Attachment 4
Appendix K Non-Conservatisms

Introduction

The Office of Nuclear Regulatory Research (RES) has investigated several models and correlations required by Appendix K of 10CFR 50.46 in support of Risk Informed Regulation. As part of those efforts, the staff stated in SECY-01-0133 that potential non-conservatisms related to Appendix K would be considered. "Non-conservatisms" refer to those physical processes and modeling features that are not Appendix K requirements, and may result in lower peak cladding temperatures (PCT) or equivalent clad reacted (ECR) than would be realistically expected in a loss of coolant accident (LOCA). The staff is considering rulemaking revisions that would replace the 1971 Decay Heat Standard by a more realistic decay heat standard. Other models, including the Baker-Just correlation for metal-water heat release, steam cooling for reflood rate below 1-inch per second, and the prohibition on return to nucleate boiling during blowdown are also being considered for revision. In each of these cases, the revision will result in a reduction in the existing conservatism in Appendix K. Thus, the non-conservatisms assume greater importance in Appendix K based Evaluation Models (EM) for LOCA analysis if not otherwise accounted for or if the existing conservatism associated with Appendix K is reduced.

RES has reviewed information made available to the staff by vendors, produced as part of previous rulemakings, and obtained through several experimental research programs. Non-conservatisms are discussed and recommendations and guidance are provided on how these non-conservatisms should be incorporated into existing and future regulatory decisions concerning revision of Appendix K and 10 CFR 50.46.

Sources of Non-Conservatisms

Non-conservatisms in Appendix K can be attributed to one of three different sources:

1. Thermal-hydraulic processes and fuel behavior that have been observed in experimental programs since 1973: Since the original rulemaking, many experimental programs have been conducted to gain a better understanding of nuclear reactor thermal-hydraulics. With this improved understanding, physical processes not recognized, or considered important in 1973 are now found to play an important role in large and small break LOCAs.

2. Large code uncertainties: Uncertainties in predicting the PCT and ECR exist because of simplifications that are made in representing some physical processes, nodalization and numerical methods used by a computer code, and models and correlations that are applied outside of their original database. Additional uncertainties exist due to variations in plant operating conditions. Because of these uncertainties, there is the possibility that the 10CFR 50.46 limits can be exceeded. This was a topic of concern described by the staff in 1986 in SECY-86-318, ("Revision of the ECCS Rule Contained in Appendix K and Section 50.46 of 10 CFR Part 50) which recommended that the Appendix K decay heat guidelines not be relaxed unless model uncertainties were accounted for.

3. Specific models required by Appendix K may themselves be non-conservative. It is possible that models specified by Appendix K are non-conservative for some applications. An example is the Dougal-Rohsenow correlation for post critical heat flux heat transfer, which was found after the original rulemaking to be over-predict heat transfer. This was corrected as part of the 1988 rulemaking. There are numerous other models specified by Appendix K for use in LOCA analy-

sis. Few have been sufficiently assessed so that their assumed conservatism for LOCA thermal-hydraulic conditions has been quantified. Currently, none of the Appendix K specified models are suspected as being non-conservative. It should be noted however, that very few of the models and correlations specified by Appendix K have been rigorously assessed so as to demonstrate conservatism.

The recent RES review of 10 CFR50.46 and Appendix K concludes that there are three major issues that require careful consideration as Appendix K conservatisms are removed as part of new rulemaking. These are downcomer hydraulics, fuel relocation, and the overall uncertainty associated with LOCA Evaluation Models. A discussion on each issue follows.

A. Downcomer Hydraulics

Downcomer hydraulics refers to two processes that were not anticipated in the original 1973 Rulemaking, nor recognized at the time of the 1988 Appendix K revision. The first process is downcomer boiling, which are the processes of subcooled and saturated boiling that may occur as fluid in the downcomer is brought to saturation by heat released by the core barrel, reactor vessel walls, and lower plenum metal. The second process is reflood downcomer bypass, which refers to the entrainment and carry-over of downcomer fluid to the break by steam that flows circumferentially around the downcomer from the intact cold legs. During the initial part of reflood, the downcomer water level is at an elevation near the bottom of the cold legs. Thus, high velocity steam entraining droplets from this stratified interface will occur, decreasing the downcomer level. Both of these processes are relatively "new". That is, the neither process was recognized as potential non-conservatisms until the early 1990's. Their effects can be observed in experimental data as well as in recent calculations with realistic thermal-hydraulic codes.

Downcomer Boiling

The issue of downcomer boiling was first reported to the staff by Westinghouse through a series of meetings and exchange of information [1-3]. Large break LOCA calculations performed using a realistic thermal-hydraulics code showed that a second reflood clad temperature rise and the PCT frequently occurred after downcomer boiling took place. This secondary reflood temperature rise was attributed to a loss in gravitational head in the downcomer due to the voids that were generated when boiling began. This loss in head significantly reduced the flooding rate, and allowed a prolonged secondary heatup to take place. Evaluation Models based on Appendix K do not necessarily capture this phenomenon, since modeling of the downcomer and subcooled boiling may be overly simplified in those types of codes.

It is instructive to note the reasons why downcomer boiling has only recently been observed and become a concern in large break LOCA analysis. Stored heat in thick metal structures is released slowly due to the thickness of the structures, and wall-to-fluid convective heat transfer coefficients. In a short reflood transient, one in which the core is quickly quenched, the downcomer fluid may not have sufficient time to reach its saturation temperature. As plants uprate in power however, large break transients necessarily become longer due to the increased decay heat that must be removed. This allows sufficient time for the fluid temperature to increase to saturation and boiling in the downcomer begins while the core still has considerable energy. Thus, the downcomer boiling process is dependent on the length of the transient. For long transients, boiling and voiding in the lower plenum during reflood may also become important.

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 [4] 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 of roughly 222 K (400 F). Similar impacts can be seen for a CE/ABB System 80+ unit in References [5] and [6]. An important point, is that prediction of downcomer boiling is not restricted to one particular thermal-hydraulic code, nor any one particular type of PWR.

Experimental verification of downcomer boiling is limited. There are few tests that show an effect of downcomer boiling on reflooding rate or peak cladding temperature. This is because most reflood test facilities have been designed for low pressure operation and the initial stored metal heat in the test facilities is much less than that in a full scale PWR. As a result, downcomer metal heat is non-conservatively scaled in most facilities, and the effect on reflood rate or PCT is not observed in the tests. In the few facilities with sufficient downcomer metal heat, an increase in cladding temperatures and reduction in reflood rate is apparent. Reference [7] provides a summary of downcomer boiling observed in experimental tests, and associated scaling issues.

Currently, there are no specific criteria in Appendix K that require downcomer boiling to be included as part of an Evaluation Model for loss of coolant accident analysis. Section A, Item 6 of Appendix K requires only that metal heat be accounted for. It does not provide guidance on the level of detail necessary to model subcooled and saturated boiling in a downcomer, and thus potentially allows an inaccurate and non-conservative modeling of these complex processes.

Reflood Downcomer Bypass

Emergency core cooling (ECC) bypass refers to process by which water in the downcomer is swept around the annulus to the broken loop. Typically, this process is of concern during the blowdown and refill periods of a large break LOCA, when steam velocities are high and in counterflow to the ECC in the downcomer. During the reflood period ECC bypass has also been found to occur, although the physical processes involved are different than those in the blowdown and refill periods. Reflood downcomer bypass refers to the entrainment and sweep out of water from the top of the downcomer. The water is entrained by steam flowing from the intact loops across the top of the downcomer liquid. ECC liquid injected to the intact cold legs may also become entrained in the steam, but can also condense part of the steam flow reducing its effectiveness to entrain flow in the downcomer.

Experimental verification of reflood bypass can be seen in the results of UPTF Tests 2 and 25, and CCTF Tests C2-4 and C2-9. These tests showed a strong relation between downcomer water level and ECC entrainment. High rates of entrainment and ECC bypass during reflood were observed when the water level in the downcomer approached the bottom of the cold legs. The tests also confirmed significant core - downcomer level oscillations, which helped contribute to ECC bypass. The entrainment of downcomer water reduces the driving head for core reflood, similar to the downcomer boiling effect. The effect of reflood downcomer bypass was concluded to be non-conservative in Reference 8, although the impact on PCT was not expected to be large. In a later study [9] however, it was concluded that the UPTF and CCTF experimental tests under predicted the effect in a PWR, and thus a larger increase in PCT due to reflood downcomer bypass was possible. Therefore, reflood downcomer bypass is considered a non-conservatism not appropriately accounted for in Appendix K.

B. Fuel Relocation

Fuel relocation refers to the movement of fuel pellet fragments into regions of the fuel rod where the cladding has ballooned during a LOCA transient. This relocation of fuel causes a local increase in the linear power density (kW/ft) in the ballooned region.and higher cladding temperatures compared to cases where the fuel does not relocate. The fuel relocation issue has been previously considered by the staff as Generic Issue 92 (GI-92), "Fuel Crumbling During LOCA."

Several experimental investigations using irradiated fuel rods have documented the existence of fuel relocation under LOCA conditions. These include the PBF-LOC tests [10, 11] in the U.S., the FR2 tests [12] in Germany, and the FLASH5 [13] test in France. In each of these tests, fuel relocation occurred with pellet fragments from upper locations falling into the ballooned region of burst cladding. As reported in recent work by IPSN [14], the fuel relocation phenomenon is not restricted to high burnup fuel, as some data indicated fuel relocation could occur at burnups as low as 48 GWd/t.

The original resolution to GI-92 [15] concluded that fuel relocation was a non-conservatism not appropriately accounted for by Appendix K, but that the estimated effect on large break LOCA peak cladding temperature of +46 F was bounded by other analysis conservatisms [16]. The issue of fuel relocation during a LOCA however, remains a topic of concern in Europe, and test programs in both the U. S. and abroad are attempting to obtain new experimental data to quantify the effect. More recent information however [14, 17] suggests that the fuel relocation effect on PCT may be significantly larger than that assumed in GI-92. Fuel relocation during LOCA therefore, should be considered an Appendix K non-conservatism with at least a +46 F impact on PCT until new data is available to help quantify the effect.

Currently, the Office of Nuclear Regulatory Research is pursuing resolution of the issue through participation in an experimental program to be conducted in the 2003-2004 timeframe. Because the issue is old, and the experimental results sould be available in the near future, GI-92 has not been re-prioritized. With the new experimental information, it should be possible to better quantify the effect of fuel relocation.

C. Code and Evaluation Model Uncertainty

The purpose of determining the uncertainties associated with a safety analysis is to provide assurance that for a postulated accident the applicable limits specified by 50.46(b) are not exceeded. In developing the original ECCS rule, it was clear that uncertainties and the retention of sufficient conservatism in the rule were considered important. As quoted from the Commission Opinion [18] on the ECCS Rule (12/28/73),

"The Commission realizes that the knowledge in regard to a number of facets of the analysis of a loss of coolant accident is imprecise; it is partly for this reason that there is an on-going Water Reactor Research Program. The Commission is confident, however, that the criteria and evaluation models set forth here are more than sufficient to compensate for remaining uncertainties in the models or in the data.

Continuing research and development will provide a more extensive data base for such items as heat transfer coefficients during blowdown and spray and reflood cooling, oxidation rates for zirconium, fission product decay heat, steam-coolant interaction, oscillatory reflood flows, fuel densification, pump modeling and flow blockage. With the additional data it may become practical to *assign a statistically meaningful measure of precision to the calculation. It is probable that, with a better data base, some relaxation can be made in some of the required features of the evaluation models. However, the Commission believes that any future relaxation of the regulations should retain a margin of safety above and beyond allowances for statistical error."*

While the Commission Opinion is primarily concerned with sufficient conservatism, it is clear that the Commission's intent was to bound the "statistical error" associated with the analysis methods. This was also a main concern of the staff in SECY-86-318 [19], which recommended that the Appendix K decay heat guidelines not be revised unless model uncertainties were accounted for.

Appendix K to 10 CFR 50 currently includes requirements such as the use of the ANS 1971 Decay Heat Standard for decay heat plus 20 percent, use of the Moody break flow model, assumption of the worst single failure, etc. In addition, Appendix K identifies other analysis models such as use of the modified Baroczy correlation for two-phase pressure friction multipliers, as "acceptable." There is no assurance that the models identified as acceptable in Appendix K are necessarily conservative for all of the plant designs or accident scenarios to which they may be applied. The selection and implementation of these acceptable models and correlations, along with other unspecified models, are determined by the applicant. As noted in Reference 20, the models and correlations contained in thermal-hydraulic codes for LOCA have numerous simplifying assumptions and questionable assumptions in their implementation. Thus, there is no guarantee that the models identified as acceptable in Appendix K have sufficient conservatism to compensate for recognized or unanticipated non-conservatisms such as downcomer boiling or fuel relocation if the 1971 ANS Decay Heat Standard were replaced with a more realistic estimate of decay heat.

It is useful to make a distinction between "code uncertainty," and "overall calculational uncertainty." The code uncertainty refers to the limit of accuracy that a thermal-hydraulic computer code can calculate the value of a specific parameter such as the peak cladding temperature (PCT) or the equivalent cladding reacted (ECR) given a set of initial and boundary conditions. The code uncertainty is due to performance of the models and correlations that are part of the thermal-hydraulic computer code, in addition to uncertainties associated with numerical methods. The overall calculational uncertainty represents the sum total of the code uncertainty plus other sources of uncertainty that may affect the results. These include factors such as the fuel behavior, power distribution, break size and location, equipment availability, pump and valve performance, and plant initial temperature distribution. It also includes uncertainty associated with the experimental data used in the code assessment process. When possible, these uncertainty sources are often conservatively bounded in a safety analysis. The "statistical error" discussed in the Commission Opinion is interpreted to be the "overall calculational uncertainty" in this attachment.

Since the 1988 rulemaking change, new information has been made available to the staff concerning both code and overall calculational uncertainties. First, three different vendors have presented to the staff statistically based methodologies using Best Estimate thermal-hydraulic codes. In each case, the uncertainties derived by comparing the predicted 95th percentile PCT to the 50th percentile PCT exceeds 300 F [21, 22, 23]. These relatively large values are due to the numerous models and correlations that are incorporated into a thermal-hydraulic code, and to the uncertainties associated with those individual models. It is important to realize that while Appendix K is prescriptive, there are many models and correlations that are "ad hoc" and have relatively poor agreement with experimental data, or are overly simplified. As noted by the ACRS

[20], *"The science of multiphase flow and heat transfer has not reached a point where predictions can be made soley from a basis of secure fundamentals (as they can for many viscous single-phase flows, for example). Codes have evolved as an elaborate tapestry of interwoven working assumptions and approximate equations and correlations that have proved to be useful. Longevity of these engineering methods is no assurance of maturity, nor does it guarantee that the codes need no further development and improvement as new questions arise."*

The staff has performed its own calculations using a recent version of RELAP to investigate code stability and uncertainty. Of particular interest is the effect of the exponentially increasing heat generation rate due the metal-water reaction no matter what model was used. For example, in one case using the Cathcart-Pawel correlation, a peak cladding temperature of 2550^{o}F at an initial power of 1.0665 times the nominal power was obtained. When the power was increased in the fourth decimal place to 1.0670, the cladding temperature increased to the melting temperature. This is very typical behavior for all codes and shows the importance of predicting a peak cladding temperature with a high degree of confidence.

An Appendix K based Evaluation Model can be expected to have an overall calculational uncertainty at least as large as those reported to the staff using realistic codes, since the thermal-hydraulic codes used in such EMs are significantly less sophisticated. The magnitude of realistic code uncertainty is approximately equal to the reduction in PCT expected if the decay heat were reduced in a large break LOCA calculation [24]. Thus, the 1971 ANS Decay Heat Standard currently compensates for other models that have a high uncertainty. With a reduction in Appendix K conservatism by replacing conservative models with more realistic ones, there is the possibility that the revised Appendix K would produce lower peak cladding temperatures than a best estimate thermal-hydraulics code for the same set of boundary and initial conditions. Indeed, the staff has already been presented with information showing that an Appendix K Evaluation Model with a realistic estimate of decay heat predicts <u>lower</u> clad temperatures than a nominal best estimate calculation without uncertainty [25]. This is a clear demonstration that Appendix K Evaluation Models have significant inaccuracies, and that conservatism in the 1971 decay heat standard compensates for other code shortcomings.

Second, the development of the Code, Scaling, Uncertainty, and Applicability (CSAU) [26] methodology concluded that both code and overall uncertainties vary in magnitude as a function of time. It was demonstrated that uncertainties propagate from initiation to the end of the transient. Uncertainties that are small for one scenario, may become very large in a different scenario or if the transient length becomes significant. The implication of this is important, as the staff considers power uprates and small break LOCA analysis. As plants uprate in power, transients can become longer due to the higher rate of decay heat. In a small LOCA, transients can be several thousands of seconds in duration even at current power levels. This leads to the possibility that models and correlations with small uncertainties can have a very large effect on PCT for a long transient when this uncertainty is propagated. Thus, a simple estimate of code uncertainty is not appropriate, and can be non-conservative if applied without regard to transient length.

Therefore, as Appendix K based Evaluation Models are made more realistic by replacing selected models and correlations, it is important to determine the overall uncertainty and incorporate the uncertainties so that they are functions of time.

D. Conclusions and Recommendations

A significant amount of research has been performed since approval of the original ECCS rule. This research enables significant improvement in the predictive capability of hypothesized accidents in nuclear power plants. In several cases, it is now possible to replace correlations prescribed by Appendix K with correlations that are significantly more accurate. In doing so, the estimate of critical parameters such as peak cladding temperature and equivalent clad reacted becomes more accurate, but this is accompanied by a loss of analysis conservatism.

This is particularly important if the requirements to use the ANS 1971 Decay Heat Standard and the Baker-Just correlation for metal-water reaction are replaced with the ANS 1994 Decay Heat Standard and the Cathcart-Pawel correlations respectively. The 1971 Decay Heat Standard is generally considered to be sufficiently conservative such that it compensates for model inaccuracies and known non-conservatisms. The proposed revision of other conservative model features, such as the steam cooling requirement for flooding rates below one inch per second and the prohibition on return to nucleate boiling during blowdown would further reduce conservatism in models that apply Appendix K.

However, as known conservatisms are removed from Appendix K, there is the possibility that results produced by Appendix K based Evaluation Models will become non-conservative. There must be clear assurance that calculations based on a revised version of Appendix K retain an appropriate level of conservatism. This is consistent with the Commission Opinion for the original ECCS rule and with the conclusions rendered in SECY-86-318. Evaluation Models using a revised version of Appendix K should:

(1) Account for the effects of downcomer boiling, and ECC bypass during the reflood phase. The Evaluation Models should be capable of calculating subcooled and saturated boiling in a downcomer annulus for conditions expected during reflood, and should be capable of calculating the resulting void generation and phase separation.

(2) Account for the reduction in downcomer inventory during reflood due to steam bypass. The Evaluation Model should be capable of determining the rate of entrainment as a function of downcomer level.

(3) Account for the effects of fuel relocation following cladding swell during an accident. The Evaluation Model should account for the local increase in power and increase in fuel - clad conductance in the relocation zone.

(4) Require that when the calculated ECCS cooling performance is compared to the acceptance criteria set forth in either an existing or revised version of 10 CFR 50.46, there is a high level of probability that the criteria would not be exceeded. This statement should require that any Evaluation Model making use of the new Appendix K provide reasonable assurance that the results produced by it are sufficiently and demonstratively conservative.

One option that the staff has used in the past to verify conservatism in an Evaluation Model is by quantifying the code and overall uncertainty. Uncertainties that have been identified as important include those from the code constituent models and correlations, models describing fuel behavior, plant initial and boundary conditions, and component performance during a hypothesized accident. Text that would require this, and has been used by the staff to address the concerns related to item (4) above is:

"Comparisons to applicable experimental data must be made and uncertainties in the analysis method and inputs must be identified and assessed so that the uncertainty in the calculated results can be estimated. This uncertainty must be accounted for, so that, when the calculated ECCS cooling performance is compared to the criteria set forth in paragraph (b) of 10 CFR 50.46, there is a high level of probability that the criteria would not be exceeded."

The staff has previously provided guidance that allows the use of realistic models in a LOCA analysis. An interim approach was discussed in SECY-83-472 [27], and Regulatory Guide 1.157 [28] provided guidance on full Best Estimate calculations of core cooling system performance. Both documents discuss estimation of code uncertainties and other features required of codes using a realistic model for decay heat. The guidance on code and overall uncertainties contained in these documents could be applied in reviews of Evaluation Models and analyses that make use of any of the Appendix K revisions proposed by SECY-01-0133.

E. References

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