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REPORT

ACRS Thermalhydraulics Phenomena Subcommittee Meeting
December 11-12, 2002
NRC, Washington, DC

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1. Introduction

The ACRS Thermalhydraulic Phenomena Subcommittee met on December 11 and 12 morning to discuss the NRC PTS analysis using the RELAP5 code, APEX PTS testing program, assessment of RELAP5 for PTS calculations, TRAC M development, and the rod bundle heat transfer program. Considerable amounts of material were presented, but much of it was not available before the meeting and caught us cold—to some extent. Nonetheless, the presentations were of good quality, and the slides that were left with us contained valuable information. I will now discuss each main area, consolidating all the PTS work under one heading, with separate headings for the TRAC M development and the RBHT Program.

2. PTS

The overall aim of this program is to predict the likelihood of through-wall cracking of PWR pressure vessels when subjected to event sequences that can thermally shock the vessel, particularly near the beltline wells, which are felt to be the most susceptible. The presentations focused on the thermalhydraulic analysis that was, of course, most appropriate for the Subcommittee, but it was clear that a more integrated presentation which took into account the event sequence analysis and the fracture modes analysis for the pressure vessel were necessary to convey a complete picture. I understand that such a presentation will be made to a meeting of the ACRS and its subcommittees sometime in February. Such an integrated perspective is necessary in order to make informed comments about the status of the program.

Nonetheless, enough material was presented regarding the thermalhydraulic analyses that some comments can be made at this stage. What was missing, however, was the thermalhydraulic uncertainty analyses that are to be performed by the University of Maryland. In view of this, the presentations even in this sub-area of the PTS problem were incomplete.

2.1 PTS Thermalhydraulics Analysis Program Comments

These comments pertain to the overall methodology proposed to analyze thermalhydraulic aspects of PTS, in particular the use of RELAP5. The OSU experimental program and their CFD calculations will be commented on in the next sub-section, titled OSU Program.

1. The background provided by David Bessette was very useful. He has clearly thought about the thermalhydraulics analysis problem and does not readily accept code calculations, which is to be commended. I am in agreement with the overall methodology that he presented, which is summarized in a slide titled, "T/H Uncertainty Process". As mentioned earlier, however, the University of Maryland T/H Uncertainty Analysis was not presented, and therefore there was a substantial gap in what we learned in this meeting. This situation needs to be rectified as soon as possible.

2. During the presentation made by Dr. Bessette, it became apparent that interest had shifted from steam line breaks and small-break LOCAs to large-break LOCAs. Until recently it had been felt that the small hot-leg break LOCA was the limiting condition for PTS, so this was a substantial shift in emphasis. It would be valuable to have more information about the analyses that have led to increased interest in large and medium break LOCAs for the risk-dominant PTS sequences. This has implications for the experiments being done as OSU, as well as the CFD analyses, and the various PIRTs that have been performed.

3. The case was also made for using RELAP5 for calculations of the temperature and heat transfer coefficient transient that the vessel wall was subjected to, based on assumed good fluid mixing in the downcomer region. Therefore, 3D consideration of the downcomer was not considered necessary. If indeed large- and medium-break LOCAs are limiting, then this is probably a reasonable assumption, since the velocities and timescales of the fluctuations are quite rapid. However, it may not be a good assumption for small-break LOCAs in which there is substantial potential for plume formation and persistence in downcomers. The OSU experiments discussed later suggest that the temperature differences between the cold and hot fluid in the cold leg are relatively small. However, this may be an artifact of the scale of the experiments, and the injection geometry, as discussed later. In any case, for medium- and large-break LOCAs, my physical sense supports the use of RELAP5 or something equivalent for the temperature transient calculations in the downcomer region. This is essentially based on the probability of good mixing. However, this does not imply the RELAP5 produces accurate temperature transients. This is a matter that can only be demonstrated by careful comparisons with experiments.

4. The discussion under Point 3 above naturally leads to consideration of RELAP5 for the thermalhydraulic aspects of PTS. At the outset, it is clear that for small-break LOCA, some consideration of 3D effects is probably necessary, though the OSU results show good mixing in the injection region and in the cold leg, which may minimize the requirements in this direction. However, for medium- and large-break LOCAs, RELAP5 may be adequate. To this end, an extensive presentation of RELAP5/Mod 3.2.2γ was made by ISL. The aim of the presentations was fairly ambitious, as assessments were made against separate-effects tests as well as experiments. The idea appeared to be to support the overall behavior of

RELAP rather than look at aspects specific to PTS. I am in favor of this, as it is necessary to demonstrate that the code does well over a broad spectrum of situations in order to have confidence that it does a good job with regard to specific aspects. However, it should be noted that at our last meeting on SREPLAP5, several deficiencies were recognized. Having said this, though, the broad spectrum of tests conducted by ISL was rather reassuring and certainly go in the right direction. More specific points are discussed below.

5. Of the many cases considered by ISL in the assessment of RELAP, the most relevant have to do with the ROSA IV tests. Most of the other facilities were either separate effects or involve scaling, which was not always easy to defend. Furthermore, some of these tests have external downcomers. Much of the analysis, particularly for ROSA IV, was limited to small-break LOCAs, and this is a concern if the dominating risk sequences are shifting to medium- and large-break LOCAs. In any case, even for the small-break LOCA conditions discussed, there were some significant differences between the version of RELAP used and experiments. These were not only with regard to the downcomer fluid temperature, which is the most crucial from a PTS viewpoint, but also with regard to break flow and pressures. For example in the 2-inch hot-leg break in ROSA IV, the RELAP5 pressures were significantly below those in the experiments, and the break mass flow was also different, though the experimental data was presented in a way that made it difficult to assess. Furthermore, the experiments showed a sudden sharp drop in downcomer fluid temperature that was not caught by RELAP. This is precisely the sort of thing that would give rise to thermal shock. It is not completely clear why the fluid temperature in the experiments dropped precipitously around 8,000 seconds, as the table showed that accumulator injection started around 6,500 seconds. The conclusion that RELAP5 "conservatively" estimates downcomer temperature is therefore incorrect. It is not the temperature that matters, really, but the rate of change of temperature (as well as the temperature). Clearly, RELAP5 did not estimate the rate of change conservatively.

6. All this leads me to the view that, while a good start has been made at putting together the story for the thermalhydraulics analysis of the PTS, some piecing together needs to be done to ensure that everything fits and the case is relatively water tight. My suggestion would be to support the use of RELAP5 for large- and medium-break LOCAs, showing, in particular, comparisons of various parameters such as pressure, downcomer temperature, and rate of change of temperature, etc., for large/medium break sizes as well as for small breaks. In addition, as discussed later with regard to the OSU work, a case can be made for assessing some small-break effects with CFD codes. Using a combination of RELAP5 and CFD calculations, one may be able to put forward a relatively defensible thermalhydraulics analysis case.

3. <u>OSU Work</u>

The OSU work related to some experiments as well as CFD analysis. The test matrix was presented and consisted almost entirely of experiments that elucidated the situation with steam line breaks, small breaks, stuck-open PORVs, etc. There did not seem to be any consideration of medium- or large-break LOCAs, perhaps because the shift in understanding of what are the risk-dominant sequences came rather recently. In any case, results were presented for steam line breaks, hot-leg breaks, and, specifically, on HPSI, mixing and downcomer plume behavior, which were perhaps the most interesting of the experiments. Some comparisons were also made with RELAP5 and the CFD code, STAR-CD. My specific comments are given below.

1. The OSU facility is scaled with reduced height, which we found to be problematic with regard to at least the AP600 scaling. Without going into details, our scaling analysis indicated that OSU data could not be collapsed in the sense the SPES and ROSA data could be with nondimensional groups that largely matched those of full-scale plants. Having said that, though, the data are still valuable for checking computer codes and getting a general idea of the phenomena that might be expected. However, it should be emphasized that considerable care must taken in drawing conclusions directly from the data. To make this more concrete, consider mixing in the HPSI injection line and the cold leg. The OSU data indicated good mixing so that the cold plume that exited into the downcomer was only a few degrees different in temperature from the surrounding fluid. These measurements are valuable in checking the predictions of CFD codes like STARCD, but it is codes like STARCD, then, that have to be used to scale up to a full-scale plant and determine whether the same small temperature difference would be obtained. The only caveat I would have about such a procedure is the turbulent mixing between the stratified streams, as it is handled in STAR-CD. For the relatively low Reynolds numbers in the OSU experiments, STAR-CD may do well but may over predict mixing at higher Reynolds numbers as stratification is difficult to account for in turbulence models. Therefore, even the use of STAR-CD as a scaling tool or any other CFD code like CFX or FLUENT, etc., must be carefully justified, not only by comparison with experiment, but by examination of numerical diffusion and turbulent diffusion.

2. While the OSU experiments have been valuable in identifying some phenomena of interest for PTS, they are less valuable when it comes to medium- and large-break LOCAs, which are now apparently the risk-dominant sequences. Therefore, the need for further experimentation with regard to PTS in the OSU facility needs to be assessed. If some medium- or large-break LOCA tests are to be conducted, I would be much more in favor of this being done in full-height facilities such as ROSA or its equivalents.

3. One of the most interesting observations in the OSU experiments was that the plume emanating from the core legs did not mix well in the downcomer. David Bessette correctly pointed out that this aspect of the experiments would be affected by the fact that the temperature difference between the cold stream and surrounding fluid was relatively small, which would give rise to correspondingly small buoyancy-driven velocity differences. In view of this, the mixing may be expected to be much better if the temperature differences were large. The upshot of this argument is that, in either case, whether the temperature differences between the cold stream issuing from the cold leg and the surrounding fluids are large or small, the ultimate result is that there will be compensatory effects that will ameliorate the changes in temperature seen at the beltline welds. Whether Bessette's

hypothesis is correct or incorrect needs to be checked directly. One way to do this might be to conduct a focused experiment in which the liquid drawn into the HPSI line and subsequently mixes in that line is eliminated. This would allow the cold leg to stratify, and the stream issuing into the downcomer would be much colder. Whether this would form a plume or mix with the surrounding fluid could then be determined. This is perhaps the only further test I would recommend at the OSU facility on PTS at this time.

4. The CFD calculations presented were interesting, but it is not clear that the turbulence model made any difference to the results. In fact, it was pointed out that if the model was suppressed, the results were almost the same. This is perhaps because the Reynolds numbers involved are rather low. However, very different Reynolds numbers can be expected in full-scale plants, and therefore this result should not be taken as being directly applicable for full-scale assessments. Nonetheless, the nodalization that was done for the OSU experiments can be carried over to the full-scale plants simply by enlarging the axial and radial dimensions of the nodes. It would be worth assessing what happens in the full-scale plant, using the code with exactly the same INPUTS but nodalization of larger dimensions. I suggested this during the meeting, and I still think it is a good idea. The Reynolds numbers obtained could also be looked at to determine whether turbulence is likely to be important in the processes or not. Another case that could be run would be to block mixing in the HPSI line and look at the effect of this on cold-leg stratification and temperature difference between the downcomer plume and the surrounding fluid. This, while useful, would not necessarily eliminate the need for experiment, as some of the mixing characteristics in the code are open to question.

5. In summary, then, the OSU experiments and CFD calculations have been valuable, and one or two more focused experiments to clarify cold-leg stratification and plume mixing in the downcomer might be useful. Numerical calculations of corresponding cases and of full-scale cases would also provide valuable insight. However, I would not be in support of medium- or large-break experiments at OSU, as the OSU facility's distortions in scale are significant, and the phenomena that are seen might be quite different than WHAT might be seen in a facility that is scaled in a more defensible way, such as ROSA.

4. <u>TRAC M</u>

TRAC M is a work in progress and has been in progress for some time. However, it is planned that an alpha release version will be available by year end to internal users and a beta version by spring 2003, with the official release at the end of 2003. If this schedule can be maintained, then we will at least begin to see the effects of this protracted effort in the near future. However, so far as I can see, the fundamental structure of the code is still similar to that of TRAC (and basically the same equations are used in TRAC and RELAP5), so many of the comments made during the SRELAP5 meeting regarding the deficiencies in the momentum equations, etc., still carry over. There have been efforts, however, to improve the numerical aspects of the code, resulting in improved computational efficiency, thus incorporating level tracking and some level of parallel processing. Much effort has been spent on making it possible to use RELAP5 decks directly with the TRAC M code and to assess the results against a variety of separate effects and integral tests. All this is to be commended, and it is also encouraging to see that serious consideration is being given to incorporating the results of the UCLA Subcooled Boiling and RBHT Reflood Programs. I have the following specific comments:

1. The basic structure of the equations being used in the code and the various closure relationships need thorough review. As pointed out by Dr. Moody, the ACRS Thermalhydraulics Subcommittee would be both willing and able to carry out a large part of this task if documentation was presented to them. I would strongly advocate that this be done as soon as possible. This would ensure that what is the basis of the code is acceptable to the ACRS.

2. I have concerns with regard to the phase separation work being carried out at OSU and the use of this data in TRAC M. For some of the advanced concepts, the flow out of the ADS4-type lines is critical and, from the previous OSU presentation, I did not get the impression that some important parameters were being measured. Therefore, the general area of phase separation, and perhaps break flow modeling, needs detailed consideration and, if necessary, some remedial action.

3. Considerable effort is going into an interfacial area transport model and use of this in a code like TRAC M. The basis for the governing equations and the various terms that go into such a model needs to be exposed to the Thermalhydraulics Subcommittee as soon as possible. At least during the time I have been associated with the Subcommittee, we have had no presentation regarding this work, which is apparently viewed as being the long-term future for the development of TRAC M.

4. Many of the model improvement needs were listed in Slide 17 in the presentation by Dr. J.M. Kelly. However, the strategy for tackling these modeling improvements was not clear, and, while some of them are being addressed in the experimental programs, others may not be. In any case, it is necessary to address how these modeling needs are being met at present, if they are at all.

5. Finally, even the separate effects tests against which TRAC M is being assessed are still large scale, e.g. for the core heat transfer FLECHT, FLECHT/SEASET and GOTA are being used, as well as some hot patch experiments done at AECL with tubes (this is an exception). I would recommend addition of a matrix of relatively simple experiments where detailed measurements have been made. These are perhaps with tubular or annular geometries for situations like reflood, reflux condensation, condensation in horizontal pipes or channels, etc. If the code does well against such fundamental experiments, then it certainly increases confidence in the overall heat transfer and fluid mechanics package. I can suggest a number of experiments in many of these categories that involve phenomena critical to LOCA prediction.

Having said all this, I must compliment the presenters for giving us much valuable information and bringing us up to date with what promises ultimately to be a very useful tool for the NRC and the nuclear community in general.

5. Rod Bundle Heat Transfer Program

The Rod Bundle Heat Transfer Program at Pennsylvania State University was extensively reviewed with regard to use of the results in TRAC M. This arose out of comments made at the last Thermalhydraulics Subcommittee meeting (held in November 2002) that expressed concerns about the integration of the experiments with TRAC M. In particular, the case for these experiments was presented very well at the current meeting and reassured the Thermalhydraulics Phenomena Subcommittee that they were really necessary. My comments are presented below.

1. Reflood is one of the critical aspects of LOCA, and it is during this phase that the peak clad temperature occurs. Therefore, improved understanding of fuel behavior in this critical phase of LOCA is extremely important. In view of this, and the new and improved measurements being made in the RBHT facility, there is no question in my mind that the program should be continued. Furthermore, it appears that the NRC people involved in the development of TRAC M are taking the results of these experiments seriously and making attempts to integrate them into the models going into TRAC M. This, then, answers some of the questions I had with regard to the integration between modeling and the experiments in RBHT at the last meeting.

2. An extensive presentation was made by Dr. J.M. Kelly regarding the model development needs and strategy. Some interesting results were presented regarding the void fraction dependence of the heat transfer coefficient above the rewet region, and this certainly justifies every effort to make such measurements in RBHT. Furthermore, the use of RBHT data, or data that will be generated in the future in the facility, was also discussed in detail with regard to the dispersed flow film boiling regime. Finally, the effect of grid spacers on vapor de-superheating, and perhaps rewet, was also shown to have important implications. I came away from all this satisfied that the main phenomena were being addressed and that the RBHT facility had an important role to play in elucidating them and the data were of direct use in developing models.

3. With regard to some of the measurements being made at RBHT, however, the remarks I made in the report on the November 12-13 T/H Subcommittee meeting still hold. I feel it is important to qualify the void fraction measurement technique, ideally by showing that it works for situations where gamma densitometer data are available, if only in tubes, or by a set of calculations. I would be interested in reviewing these. Furthermore, my remark regarding the testing of the steam temperature probe, if necessary in a separate facility, still holds. Finally, the effect of oscillations on carry-over is perhaps something that needs to be addressed, as it is thought to occur in full-scale plants and is known to significantly impact carry-over. In this regard, there were a series of small-scale experiments carried out at UC Berkeley in the early 1980s that I referred to in my last report that should be assessed and, if possible, incorporated into the TRAC M separate effects assessment matrix.

4. The presentations with regard to RBHT and TRAC M were valuable, as they clarified the situation much more than what we were left at in the last T/H Subcommittee. Again, as Dr. Moody mentioned, it would be valuable to keep the T/H Subcommittee up to date on this work and use them as a sounding board for various models, measurement techniques and future experiments. In fact, the Subcommittee can act as something of a peer-review group, which will in any case be valuable for the overall program.