in the superheated wall test than in the saturated wall test, which decreases the core heat transfer.

The effect of downcomer boiling on the core in CCTF Tests C1-2 and C1-3 was a slight increase in the cladding temperatures, and an increase in the quench times. This is shown in Figure 11. The increase in PCT and quench times are small because of the relatively low initial core temperatures. Note in Figure 2, for an actual PWR, the clad temperatures following blowdown in the hot assembly are much higher than those in CCTF. The effects become magnified as the clad temperatures increase above 1900 F and metal-water reaction becomes important.

A detailed description of the CCTF tests and the observed downcomer effect is provided by Reference 7.

Another important evaluation concerning downcomer hydraulics during reflood was performed using data from the Upper Plenum Test Facility (UPTF) [8]. Tests in UPTF provided experimental data on the three-dimensional thermal-hydraulic behavior for a full scale PWR. The facility was used to conduct separate effects tests with cold leg injection for a simulated cold leg break to examine flows in the downcomer. The main objective of Test 25 was to investigate downcomer water level and ECC entrainment to the break due to circumferential steam flow from the intact loops. Conditions in the test were intended to represent those expected during the reflood period of a large break LOCA.

The test itself consisted of two major steady state phases, each with several subperiods in which the steam flow rate was varied. Phase A included four subperiods designed to address water level and entrainment with superheated downcomer walls. In Phase B, one of the subperiods was run with no wall superheat. (The other Phase B subperiods were designed to examine cold leg flow regimes.)

The evaluation of Test 25 data concluded that downcomer water level and hence the driving head available for core reflooding is affected by both ECC entrainment in the loop steam flow and by boiling on superheated downcomer walls. Figure 12 shows an estimation of the downcomer water level in a PWR. The report further concluded that assuming the downcomer remains completely filled to the bottom of the cold leg nozzles during reflood is a nonconservative assumption, but expected the increase in PCT due to downcomer boiling to be small based on a sensitivity using CCTF data.

Scaling Considerations

Neither the CCTF nor the UPTF experiments investigating the downcomer boiling effect are completely satisfactory. Both facilities were designed for maximum pressures typical of the refill and reflood phases of a large break LOCA, and because of that design limitation were not capable of initializing the downcomer with the superheat expected in a full scale PWR. As a result the downcomer boiling effect may be underestimated by the CCTF and UPTF data.

Figure 13, from Reference 8, compares the conduction-limited heat wall release for UPTF and a typical PWR. Note that the PWR heat release is significantly greater than that in UPTF due to the excess wall superheat available in the full scale plant. This can be expected to increase the voiding in the downcomer during reflood and reduce the flooding rate well beyond that estimated by the UPTF and CCTF data.

In order to quantify the differences between the CCTF and UPTF facilities and the PWR, a scaling ratio to indicate the potential for downcomer boiling to occur in a transient can be defined as the ratio of the energy available in the surrounding metal walls to the energy necessary to raise the downcomer water to saturation:

$$\frac{(Mc_p)_w \Delta T_{SH}}{(Mc_p)_f \Delta T_{sub}} = \frac{M_w c_{p,w}(T_i - T_{sat})}{M_f c_{p,f}(T_{sat} - T_{SI})} = \frac{\text{Energy available in DC metal}}{\text{Energy required to cause boiling}}$$

where, T_i = wall initial temperature, T_{sat} = saturation temperature corresponding to containment pressure during reflood, T_{SI} = temperature of accumulator / safety injection water.

For a typical PWR, the initial downcomer wall temperature = T_{cold}, and reflooding occurs at 20 approximately psia. So,

$$\left[\frac{(Mc_p)_w \Delta T_{SH}}{(Mc_p)_f \Delta T_{sub}}\right]_{PWR} \approx 3.7$$

For CCTF, using the maximum attainable test pressure, this value is,

$$\left[\frac{(Mc_p)_w \Delta T_{SH}}{(Mc_p)_f \Delta T_{sub}}\right]_{CCTF} \approx 1.0$$

For UPTF, using values for Test 25, this value is,

$$\left[\frac{(Mc_p)_w \Delta T_{SH}}{(Mc_p)_f \Delta T_{sub}}\right]_{UPTF} \approx 0.72$$

Thus, in the PWR there is significantly more energy available for downcomer boiling than there could have been in either CCTF or UPTF. The effect of downcomer boiling thus can be expected to be greater in a PWR than that in the experiments. Therefore, downcomer boiling is non-conservatively scaled in experiment relative to the PWR.

The only facilities that utilized an annular downcomer and were capable of initializing a downcomer walls with an appropriate amount of superheat were Semiscale and LOFT. Both facilities were part height. The Semiscale Mod-I facility was intentionally scaled to be a counterpart test to LOFT. Because the facilities were only part height, the transients took place faster than they would at full scale. Quench generally occurred within 100 seconds following the break.

As part of the Semiscale MOD1 program [9] however, several tests were conducted to investigate reflood for a large break LOCA. In those tests, a second reflood peak, similar to that predicted by realistic codes was observed. Figure 14 shows clad and fluid temperatures for Semiscale Mod-I test S-04-5L. The downcomer reached saturation at approximately 100 seconds in this experiment. As soon as the downcomer boiling occurred, the clad temperatures stopped decreasing, and began increasing again due to the loss of downcomer head. Quench was significantly delayed.

Conclusions

Downcomer boiling is a physical process that has the effect of increasing the peak cladding temperature in a large break LOCA. It has been observed in experiments, but due to poor scaling of the initial wall stored heat in reflood test facilities its effect on separate effects tests is significantly less than what it may be in a hypothetical large break in a PWR. The downcomer boiling effect is predicted to be significant by realistic codes such as WCOBRA/TRAC and RELAP. Both experimental and numerical studies have shown that neglecting downcomer boiling in a large LOCA is a nonconservative assumption.

The findings discussed in this report are not meant to imply that calculations made using Appendix K based Evaluation Models underestimate the peak cladding temperature (PCT) or equivalent clad reacted (ECR) in a large break LOCA. Appendix K requires the use of the 1971 ANS decay heat standard, which is known to be very conservative. Appendix K also requires several other conservative modeling assumptions. The conservatism associated with the 1971 decay heat model and these other Appendix K requirements sufficiently compensates for the downcomer boiling effect.

References

[1] Technical Program Group, "Quantifying Reactor Safety Margins, Application of Code Scaling Applicability, and Uncertainty Methodology to a Large Break Loss of Coolant Accident," NUREG/CR-5249, December 1989.

[2] Holman, J. R., Heat Transfer, McGraw Hill, 4th Ed., 1976.

[3] Memorandum from G. S. Shukla, Project Manager, Section 2, PDIV&D, to S. A. Richards, Director, PDIV&D, "Summary of March 27, 2001 Meeting with Westinghouse on Downcomer Boiling Modeling," April 16, 2001.

[4] Watts Bar Nuclear Plant Final Safety Analysis, UFSAR Amendment 2.

[5] Palazov, V. V., and Ward, L. W., "A System 80+ RELAP5/MOD3 Model for Downcomer Boiling Following a Large Break LOCA," ISL-NSAD-NRC-01-009, Jan. 2002.

[6] Pottorf, J., and Bajorek, S. M., "Large Break LOCA Safety Injection Sensitivity for a CE/ABB System 80+ PWR," Proc. of the 10th International Conference on Nuclear Engineering, ICONE10-22519, April 2002.

[7] MPR Associates, Inc., "Research Information Report on the Results of the Core I Test Series at the Japan Atomic Energy Research Institute Cylindrical Core Test Facility, " MPR-863, October 1985.

[8] MPR Associates, Inc., "Summary of Results From the UPTF Downcomer Separate Effects Tests, Comparison to Previous Scaled Tests, and Application to U. S. Pressurized Water Reactors, " MPR-1163, July 1990.

[9] Ball, L. J., Dietz, K. A., Hanson, D. J., and Olson, D. J., "Semiscale Program Description, NUREG/CR-0172, May 1978.

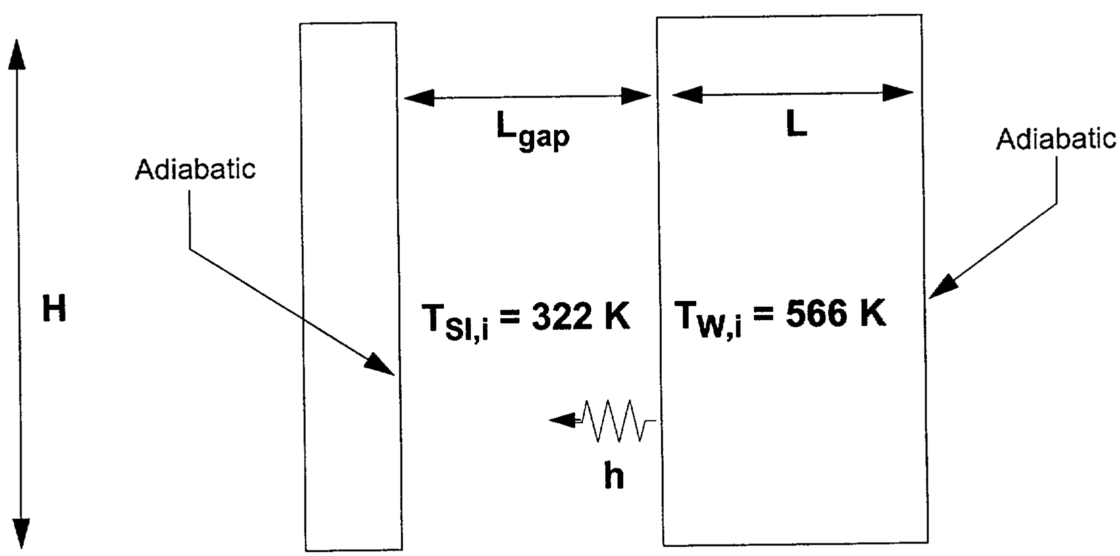

Figure 1. Transient Conduction in Vessel Wall.

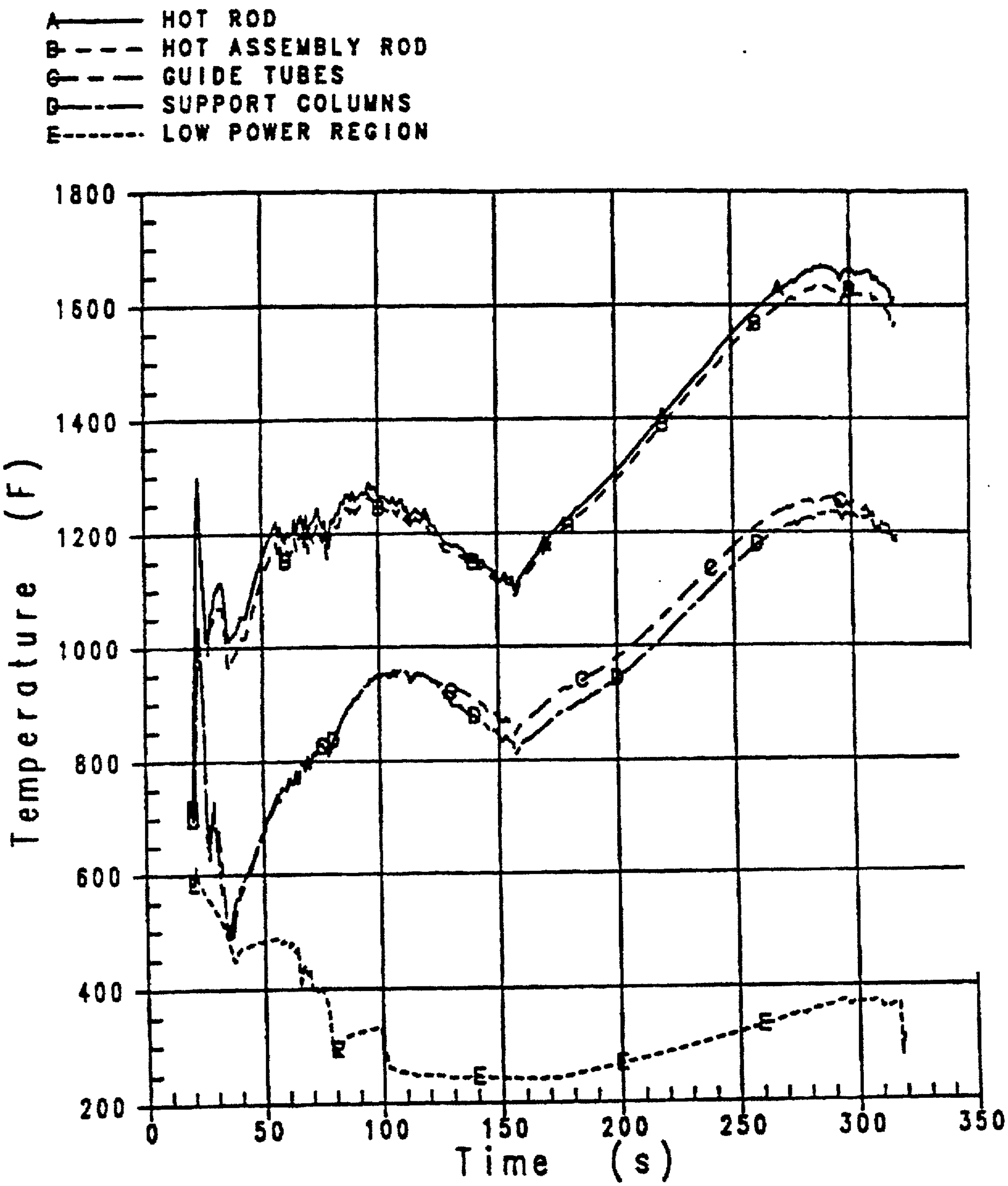

Figure 2. Watts Bar FSAR Peak Cladding Temperature (PCT) [4].

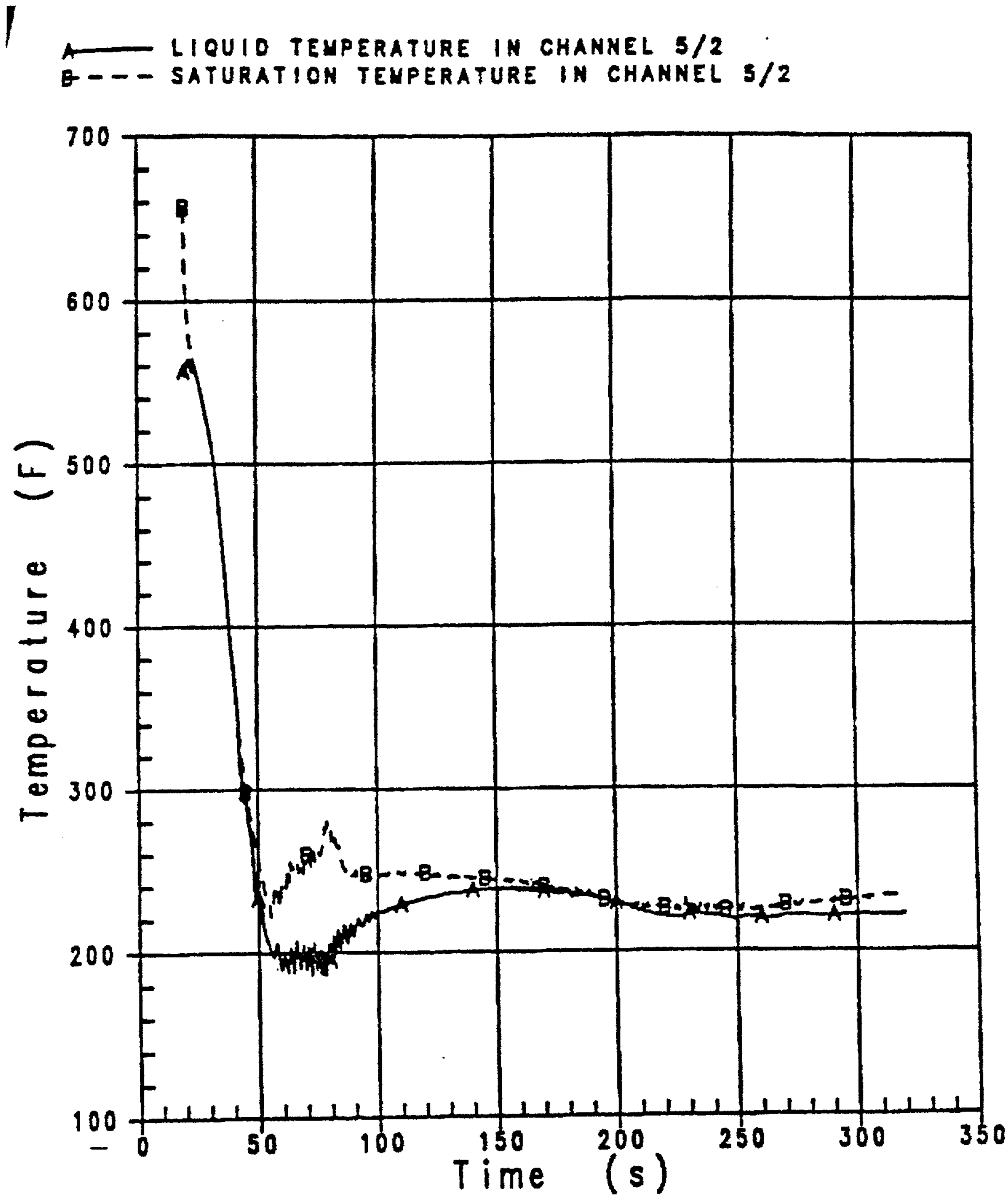

Figure 3. Watts Bar FSAR Downcomer Fluid Temperature and Saturation Temperature [4].

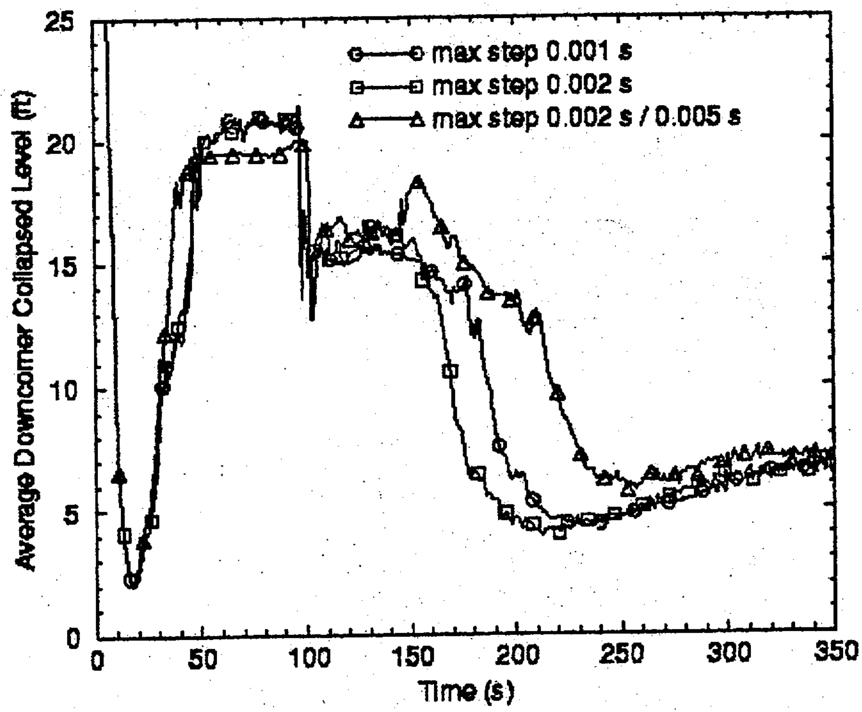

Figure 4. Predicted Downcomer Water Level for CE System 80+ PWR Using RELAP5/MOD3 [5]

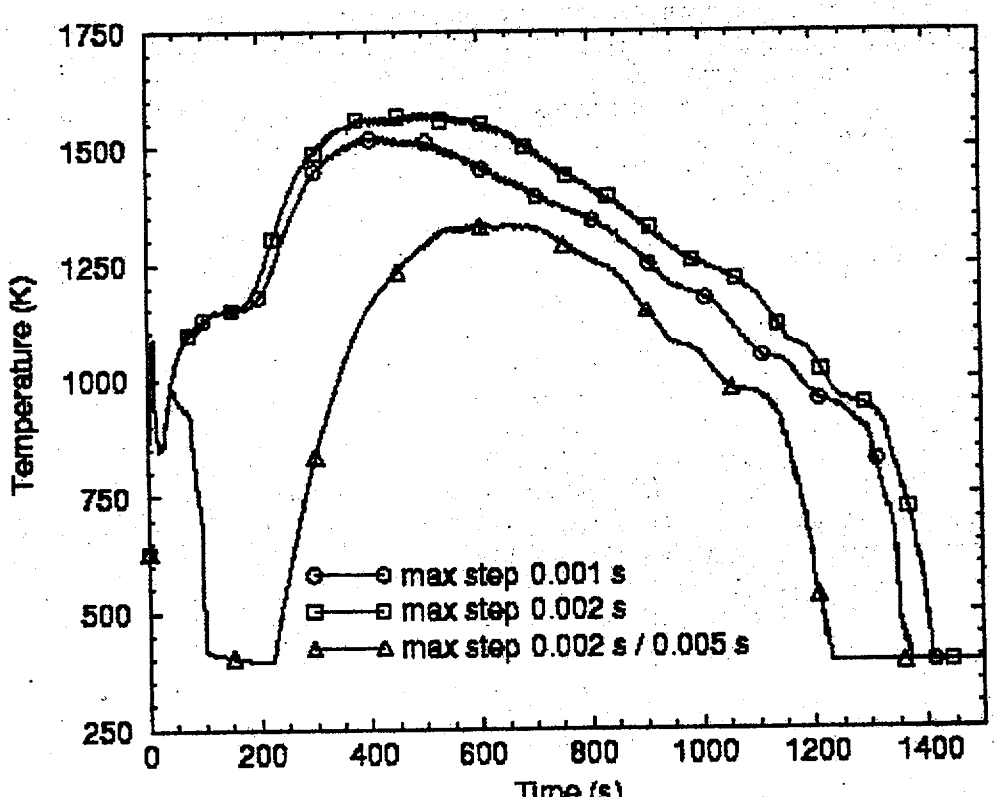

Figure 5. Predicted PCT Response for CE System 80+ PWR Using RELAP5/MOD3 [5].

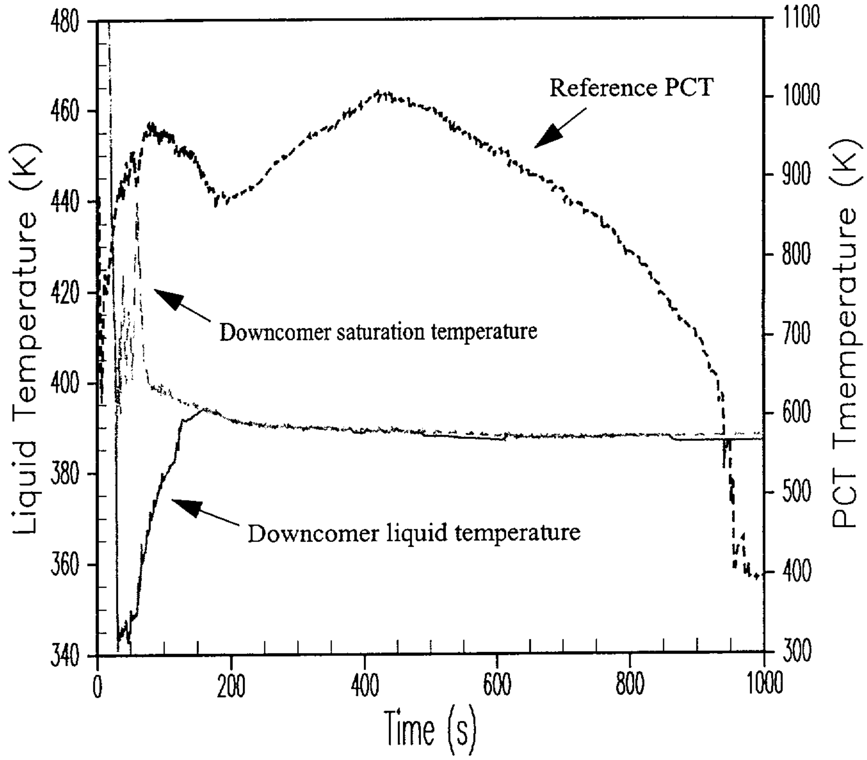

Figure 6. Downcomer liquid and saturation temperatures for CE System 80+ using WCOBRA/TRAC [6]. The downcomer fluid reaches saturation at approximately 160 seconds.

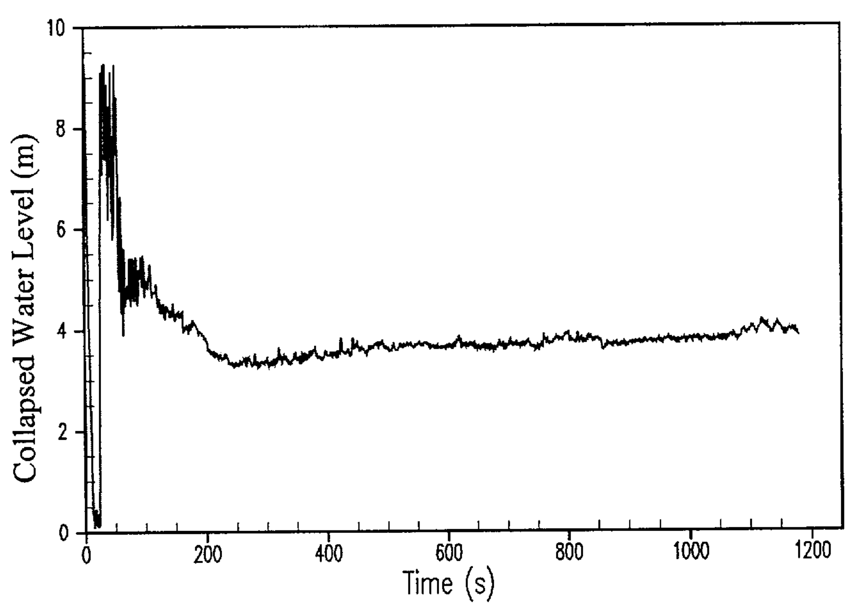

Figure 7. Downcomer collapsed liquid level for CE System 80+ using WCOBRA/TRAC [6].

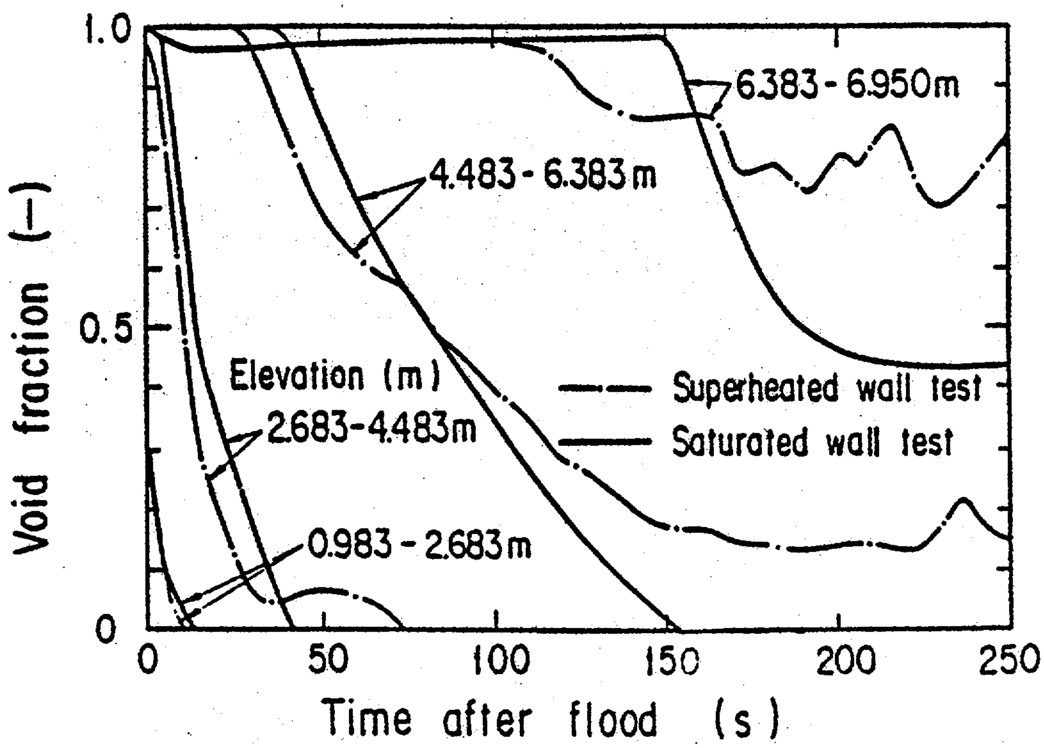

Figure 8. Effect of Downcomer Wall Temperature on Core Void Fraction [7].

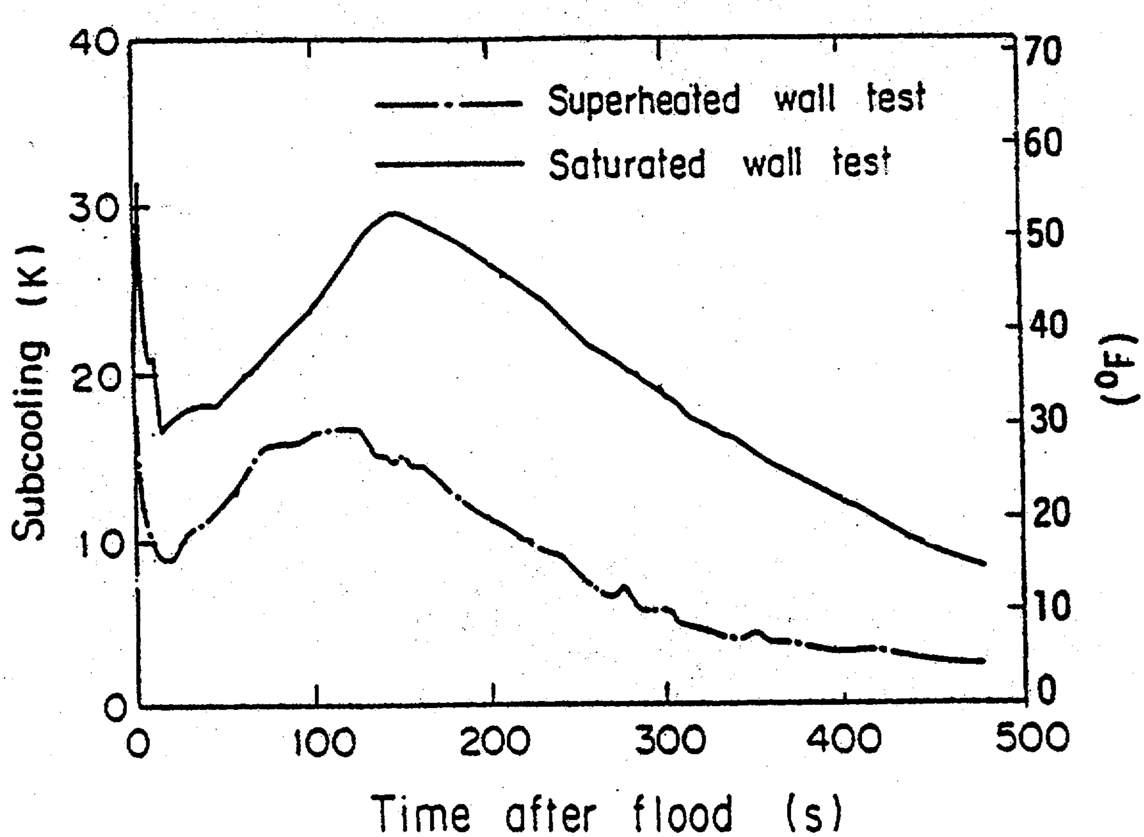

Figure 9. Comparison of Core Inlet Subcooling in CCTF Tests C1-2 and C1-3 [7].

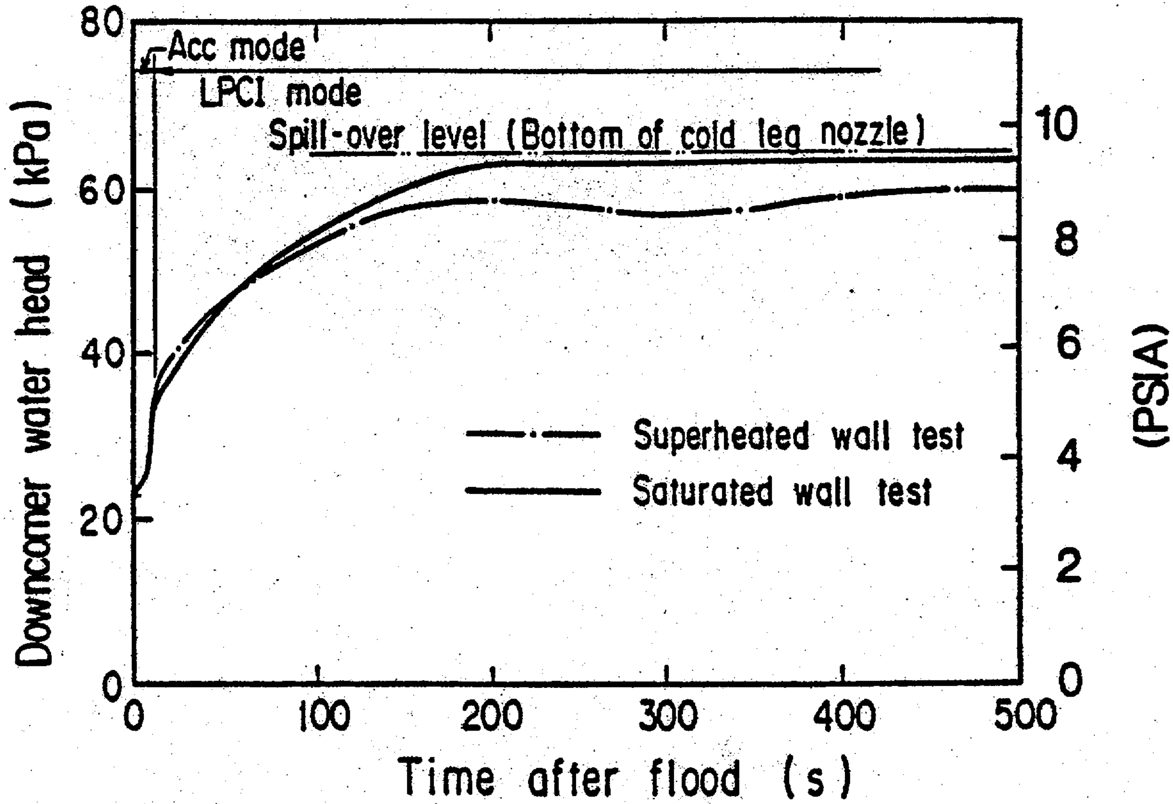

Figure 10. Comparison of Downcomer Water Head in CCTF Tests C1-2 and C1-3 [7].

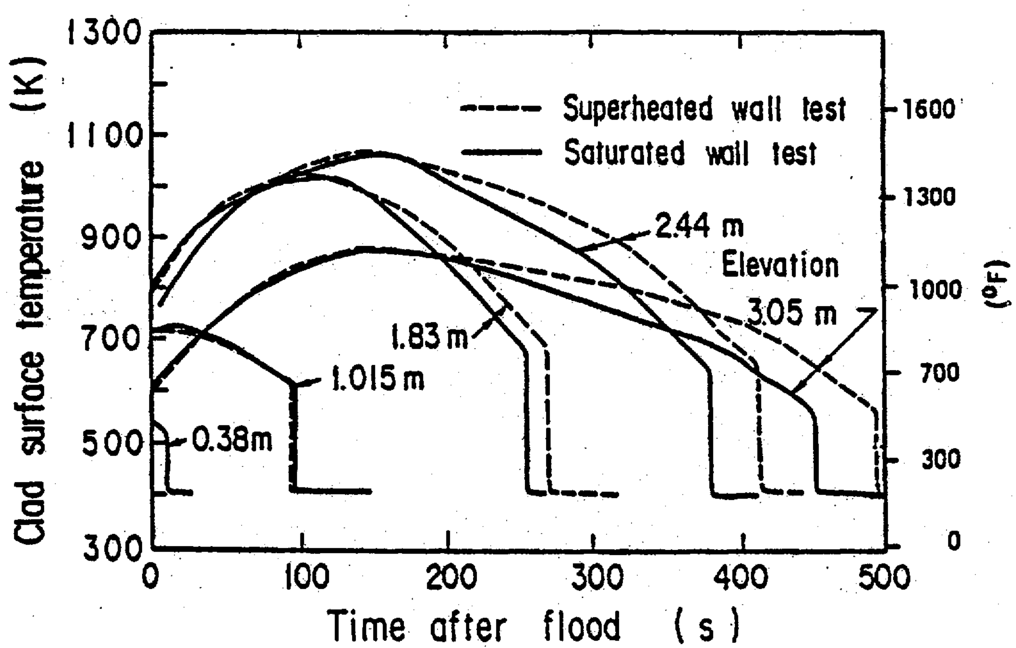

Figure 11. Comparison of Clad Temperatures in CCTF Tests C1-2 and C1-3 [7].

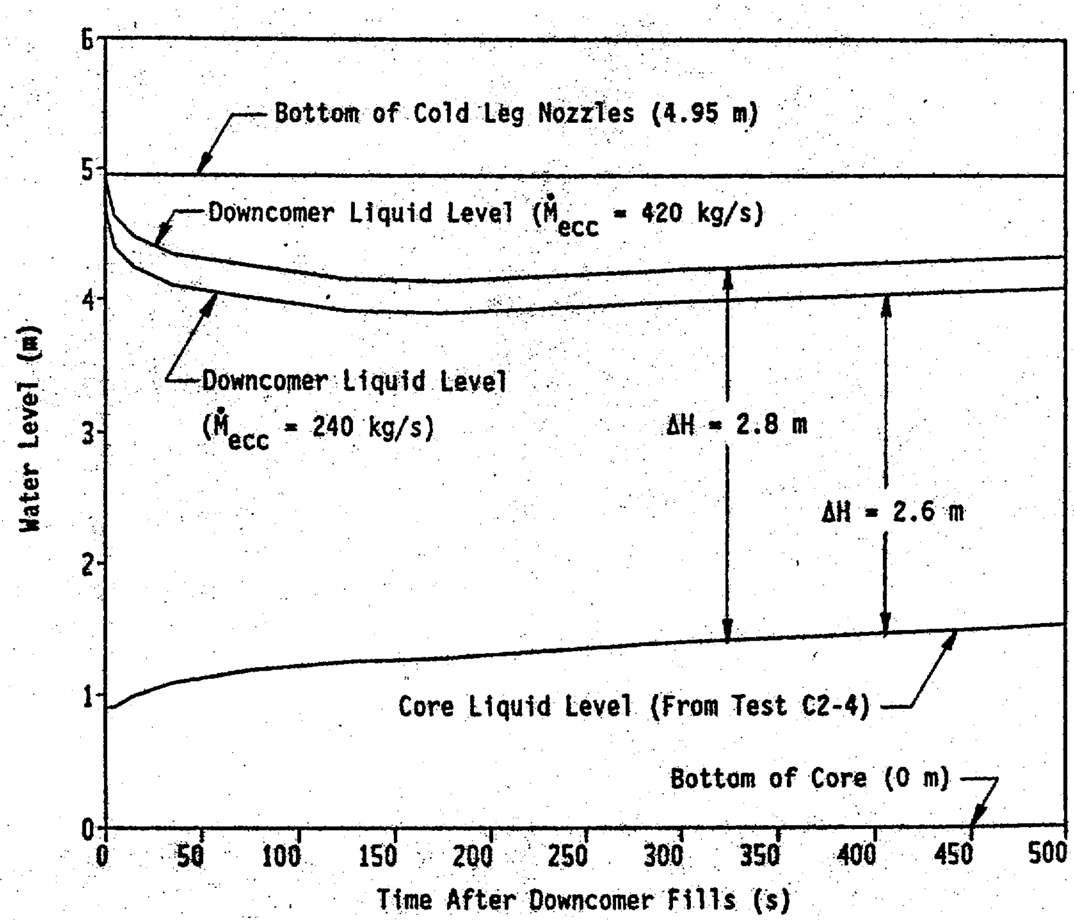

Figure 12. Estimated PWR Downcomer Water Level During Reflood [8].

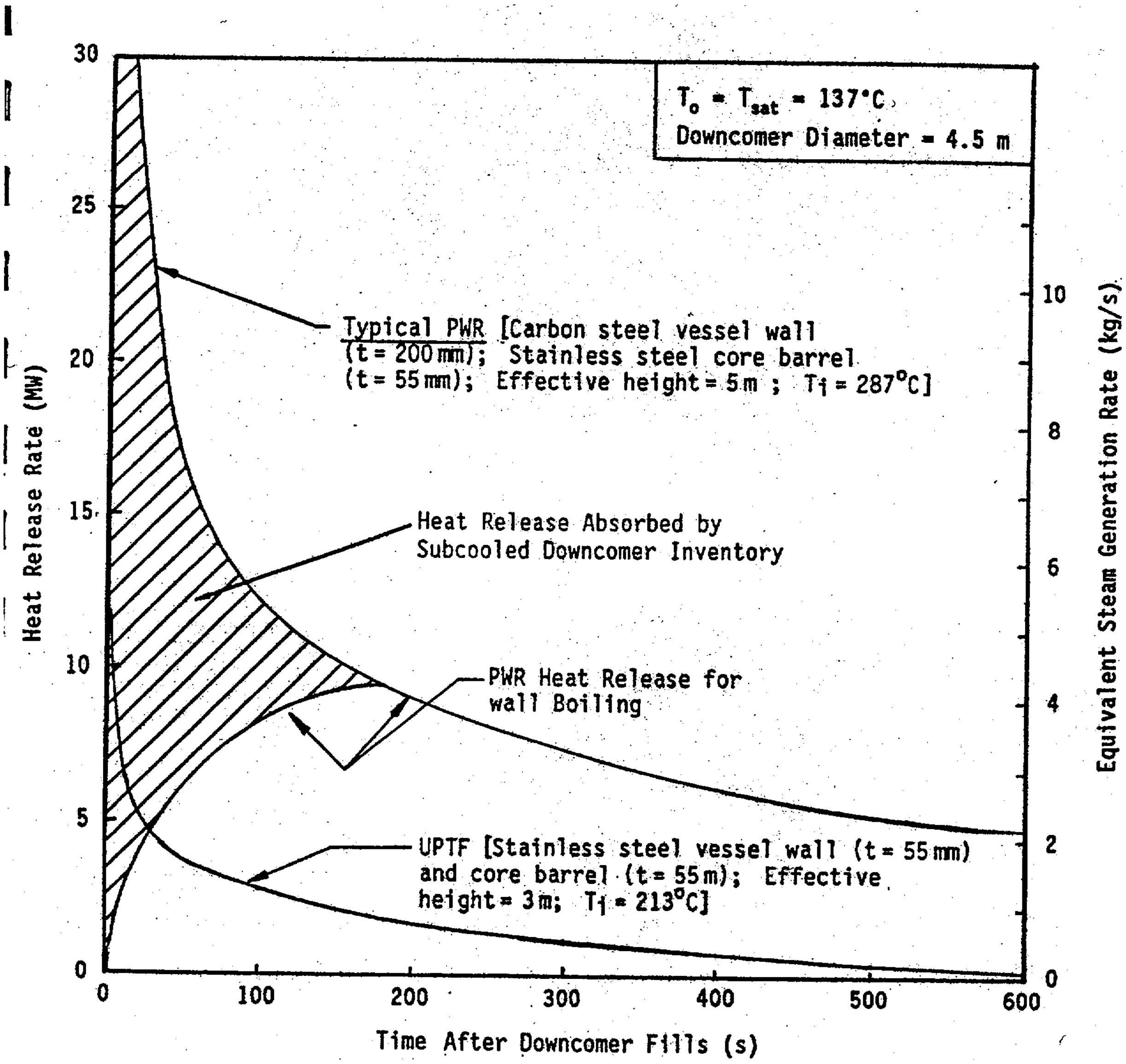

Figure 13. Conduction-Limited Wall Heat Release Rate in the Downcomer for UPTF and a Typical PWR [8].

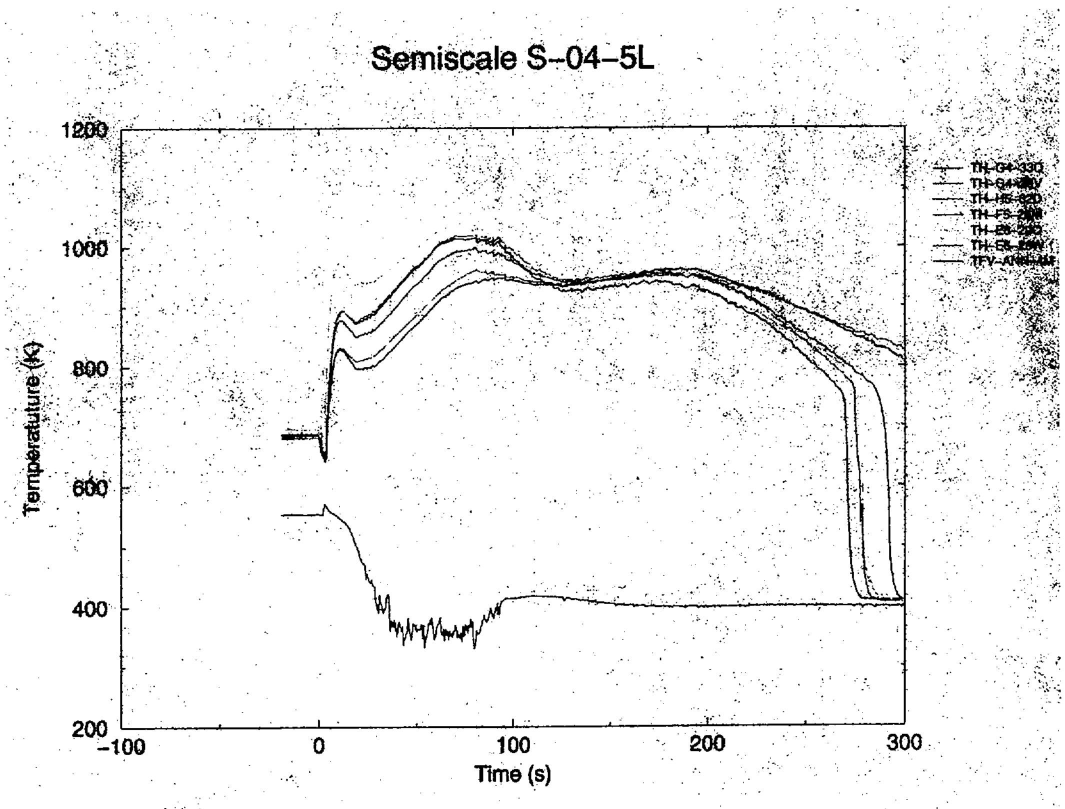

Figure 14. Clad temperatures in Semiscale Mod-I Test S-04-5L. The downcomer fluid reaches saturation at approximately 120 seconds.