Attachment 3

Return to Nucleate Boiling During Blowdown and Steam Cooling Restriction

Introduction

Reference 1 also identified several possible changes described in evaluation model requirements in 50.46 and Appendix K. Included are:

a. Deleting the requirement for reflood steam cooling only for small reflood rates in Appendix K.

and,

b. Deleting the prohibition on return to nucleate boiling during blowdown in Appendix K.

This section discusses the possible revision of these two requirements.

1. *Steam Cooling Only for Low Reflood Rate in PWRs* - Paragraph I.D.5.b. of Appendix K states that:

"During refill and during reflood when reflood rates are less than one inch per second, heat transfer calculations shall be based on the assumption that cooling is only by steam, and shall take into account any flow blockage calculated to occur as a result of cladding swelling and rupture as such blockage may affect both local steam cooling and heat transfer."

During the reflood phase of most reactor designs, the emergency core coolant is injected so that it passes through the downcomer and lower plenum and then up into the core. "Bottom reflood" of the core is the predominant mode of core recovery, and many experiments have been conducted to investigate the processes important in bottom reflooding.

Depending on the reflood rate, a number of different flow regimes may develop ahead of the quench front. Flow visualizations and measurements from several different test facilities have shown that a froth region exists above the quench front. Above the froth there is a region of dispersed droplet flow, and above this a region along the rod of steam only flow. In order to apply the proper heat transfer mechanisms when calculating heat transfer from the hot clad to the fluid, a detailed knowledge of the two-phase flow field must be known. The transition point between dispersed droplet flow and steam only flow depends on numerous processes; entrainment rate at the quench front, droplet size distribution, interfacial area and associated heat and mass transfer between the entrained droplets and the steam.

For most tests however, the steam only cooling period at any location in the bundle is short. Tests conducted at less than one inch per second as part of the FLECHT and FLECHT-SEASET programs confirmed high rates of carryover from the bundle. (See for example, Figure 6.2-11 of Reference 2.) These, along with other tests demonstrated the following [2]:

1. Bottom reflood progresses very quickly during the onset of reflood. However, the intense steam generation soon retards the overall progression of the quench front to a relatively uniform progression. Never the less, good core quenching rates are achieved even for flooding rates of one inch per second.

2. During reflood, the flow regime, cladding temperature rise and quench behavior is strongly dependent on the flooding rate.

3. The effect of bundle geometry on reflood heat transfer is minimal as long as generated power and stored energy per unit flow area is similar.

4. The flow regime ahead of the quench front is characterized by a froth region. An assumption of steam cooling heat transfer above the quench front for reflood rates is not appropriate.

Reference 2 contains a comprehensive summary of reflood test results and discussion on heat transfer in rod bundles. The test results do not support the assumption of steam cooling only for flooding rates below one inch per second. Thus, there is no firm basis to retain the steam cooling requirement in Appendix K. However, it should be noted that the effect of flooding on reflood thermal-hydraulic phenomena is a first-order effect. The higher the reflood rate, the larger the froth region, and the better the downstream heat transfer. At very low flow reflood rates, the heat transfer is poor and single phase convective heat transfer to steam can become the dominant mode of heat transfer. The measured peak clad temperatures, turn around times, and quench times increased significantly in tests with flooding rates less than two inches per second. (See Figure 6.4-6 of Reference 2.)

Modeling reflood heat transfer at low flooding rates is complex. Most of the closure relations in a thermal-hydraulic code will be fully exercised. For example, during the reflood process, fluid flow regimes from subcooled liquid to superheated vapor are encountered. Entrainment at the quench front must be modeled, and this modeling requires an accurate determination of the number and size of droplets produced. As a result, the equations of interfacial mass, momentum and energy and their flow regime dependent constitutive equations are used over a wide range of conditions. The uncertainty associated with this modeling is expected to be significant.

The requirements for steam cooling during low reflood rates are related to cladding swelling and rupture. It is not known how separating the linkage between flow blockage and steam cooling would affect the conservatism of Appendix K evaluation models. The effect is going to be dependent on the particular implementation of this requirement in each evaluation model.

2. *Prohibition on Return to Nucleate Boiling During Blowdown* - Paragraph I.C.4.e. in Appendix K prohibits the return to nucleate boiling heat transfer even if the fluid and surface conditions apparently justify the return.

One of the assumptions required as part of Appendix K is that once departure from nucleate boiling (DNB) or the critical heat flux (CHF) is calculated to occur during the blowdown phase, a return to nucleate boiling is not allowed until the reflood period begins. This process has been investigated in several experimental programs such as LOFT. LOFT was an integral test facility with nuclear rods. Results from the LOFT series of large break experiments showed that rod quench could occur during the blowdown period [3]. Early rewet was found to occur and remove a significant portion of the stored energy.

In LOFT however, the thermocouples were externally mounted. This increases the uncertainty in the blowdown results since it is possible that the externally mounted thermocouples may have prematurely quenched. Very few other tests have been conducted with prototypical fuel rod cladding under conditions expected during the blowdown phase of a large break LOCA. Such data is necessary to develop and quantify reliable correlations for blowdown rewet and the minimum film boiling temperature during blowdown. Thus, while rewet during blowdown is expected and supported by experimental data in LOFT, there is no simple method for allowing deletion of the requirement for no return to nucleate boiling during blowdown.

Conclusions

Based on this review of information, two conclusions are reached:

(1) Delete the requirement for only reflood steam cooling for reflood rates less than one inch per second in a new, optional Appendix K. This is supported by a large quantity of reflood test data that is applicable to a wide range of rod bundle designs.

(2) Retain the prohibition on return to nucleate boiling during blowdown in a new, optional Appendix K. While existing experimental information shows rewet during blowdown, the relatively small data base for blowdown quench make elimination of this requirement difficult.

References

[1] USNRC, "Status Report on Study of Risk-Informed Changes to the Technical Requirements of 10 CFR Part 50 (Option 3) and Recommendations on Risk-Informed Changes to 10 CFR 50.46 (ECCS Acceptance Criteria)," SECY-01-0133, July 23, 2001.

[2] USNRC, "Compendium of ECCS Research for Realistic LOCA Analysis," NUREG-1230, Dec. 1988.

[3] McCormick-Barger, M., "Experiment Data Report for LOFT Power Ascension Test L2-2, NUREG/CR-0492, TREE-1322, EG&G Idaho, Inc., Feb. 1979.