UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

September 6, 1996

MEMORANDUM TO: Chairman Jackson
Commissioner Rogers
Commissioner Dicus
Commissioner Diaz
Commissioner McGaffigan

FROM: James M. Taylor
Executive Director for Operations

SUBJECT: THERMAL-HYDRAULIC FIVE-YEAR RESEARCH PLAN

Thermal-hydraulics has been a major area of nuclear safety research since regulatory research began at NRC. Traditionally, thermal-hydraulic research has had two principal aspects: developing system-level computer codes and conducting of both large- and small-scale experiments. The staff's use of NRC-developed thermal-hydraulic codes has been an integral part of the licensing process, and these codes have provided the NRC with the ability to perform independent analyses as mandated by the Energy Reorganization Act of 1974 (P.L. 93-438) and as expected by the public. Over the past two decades, the NRC has spent, and is continuing to spend, substantial resources to demonstrate that its thermal-hydraulic codes are valid to analyze complex transients, accidents, and other off-normal conditions. In addition to improving and validating these codes, the NRC has performed, and most recently, is performing, in support of the AP600 certification, sufficient thermal-hydraulic experiments of various sizes and scales to gain an understanding of thermal-hydraulic phenomena. These tests have aided in improving NRC's analytical methods and in assessing the design, testing, and analysis of vendors and licensees.

The safety issues that drive the need for thermal-hydraulic research include:

- Operational events and operational concerns continue to be of safety importance both domestically and internationally. These events require analysis by the NRC to understand their potential safety and generic implications. These events and conditions include: BWR oscillations, steam generator tube rupture, PWR RCP seal failure, cooldown by natural circulation, station blackout, BWR vessel thermal stratification, boron mixing during ATWS, pressurized thermal shock, inter-loop blowdown, and performance of safety features.

- International thermal-hydraulic research continues, using integral test facilities such as ROSA (Japan), BETHSY (France), and PIPER (Italy). There is a potential for new data from these test facilities to alter our present understanding of accident scenarios. This could lead to the reevaluation of design margins or procedures.

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- Requests from the nuclear industry to modify operating licenses (e.g., power upgrades), technical specifications, and emergency procedures will continue to be received and will require a capability for independent analysis.

- Risk-informed regulation is becoming more important in the agency's decision-making process. For the agency to understand the risk significance of various sequences, those sequences must be properly analyzed with a code that is robust and fast running.

- Applications for the certification of new designs may be received in the future. An advanced analysis capability that is flexible enough to be readily modified to account for new design features is needed to facilitate the agency's review.

The objectives of this paper are to inform the Commission of the staff's plan to improve and maintain its capability in thermal-hydraulics, including:

1. The major goals (near-term and long-term) of the thermal-hydraulic research program (THRP);

2. The specific activities associated with maintaining core competency in the areas of thermal-hydraulics, reactor physics, and plant-transient analysis codes, including international leadership and cooperation;

3. The staff's plan to develop a state-of-the-art plant transient code to replace current codes;

4. The experimental programs to obtain fundamental data and information to support the development of advanced thermal-hydraulic models.

BACKGROUND:

After the NRC promulgated the revised ECCS rule, both the funding and prominence of thermal-hydraulic research at NRC declined. The recent advent of advanced light water reactor designs emphasized the importance of maintaining a viable, world-class thermal-hydraulic research program, including developing and assessing the thermal-hydraulic computer codes (the codes), and has resulted in our rebuilding our thermal-hydraulic capability.

The basis for the existing thermal-hydraulic codes was developed 20 to 30 years ago to analyze large break loss-of-coolant accidents using coding architecture and numerical methods that are now obsolete. Operating experience and applications for passive reactor designs have demonstrated the need for a wider range of capability. This, in turn, led the code developers to modify the codes in an ad hoc fashion, which resulted in difficulty in preparing or modifying plant input decks, difficulty in interpreting the results, and frequent user intervention during the simulation of a transient because the codes are slow running. Given our extensive data base and knowledge of numerical modeling techniques, combined with a new generation of high speed parallel computers, these codes no longer provide the best tool for the job. Moreover, maintaining and running the existing codes is excessively labor intensive, requiring many skilled people at different national laboratories. NRC can restructure the existing codes into a single code that is faster, more robust, and more user-friendly, which provides substantial saving in staff and contractor time to use and maintain the code.

DISCUSSION:

A large amount of thermal-hydraulic research results now exist, and this plan is intended as a needed step to the critical and focused examination of the NRC's future needs. These needs, including the analytical tools, experimental data, and staff and contractor capability, are presented below.

The NRC is recognized as a leader in nuclear safety and is called upon to address issues that are facing the industry domestically and internationally. To sustain and enhance these capabilities, a stable, challenging research environment must be maintained. This includes providing stable long-term funding and interesting work to retain talented researchers. This section contains an analysis of the issues associated with developing of long-term research to maintain technical expertise, including maintaining, updating, and restructuring the codes and maintaining certain experimental facilities. This plan reflects the commitment made in a memorandum dated June 30, 1994, to the Commissioners.

Goals of the Thermal-Hydraulics Research Program:

The near-term goals of the thermal-hydraulic research program are to:

1. Develop and maintain in-house capabilities:

   a) Perform plant transient analyses using the current thermal-hydraulic codes and modify and assess the codes as necessary.

   b) Participate in the development and evaluation of experiments needed for code development, assessment, and improvement.

   c) Provide the technological bases for regulatory decisions involving thermal-hydraulics.

2. Maintain the existing NRC plant transient analysis codes (RELAP5, TRAC-P, TRAC-B, RAMONA). In this context, maintenance not only includes correcting errors identified by users but also includes needed development, improvement, and assessment.

The long-term goals are:

3. Maintain some experimental capabilities to address phenomena relevant to nuclear safety and to provide validation data to cover plant parameter ranges of interest. This includes continued support of the domestic experimental programs at Oregon State University (OSU), Purdue University (PUMA), and the University of Maryland (UMD). We will continue to interact with other international programs, e.g.,

ROSA (Japan), and BETHSY (France), to share information and participate in cooperative programs of interest to the NRC. We also plan to maintain the Code Applications and Maintenance Program (CAMP).

4. Combine the different modeling attributes embodied in the RELAP5, TRAC-P, TRAC-B, and RAMONA codes into a single state-of-the-art computer code. This will be accomplished by capitalizing on lessons learned from previous code development programs and exploiting new technology that has been developed or that is evolving, e.g., parallel computing environment, advances in modeling, and computation of two-phase fluid dynamics. In addition, the staff will remain cognizant of developments in computational fluid dynamics technology. The most successful of these technologies would then be considered for incorporation in the plant transient code or as a stand-alone tool to address specific issues that require such complex computational technology.

5. Incorporate user experience into an expert system. Such a system can advise the user on the type of nodalization to use, the uncertainty in the results, and can provide ready visualization of the processes that occur in a transient.

The staff's current estimate is that the near-term program will continue to meet NRC's existing needs but in less than an optimum manner. The long-term goals will continue to provide valuable information for the foreseeable future, and substantial improvements in code performance will be achieved in five years.

<u>Maintaining Core Competency:</u>

To maintain competency, key researchers and the capability for plant analysis must be maintained. However, as a practical matter, this will happen only if researchers can be assured of a stable program and are involved in interesting and creative work, not just "maintenance of code." Cooperative research and agreements designed to spur collaboration with international organizations can also play a role. The intent is to maintain a cadre of researchers in-house and at different universities and contractors' site. These experts will be available to respond to technical questions as they arise and to develop models that can be incorporated into NRC codes.

The research plan, discussed in detail in the Appendix, spans four different areas that are strongly related to each other: 1) reactor safety code development, 2) two-phase flow modeling, 3) thermal-hydraulic experiments, and 4) in-house capability. The following is a summary of the plan.

<u>Reactor Safety Code Development Program and Two-Phase Flow Modeling:</u>

In the area of code development, the NRC plant transient codes embody much of the staff's knowledge about thermal-hydraulics and reactor physics; and they are essential to maintaining a strong and effective regulatory program. Future uses of the codes include support for increased power ratings, risk-informed regulation, analyses of operating events, and addressing issues that are facing the industry domestically and internationally. Currently, the NRC supports the development and maintenance of the RELAP5, TRAC-P, TRAC-B, and RAMONA codes at INEL, LANL, Penn State University, and BNL, respectively. Since each code has its own mission and is maintained at a separate institution, there is little opportunity to consolidate the available talent base and costs. This plan will consolidate the thermal-hydraulic activities and thus promote greater sharing of expertise and experience.

As we reflect on our operational experiences with these codes, it has become increasingly evident that we need to consider modifying our overall thermal-hydraulic code strategy and realign the objectives for each code so they better match today's and future needs. Furthermore, with the increased demand to reduce the budget, we have questioned our adherence to maintaining several codes that embody the same characteristics and diverge only on few models designed to address specific safety issues. It is our conclusion that the current advances in software engineering, data distribution, expert systems and graphical user interfaces, machine intelligence, and knowledge of thermal-hydraulic phenomena will enable us to consolidate the NRC transient analysis capabilities into a single code without adversely impacting the existing capabilities.

Therefore, in FY 1997-1998, we will combine the different modeling attributes embodied in the TRAC-P, TRAC-B, and RAMONA codes into a single TRAC code as a first step in consolidation. In addition, over the next 3-5 years, we will support, as our ultimate goal, the development of a state-of-the-art code and data base to embody the capabilities in the combined TRAC code with those now existing in the RELAP5 code. This is summarized further below and in more detail in the Appendix.

<u>Development of a State-of-the-Art Plant Transient Code:</u>

As stated earlier, the underlying basis for the current codes was developed 20-30 years ago using coding architecture that is now obsolete. Using modern computer techniques (e.g., parallel processing) and more efficient user interfaces, maintenance and modification costs can be reduced, execution can be improved, and portability can be enhanced. In the long term this will be a cost saving.

The consolidated code will be organized along functional lines, with a staff member responsible for each subject area. It is expected that, for some disciplines, the staff will initially need the assistance of consultants who specialize in a given area, but if that discipline is considered to be integral to developing expertise within the NRC, it is also expected that the staff will develop the expertise during the course of the project. The functional areas are:

- Physical Model Development - to upgrade or develop the constitutive models necessary to enable the simulation of important phenomena with good fidelity.

- Numerical Methods - to explore solution strategies for the two-fluid equation set and advanced matrix solution techniques.

- Data Base Structure and Code Architecture - the consolidated code will be modular and will have component-based input/output and physical models. The data structure will be chosen so as to not overly restrict development and modification activities and it will be easily amenable to parallelization.

- Neutronics - a 3-D coupled thermal-hydraulics, neutronics capability will be included in the consolidated code.

- Graphical User's Interface (GUI) - to make the code easier to use, from the perspective of both input and output. We would employ the services of a professional software development company. A staff member thoroughly familiar with reactor plant systems, and experimental facilities, and the input to a thermal-hydraulic code would work with the GUI developer to make certain that the product will meet our needs.

- Compatibility with other codes - such as the SCDAP code for severe accident analysis or the CONTAIN code for coupled reactor system/containment analysis. In addition, a translator must be provided to preserve investments in the preparation of plant input decks for the current versions of the codes.

- Developmental Assessment - the consolidated code will be assessed against a wide variety of conditions to establish confidence in the results. Some of this activity can be performed within the agency. Additional assessment, maintenance, user support, and archiving activities of the consolidated code will be the responsibility of a contractor. In preparing the detailed procedures for the assessment process, we will use the guidance provided in the agency Code Scaling, Assessment, and Uncertainty methodology to establish and measure acceptable limits for code accuracy and uncertainty.

- Documentation - documentation will be maintained contemporaneously with the development and maintenance of the code. User's manuals and other documentation will be in Hypertext Markup Language (HTML) to allow cross reference to documents that can be physically located in the same computer or another computer connected to a network.

To accomplish the above, a group of experts has been convened to identify approaches and to comment on a staff-developed plan to develop the code. This plan, which specifies the functional requirements for a consolidated code, will also be discussed at an OECD/CSNI workshop, hosted by the NRC in Annapolis, Maryland on November 5-8, 1996. We will discuss this plan and all facets of its implementation with the ACRS in early 1997, including the experimental programs discussed below. In addition, the implementation of this plan will include the full participation of the NRC internal thermal-hydraulic users from NRR, AEOD, RES, in the detailed design, development, modification, and maintenance of both the existing suite of codes, as well as the next generation code.

Experimental Programs:

In the area of experimental programs, we are planning to maintain a boiling-water reactor test facility at Purdue University (PUMA), a pressurized-water reactor test facility at Oregon State University (APEX) and a B&W once through steam generator test facility at the University of Maryland (THECA) to:

- Perform independent confirmatory tests of an applicant's design to ensure that potential problems are fully explored
- Provide additional independent data in areas of particular importance for existing plants
- Provide a data base for thermal-hydraulic code validation

In addition, where practical advanced instrumentation will be used to obtain reliable multi-phase mass flow measurements, void fractions, two-phase density, and other needed information to improve basic modeling of the two-phase processes. It should be noted that modification to the OSU and PUMA facilities may be needed to preclude any infringement on Westinghouse and GE proprietary design information that is incorporated in the design of these facilities. An OECD/CSNI Specialists Meeting on Advanced Instrumentation and Measurement Techniques, hosted by NRC, will be held from March 17-20, 1997, in Santa Barbara, California, which will identify state-of-the-art instrumentations as well as promising concepts.

In-house Capabilities:

In regard to in-house capabilities, it should be noted that the capability to analyze potential plant transients and accidents is necessary for carrying out the NRC mission. The need to perform plant transient analysis; e.g., design-basis accidents as well as non design-basis events, such as multiple system or component failures, common-mode failures, or operator errors, will not diminish with the completion of the certification of AP600.

Until recent years, NRC has maintained little or no in-house capability to independently assess safety issues for advanced reactors or operating plants of either domestic or foreign design. As our budget is reduced, there will be more reliance on the staff to fill the gap created by reduced contractor support. Because of the complexity of the different thermal-hydraulic and reactor physics issues, replacing the contractors' capabilities developed over the past 20 years of research by in-house capabilities will require a commitment to maintain staff. In the last four months, RES has recruited four engineers with experience in thermal-hydraulic phenomena, numerical methods, and code development. In the fall of 1996, a graduate fellow will rejoin the staff after finishing her Ph.D. at MIT. Finally, a new graduate fellow will join the staff in the fall of 1996. NRC now has a nucleus for a good thermal-hydraulic team and will continue to recruit and hire individuals with skills we need, and to train young engineers to replace those leaving the staff. Establishing in-house capabilities supplemented by potential sources of outside expertise will enable NRC to respond effectively to emerging needs.

Finally, we will keep the codes and the staff at a state-of-the-art level through participation in CAMP, OECD/CSNI, and other international programs; using the codes in response to specific requests; and checking them against new experimental data developed by the NRC and others.

RESOURCE COMMITMENT:

The FTE and dollars shown in the FY97 and FY98 columns of Table 1 are included in the budget request to OMB (FY98 Blue Book). In preparing this research plan, the staff assumed these funding levels will be sustained through FY 2001. The following table identifies the staff and contractor resource estimates by functional area. Additional computer resources, not specifically addressed in this plan, will be needed to upgrade the NRC infrastructure that will be necessary to support this plan.

In order to leverage resources, the plan seeks cooperative research on thermal-hydraulics and on the state-of-the-art plant transient code with OECD member countries, the Commission of European Communities (CEC), JAERI and NUPEC in Japan, and CEA in France. Further leveraging of our resources will be sought by offering experimental research, such as that being conducted at Purdue University, Oregon State University, and the University of Maryland, as a quid pro quo to obtain relevant data from international experimental programs such as ROSA in Japan and BETHSY in France.

RELATIONSHIP TO COMMISSION'S STRATEGIC ASSESSMENT

The Thermal-Hydraulic Research Plan will be modified to take into account the Commission's final views on NRC's research program as set forth in the Strategic Assessment Issue Paper on Research (DSI 22).

COORDINATION

A draft version of this plan was reviewed by selected members of the Thermal-Hydraulic Expert Consultants (See memorandum dated January 9, 1995, from James Taylor to the Commissioners). The consultants comments are reflected in the enclosed plan. In particular, we received comments from Professors Todreas (MIT), Wallis (Dartmouth), Ishii (Purdue), Banerjee (UCSB), and Reyes (Oregon State University)

Finally, the staff will meet with and brief both the ACRS Subcommittee on Thermal-Hydraulic Phenomena and the full ACRS on this plan. These meetings are tentatively scheduled for September and October 1996. We will incorporate the ACRS comments as appropriate and finalize the plan.

Attachments:
1. Table 1
2. Appendix

cc: SECY
OGC
OCA
OPA

Notes to Table:

◆ For existing codes (RELAP5, TRAC-B & P, RAMONA).

◇ For the consolidated code (TRAC-B & P, RAMONA to be completed FY98, RELAP5 new architecture in FY01).

△ Capabilities already exist in-house.

‡ A staff member will work closely with a contractor.

• It is more beneficial to rely on contractors with software development capabilities.

□ Because of the large user community, support will be provided by contractors.

℞ Develop new models and peer review staff-developed models.

@ Phase I of the consolidation of TRAC-B, TRAC-P, and RAMONA will be completed in FY98.

* The FY97 and FY98 budgets include $10.3M and $9.8M respectively for plant performance research. This plan accounts for $6.6M in each fiscal year as shown in the table for thermal-hydraulic research. Of the remaining $3.7M in FY97, $2.1M is to conduct a high-burnup fuel cladding test program and $1.6M for work related to the Westinghouse AP600 design. Of the remaining $3.2M in FY98, $2.1M is to conduct a high-burnup fuel cladding test program and $1.1M for work related to the Westinghouse AP600 design.

** Acquisition FOR TRAC-BWR Thermal-Hydraulic Code Maintenance and consolidation, (Memorandum from EDO to Chairman Jackson forthcoming on this matter).

APPENDIX

STRATEGIC RESEARCH PLAN FOR MAINTAINING CORE COMPETENCY IN THERMAL-HYDRAULICS

It is essential for the NRC to maintain a high level of research expertise in thermal-hydraulics and reactor safety and to continuously improve our capability to analyze plant transients. The goal of this plan is to ensure that the NRC is able of providing thermal-hydraulic support for regulatory decision making. To meet this goal, the staff must have expertise in four areas that are strongly related to each other:

1. Reactor Safety Code Development
2. Two-Phase Flow Modeling
3. Thermal-Hydraulic Experiments
4. In-house Capability

Each of these four areas is discussed below. For each area, an introduction is followed by sections on the significance of the problem, the identified needs, and a strategic plan for that area.

1. Reactor Safety Code Development

To audit vendor or licensee analyses of new or existing designs, to establish and revise regulatory requirements, to study operating events, and to anticipate problems of potential significance requires thermal-hydraulic analysis capabilities that are unique to the NRC. This is because the appropriate tools do not exist outside of the nuclear industry and entities within the industry have inherent conflicts of interest with the NRC. Therefore, the NRC must have a capability for independent analysis, including both the tools and a cadre of experts capable of using them. The NRC currently relies on four different thermal-hydraulic system analysis codes. Consolidating the modeling attributes embodied in these four codes into a single state-of-the-art code is the goal of the research effort detailed here. This consolidation would exploit new technology in the areas of parallel computing, two-phase flow modeling, and computational methods.

1.1 Code Development: Background

The NRC currently maintains four thermal-hydraulic computer codes of similar, but not identical, capability. For pressurized water reactors, the RELAP5 code provides a primarily one-dimensional representation of the flow field (some limited capability to model transverse flows is also available through the use of "cross-flow" junctions) and includes both point and one-dimensional reactor kinetics models. RELAP5 is used primarily for small-break LOCA and plant transient analyses but lacks models needed for the analysis of large-break LOCA transients. Analyses requiring the modeling of multidimensional flows, and in particular large-break LOCAs, use the TRAC-P code. In principle, RELAP5 was supposed to be a fast-running "simple" code for long-term transients, while TRAC-P would provide a more detailed description of the flow field and be suitable for faster (i.e., shorter) transients and also for benchmarking RELAP5. Over the years, this distinction has been blurred, and today many of these two codes' capabilities overlap, yet the two codes often use different constitutive models for the same phenomena.

For analyzing boiling water reactors, the situation is somewhat similar. The RAMONA code provides a very simple one-dimensional representation of the flow field but contains a three-dimensional reactor kinetics package. For a more detailed representation of the flow field, the TRAC-B code was developed from the TRAC-P code. In addition to adding BWR-specific models (e.g., jet pumps), the TRAC-B code implemented a different constitutive package and numerical scheme from its namesake; and since their separation, each of the two TRAC codes has followed its own independent path of development. It should be recognized that all four of these codes were initially developed for large main frame computers and have been modified in a piecemeal fashion for use on workstations.

1.2 Code Development: Significance of the Problem

As briefly outlined above, the NRC currently supports four different thermal-hydraulic analysis codes. The cost of this support is prohibitive, in terms of both budget and impact on our effort to rebuild and maintain a core competency in the area of thermal-hydraulics.

Part of the problem is the dilution of resources by supporting four codes; but of equal or perhaps greater importance, is the diminishing return on future research investment when it is invested to "fix up" old computer codes that are mired in obsolete technologies. The problems caused by having four codes are discussed below in three general categories: direct costs, impact on staff capability, and thermal-hydraulics code capabilities. The last subject area, thermal-hydraulics code capabilities, contains more detail and is further subdivided into four areas: maintainability, code accuracy, code speed and robustness, and user friendliness.

1.2.1 Direct Costs

Direct costs are the support needed to maintain four code development and maintenance teams at three DOE laboratories and one university. Other direct costs accrue because of the nature of doing things in quadruplicate. For example, as part of the ALWR program, NRC funded both INEL and LANL to develop AP600 input decks for the RELAP5 and TRAC-P codes respectively. Concurrently, NRC Research also funded BNL to develop SBWR input decks for the RELAP5 and RAMONA codes. NRR often faces the same duplication of costs in needing plant decks for both RELAP5 and TRAC-P. These costs are not limited to just the initial input deck development, but they continue as the input decks have to be "maintained" as the code input description changes with more recent code versions. Also, part of maintaining a thermal-hydraulics code is ensuring its simulation fidelity through the process of developmental assessment. Again, this effort must be duplicated as each code must be assessed for the complete range of phenomena over which it will be applied and not just for those that are unique to its particular application. Finally, as will be discussed below under thermal-hydraulic code capability, the archaic nature of the architecture used in these codes makes their maintenance, finding and correcting user-identified errors, much more time-consuming (by a factor of 2 to 4) than for a well-engineered software product.

1.2.2 Staff Capability

One of the goals is to upgrade staff capability to a world-class level of expertise on thermal-hydraulics. Splitting up our efforts into four parts is not an efficient way of achieving this. First, the staff must be trained not only to use four different codes but also to understand their numerical and physical models (and their underlying assumptions and limitations). Second, the existence of four codes means that there are (at least) four different contracts that need to be managed with all the associated paperwork and contractor interaction that siphons off some of the available staff resources. Finally, the upgrade of staff capabilities is further impeded by the fact that all four of these codes are very difficult to use, both in the sense of input deck preparation and the interpretation of results. Although building a graphical user's interface is a priority item, a good interface will include code specific features such as automatic user guidelines and on-line help. This will be expensive and cannot be done four times.

1.2.3 Thermal-Hydraulic Code Capabilities

The subject of thermal-hydraulic code capabilities is divided into four parts: maintainability, code accuracy, code speed and robustness, and user friendliness.

1.2.3.1 Maintainability

As regards maintainability, one overriding factor, that also affects the other three areas, is simply the age of the codes. These codes were developed in the 70s, long before the revolution caused by the introduction of high-performance workstations and memory that is cheap, fast, and abundant. Consequently, these codes were developed with an architecture aimed at optimizing performance on obsolete machines that were severely limited in memory. To overcome these memory limitations and allow dynamic memory allocation, the code developers were forced to employ elegant programming styles (such as "container arrays" and "bit packing") that have severely compromised readability, maintainability, and portability (e.g., separate code versions with machine-dependent options for different types workstations). Engineers then spend their time not resolving fundamental deficiencies in the numerical and physical models but rather trying to decipher cryptic coding and work around the limitations inherent in the data base structure. One result of this is that current efforts to update models in these codes for advanced light water reactor analyses are costing several times more than necessary in terms of both time and money.

1.2.3.2 Code Accuracy

Code accuracy concerns the simulation fidelity of important phenomena for both reactor systems and experimental facilities over the full range of parameters for which these phenomena are expected to occur. The majority of the constitutive packages are different for all four codes, even though most of the phenomena are the same. As noted above, the code architecture makes it very difficult to modify the models in these codes (without introducing a large number of "bugs"). Furthermore, the code models have been hardwired into a package of correlations, using smoothing functions to minimize discontinuities between correlations and explicit ramming functions to solve difficulties caused by the interaction of the physical models with the numerical scheme. Consequently, the numerical solution algorithms and the physical models are not separable, so that improving the physical behavior of one model can degrade the overall performance in unanticipated ways. Consequently, there is inherent difficulty to modifying the code to upgrade the physical models to keep them state of the art.

Code accuracy is further adversely impacted because the majority of the physical models to be found in the literature were not formulated to be compatible with the framework of a two-fluid code. Also, the models are developed to be applicable to one regime and not as part of a consistent package, leading to a patchwork quilt of correlations stitched together out of expediency. Therefore, the current sets of constitutive relations do not take full advantage of the current data base, which leads to a larger degree of uncertainty in our calculations and to potentially erroneous calculations.

1.2.3.3 Code Speed and Robustness

The real time required to simulate a transient is a product of both the code's speed and robustness, both of which greatly impact the efficiency of the analyst using the code. Current codes are often poorly structured, because new features were often added in a quick "fix up" mode, so that the resulting coding is very inefficient. Also, complex data structures, resulting from optimization for machines with small memories, impede the ability to apply new and potentially more efficient matrix solution algorithms, as the programming effort (and the probability of introducing errors) is enormously increased. These same factors also limit the potential of present codes to take advantage of one method to speed up codes by parallel processing.

Time-step size is the other factor affecting code speed, and it is primarily governed by stability and convergence considerations. A systematic effort will be needed to trace the source of these limits so that the efficiencies of more implicit schemes can be realized.

Robustness concerns the ability of a code to calculate a given transient through to completion without user intervention. When the code fails frequently and is restarted by the user with a different time-step strategy, it takes longer to reach the end of the transient. Code speed and robustness affect all users but are of particular significance to those conducting PRA studies, as they must run large sensitivity matrices of calculations.

1.2.3.4 User Friendliness

User friendliness concerns the degree of difficulty one encounters in using a code, for both the laborious task of input deck preparation and the equally daunting task of interpreting the output. Overlaying both of these issues is the so-called "user effect," that is, the likelihood of different code users getting significantly different results for the same transient even though using the same code.

The current codes require monumental efforts to prepare the input decks and often put a large burden on the user, in the name of providing flexibility, by giving the user too many input options and no on-line guidance. Further, the current codes have demonstrated a distressing tendency to produce results that are time-step dependent, and the time-step control is largely left in the user's hands. Finally, interpreting the results has become somewhat easier because of the development of back-end interfaces, XMGR5 for the RELAP5 code and XTV for the TRAC-P code, but much remains to be done to bring this to the current state of the art in the software industry. Again, dividing resources between multiple efforts not only dilutes the effort but also makes the user's task more difficult as multiple code interfaces, each with its own philosophy, must be learned.

In summary, our current suite of thermal-hydraulic analysis codes suffers significant deficiencies with respect to the current state of the art in terms of: programming style, numerical techniques, the two-phase flow model, the reactor kinetics model, the constitutive relations, and user interfaces. Correcting these deficiencies is greatly encumbered, if not prevented, by both the multiplicity of codes and by the difficulty of modifying these codes because of their antiquated programming styles.

1.3 Code Development: Identified Needs

As regards the tools that will be needed to provide the NRC with the necessary analysis capability, the primary need is for a system thermal-hydraulic code applicable to current generation PWRs and BWRs for both large- and small-break LOCAs and for operating transients. This basic capability must be modular in nature to allow for future enhancements that might be needed to accommodate other designs, such as advanced passive LWRs or university research reactors. This basic system thermal-hydraulic analysis capability also needs to be compatible with other codes to perform coupled reactor system/containment, coupled thermal-hydraulics/neutronics calculations, and coupled thermal-hydraulic/severe accident calculations. Finally, though our present analysis tools meet some of these needs, significant deficiencies exist and upgrading is needed in several areas.

- Accuracy: Present calculational uncertainties are larger than our data base warrants, possibly leading to overly conservative calculations.

- Speed and Robustness: Determining uncertainties requires the simulation of a large number of transients. These runs need to execute quickly and without frequent "crashes" that require user intervention.

- User Friendliness: Both pre- and post-processing tools need to be upgraded to make input deck preparation and modification simpler and less sensitive to "user effects," as well as to make the code results easier to comprehend.

Along with the above computational tools, a core competency in thermal-hydraulic code development and reactor safety analysis needs to be rebuilt and subsequently maintained. Experience over the last several years has shown that trying to rebuild this capability in a "crash program" to meet a specific need, e.g,, the analysis of advanced passive reactor designs, is very costly in terms of both time and money.

To effectively and efficiently meet the future thermal-hydraulic analysis needs of the NRC, a sustained long-term effort is needed. The effort envisioned by the staff would entail the development of a next-generation reactor safety thermal-hydraulic analysis code with a viable experimental program and the development of a world-class thermal-hydraulic research team within the NRC. The proposed research is outlined below showing how these three elements can be woven into one cohesive program.

1.4 Code Development: Strategic Plan

As briefly outlined above, the NRC currently supports four different thermal-hydraulic analysis codes involving three different DOE laboratories and one university. The continuance of this situation indefinitely - in a future of declining budgets - is clearly untenable as ever-higher fractions of the available research resources would be needed to maintain outmoded technologies with little or no advancement to keep up with the state of the art. To effectively address this situation, both a short-term and a long-term strategy are needed.

The short-term strategy is to combine the capabilities of the codes so that they can be used to meet NRC's current analysis needs in a more efficient manner. To meet the objectives of the short-term strategy, the two versions of the TRAC code will be merged and a 3-D neutronics package will added during the next 2 to 3 years. The resulting single code will replace the RAMONA, TRAC-B, and TRAC-P codes for large-break LOCAs, ATWS, and reactivity accident calculations, leading to a reduction in maintenance costs. Though some modernization of the TRAC architecture will have been accomplished during this effort, the combined code will retain the "procedural" structure of its progenitors as opposed to a thoroughly modern "object oriented" architecture. After the consolidation period is complete, the combined TRAC code will be put in a maintenance mode until its replacement by the next generation code.

Concurrent with the above consolidation effort, a general purpose thermal-hydraulics graphical user's interface will be developed by a contractor. Also, the RELAP5 code will be maintained as the tool for analyzing small-break LOCAs, operational transients, and passive ALWRs. This maintenance period for RELAP5 will be for five years, during which time the development of the next generation code (see below) will have progressed to the point that the capabilities of RELAP5 and the consolidated TRAC code will have been recovered and they can be replaced. After two years of testing and assessment, maintenance of the TRAC and RELAP5 codes will be discontinued.

The long-term strategy will result in a thermal-hydraulic systems code employing the following elements:

- Start with the capabilities of the current four codes,
- Implement modern code architecture,
- Upgrade the numerical solution scheme,
- Improve the two-phase flow model,
- Improve the constitutive models and correlations, if needed, and
- Improve the user's interface and reduce the magnitude of the user effect.

In this way, the different modeling capabilities embodied in the RELAP5, TRAC-P, TRAC-B, and RAMONA codes will be combined into a single state-of-the-art computer code, exploiting new technology in the areas of parallel processing, two-phase flow modeling, and computational methods, thereby enabling us to capitalize on lessons learned from existing code development without substantially changing models that are shown to be acceptable. A brief description of these elements, the rationale for their inclusion in a new thermal-hydraulic analysis code, and their relationship to other elements of the long-term strategy is given below.

1.4.1 Modern Code Architecture

In the future, the outmoded programming techniques used for the current codes would continue to hinder our efforts to maintain a state-of-the-art analysis capability. Implementing a modern code's architecture is essential, one that would have the following attributes.

- Adapts easily to a parallel processing environment (increased speed),
- Is highly readable and has a data base that is easy to modify (minimized maintenance/development costs),
- Maximizes portability and minimizes machine and compiler dependency,
- Keeps the numerical scheme and constitutive models separate and employs a component-based structure for the physical models (easy to upgrade numerics and models).

Implementing a modern architecture consists not only of using a modern programming language, either C++ or Fortran 90, but also of using a modern data base and modular structure. To make the next generation code truly modular, that is, modular by both component and function, the modern software development paradigm of an object oriented programming will be adopted. To accomplish this, it will be more efficient (and produce a higher quality product) to "re-engineer" the models from the existing codes into a new architecture, than to try to retrofit a new architecture onto an existing code.

In addition, substantial improvements could be made in significant areas: the numerical scheme, the two-phase flow model, the physical models and correlations, and the user's interface. In some cases, the technology needed to make these improvements is readily available and requires an implementation effort as opposed to a research effort. These upgrades will be implemented directly into the systems code. In other cases, a significant component of the technology remains to be developed and small exploratory research efforts will be launched to develop this technology. In the description of the activities given below, the distinction between evolutionary improvements (ones that require implementation only) and more revolutionary efforts (that require development beyond the current state of the art) will be indicated.

1.4.2 Numerical Solution Scheme

To improve code speed and robustness, it will be necessary to upgrade the numerical solution scheme. At present, long-term analyses using the RELAP5 code are hindered by the explicit nature of the numerical scheme as the time step is limited by the Courant condition. Often, the resulting time step is on the order of 0.005 seconds. A more implicit scheme could employ time steps on the order of seconds or even tens of seconds, thereby greatly reducing the time needed to complete a calculation. A more implicit scheme has been successfully implemented in the TRAC-P code, however, its performance can be degraded by "problem numerical stability," leading to time-step reduction, code failures, or numerically driven oscillations. Improvements in the numerical scheme would lead to reduced run times and less frequent code crashes requiring user intervention.

The SETS (Stability Enhancing Two-Step) method from the TRAC-P code will be used as the base numerical solution algorithm. Also, a systematic effort will be conducted to uncover and eliminate the root causes of "numerical events." In particular, efforts will be devoted to the handling of phase disappearance, the appearance of non-condensable gases, "water packing," and intelligent time-step control. These efforts are evolutionary in nature and will include investigating the use of methods such as the stiffly stable schemes, higher order differencing schemes (for thermal stratification and two-phase level tracking), and multidimensional solution schemes that have a higher level of implicitness.

Although the thermal-hydraulic codes that are discussed in this paper are essential to understanding fluid system performance, in certain situations it is important to understand the phenomena that occur within particular components (such as steam generators) themselves. For this purpose, our system-level codes are not well suited, and we need to have a tool available that has different capabilities. These codes are known as computational fluid dynamics (CFD) codes, and they are used in many commercial applications, such as chemical plants, combustion systems, and aerodynamics, to provide detailed information about fluid behavior.

To support the agency need in this area, a series of pilot projects will be initiated to determine how this technology can best fit into the agency's toolbox. These projects may be carried out in collaboration with universities, outside corporations, international organizations, and in-house staff, and they will consider various CFD products that are available from both U.S. Government and commercial sources. We will evaluate the ability of different codes to track complex fluid interfaces in viscous multi-phase flow geometries, as well as their ability to model mixtures of vapor and liquid that contain small bubbles or drops. The evaluation is expected to improve our insights in fluid dynamics and might eventually lead to adopting of similar methods for interface tracking and adaptive meshing, particle and lattice gas methods, and sub-grid scale modeling in the system codes. Even if these techniques are not incorporated into the system codes, we expect that the pilot programs will identify the appropriate CFD technology that the agency should use for component-level analysis of fluid-dynamics problems, such as in steam generators.

1.4.3 Two-Phase Flow Model

In concert with improving the efficiency of the computational tools, it is necessary to improve the fidelity of their simulations as well, which will require improving the degree of sophistication in the representation of two-phase flow. Immediate gains can be made by adding a droplet field to the current two-fluid model (as was done in the COBRA/TRAC code, developed initially by the NRC and now used by Westinghouse). The addition of a droplet field allows for a much improved representation of the two-phase flow field for regimes in which the liquid phase has two characteristic velocities, such as the annular/mist flow regime. Upgrading the two-phase model from the two-fluid to the three-field formulation is an evolutionary effort and will be incorporated in the systems code.

Of equal significance would be the replacement of flow regime maps used to characterize the nature of the two-phase interface with a dynamic flow regime model. Here, the traditional flow regime map would be replaced by introducing interfacial area transport equations whose source/sink terms represent the processes that govern the creation or destruction of interfacial area (e.g., bubbles coalescence or break up). Thus, the empiricism inherent in the modeling of two-phase flow would be moved to a more fundamental level. This technology is far from being fully developed and must be considered revolutionary in nature, especially for two-phase flow in complex geometries such as reactor coolant systems. However, the instrumentation has now matured (see the discussion under two-phase flow modeling in Section 2) and an experimental program, going hand-in-hand with the effort to improve the computational model, would greatly enhance our predictive capability.

1.4.4 Models and Correlations

Even with a more fundamental model for two-phase flow as described above, a systems thermal-hydraulic analysis code will retain a set of models and correlations that includes hundreds of empirical relations. At present, the models and correlations employed in these four codes are inconsistent (i.e., different models are employed for the same phenomena in different codes), often employ ad hoc formulations or undocumented smoothing functions, and do not reflect the knowledge embedded in the existing experimental data base. Together with improving the description of two-phase flow (see above), some of the greatest gains can be realized through a comprehensive upgrading of the models and correlations.

This effort will include the establishment of an electronic data base that contains the supporting empirical evidence for each of the models or correlations for phenomena judged to be of high importance.[1] Then, a quantitative review of the applicability of the models/correlations in the current codes will be conducted. For these high-ranked phenomena, if the accuracy of the present model is found to be insufficient, either a new model will be developed from the existing data base or separate effects tests will be conducted to generate the needed data base as necessary. In this approach, there are two features that have not generally been present in the past: (1) the needed models will be developed within the framework of a two-fluid code and (2) the associated data base will become part of the code documentation and electronic archive such that it will be readily available for assessing future model upgrades.

This effort to upgrade the models and correlations is evolutionary. If the research into modeling two-phase flow through the use of interfacial area transport equations has promising results, an experimental program will be needed to develop the necessary constitutive relations as part of the exploratory research effort.

One of the key processes in assessing the system code capability for transient analyses of nuclear reactors is establishing of the code scale-up capability to plant conditions. Although it would be most desirable to verify code performance against actual plant transients and accidents, this is usually impractical. Instead, the codes are verified primarily by comparing their predictive results against the measured results of scaled experimental test facilities. In order to establish that the code behavior at small scale is applicable to analyses of the full-scale reactor systems, three important activities need to be performed:

1. The code assessment team must first assess the scaling base for the various experimental facilities to ensure that the test equipment does not distort the phenomena of interest in a significant way.

2. The assessment team must then establish that the application of the code at the reduced scale of the test facilities does not violate any limits of applicability of any internal code models.

3. The assessment team must then establish that the code performance in predicting the behavior of the experimental test facility can be scaled up to the full scale of the operating reactor.

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[1] The results of currently existing phenomena identification and ranking tables (PIRTs) will be used to help establish priorities in upgrading the constitutive relations.

These three activities, when taken together, are used to demonstrate that the code models and constitutive relations within the code, and the code as a whole, can be applied to analyses of the full-scale plant. As part of this thermal-hydraulic research plan, we will review scaling philosophies and programs used in the past and will develop a unified philosophy for addressing scaling effects as a part of overall code assessment.

1.4.5 Improved User's Interface

The term "users' interface" essentially relates to the degree of difficulty encountered in using a code, for both the laborious task of input deck preparation and the equally daunting task of interpreting the output. Overlaying both of these issues is the so-called "user effect," that is, the likelihood of different code users getting significantly different results for the same transient even though using the same code. Current codes require monumental efforts to prepare the input decks and often put a large burden on the user, in the name of providing flexibility, by giving the user too many input options and no on-line guidance. Clearly, the area of user interfaces is one in which a large effort is needed to:

- Make input more "hardware" oriented instead of "code" oriented. For example, a user would enter the pipe schedule and diameter instead of individual volumes and flow areas for computational volumes.
- Build user guidelines into the user interface so that default noding schemes are automatically generated.
- Provide greater guidance on the objectives and limitations of the user input option and provide more default settings.
- Implement more "intelligent" time-step control algorithms decreasing the sensitivity of the results to time step size, with an option for "hands-off" use.
- Make the post-processing tool more flexible and easier to use so that the analyst has more help when trying to interpret the code results.

The activity to improve the user's interface was started in FY-96.

1.5 Summary of Code Development Plan

In summary, the proposed long-term strategy is to develop a single state-of-the-art code, taking the best of all the available codes, using modern code development practices, and incorporating advances in modeling, numerical methods, and graphical interfaces from other disciplines. As discussed below, some research effort would be executed in-house, drawing on outside expertise of consultants, so that the resulting knowledge base would be developed and reside in the staff.

2. Two-Phase Flow Modeling

The success and the quality of the future plant transient code largely depends on the availability of a significantly improved two-phase flow formulation and constitutive relations supported by detailed experimental data. Therefore, this Research Plan calls for significant research effort in the areas of two-phase flow modeling, instrumentation, and separate effect experiments that should be pursued systematically and with clearly defined objectives. Phenomena Identification and Ranking Tables will be used to determine the various characteristics and properties of models and processes that should be formulated clearly, on a rational basis, and supported by experimental data. For this purpose, specially designed instrumentation and experiments are required that must be used in conjunction with and in support of analytical investigations.

2.1 Significance of the Problem

The weakest link in the two-phase flow formulation is the constitutive equations for the interfacial interaction terms. The difficulties arise from the complicated motion and geometry of interfaces in a general two-phase flow. Furthermore, these constitutive equations should be expressed by the macroscopic variables based on proper averaging.

The interfacial transport terms are strongly related to the interfacial area concentration and to the local transport mechanisms such as the degree of turbulence near interfaces. The driving forces for the interfacial transport depend on the local turbulence, transport properties, driving potentials, and some length scale at the interfaces. This length scale may be related to a transient time such as the particle residence time or to the interfacial area concentration and void fraction.

One of the major difficulties in developing a reliable two-fluid formulation is modeling of the constitutive relations for the interfacial transfer of momentum and energy, which does not have a counterpart in a single-phase flow analysis. To mechanistically model the constitutive relations for the interfacial transfer and turbulent transfer in two-phase flow requires detailed local measurements of the interfacial area, interfacial velocity, phase velocities, and turbulence, which were not available until quite recently. In the last five years, there have been excellent advances in local instrumentation technology for two-phase flow. These developments were due to advances in electronics, local multi-sensor techniques, and optical methods. Now the local interfacial area concentration, void fraction, interface velocity, Sauter mean diameter, phase velocities, and turbulence in two-phase flow can be measured. These parameters give great insight into the interfacial transfer and turbulent transfer mechanisms. Many of the three-dimensional transfer phenomena can now be measured and quantified such that modeling of the constitutive relations for the interfacial and turbulent transfers becomes realistic.

The new approach for modeling of the interfacial structure that replaces the conventional flow regime maps and criteria should be one of the focal points of the research. The introduction of the interfacial area transport equation or multi-field approach is now possible. The modeling of the interfacial structure is directly related to the foundation of the new two-fluid model.

2.2 Identified Needs

The conceptual models that describe the steady state and dynamic characteristics of structured multi-phase media should be formulated in terms of the appropriate field equations and closure relations. However, the derivation of such equations for the flow of structured media is considerably more complicated than for single-phase flow. In multi-phase or multi-component flows, the presence of interfaces introduces great difficulty in the mathematical and physical formulations of the problem. From the point of view of physics, the difficulties that are encountered in deriving the field and closure equations appropriate to multi-phase flow systems stem from the presence of the deformable interface and the fact that both the steady and dynamic characteristics of multi-phase flows depend upon the structure of the flow.

From the standpoint of analysis, there is a need for improved methods of accounting for the structure and local phenomena in two-phase systems. From the standpoint of experimentation, there is a need for new and improved measurements for local phenomena to support constitutive equation development. The two must proceed in concert for success in producing new reliable computational methods. Also, development of advanced instrumentation development for two-phase flow systems is a necessary component of thermal-hydraulic research. The instrumentation is the basic tool for the fundamental experimental research focused on the important phenomena in two-phase flow.

2.3 Strategic Plan

The strategic plan for the advancement of the state of the art in two-phase flow modeling contains three complementary activities:

1. Use of advanced two-phase flow instrumentation
2. Performance of fundamental two-phase flow experiments
3. Development of improved phenomenological models

For each of these three activities, a list of proposed research efforts is given below.

2.3.1 Use of Advanced Two-Phase Instrumentation

Some advanced instrumentation development will be included in the program as listed below:

- Multi-sensor conductivity probes for the measurement of local interfacial area, void fraction, particle size, and interfacial velocity, particularly for a boiling water system
- Measures of entrainment rate, deposition rate, and droplet size, in high velocity two-phase flow.

- Measures of mass flux and vapor quality
- Measures of critical flow
- Flow visualization and characterization of interfacial geometry
- Measures of liquid flow rate using modified magnetic flow meters or other methods
- Global void sensors

The use of such advanced instrumentation will enable us to obtain data needed for model development and code assessment.

3.3.2 Fundamental Two-Phase Experiments

Using state-of-the-art instrumentation, fundamental experiments focused on the important problems and phenomena can be studied and a database for a model development effort can be established. The following are some of the recommended experiments that will be part of the overall experimental program described in section 3.

- Interfacial area measurements focused on developing a data base for the coalescence sink term and disintegration source term in the area transport equation. This should be performed for both vertical and horizontal flow at several hydraulic diameters.
- Dynamics and instability experiments for single phase and two-phase natural circulation.
- Flashing phenomena in stagnated fluid or in a natural circulation system
- Annular flow experiment focused on the entrainment rate, deposition rate, droplet size, film thickness, and interfacial shear

2.3.3 Development of Phenomenological Models

The proposed model development activities are listed below. Note that some of these efforts are dependent on the experimental activities regarding instrumentation.

2.3.3.1 Interfacial Area Modeling

For predicting the thermal-hydraulic behavior of two-phase flows, the interfacial structure is one of the most important factors. Traditionally, the effects of the interfacial structure have been analyzed using the two-phase flow regimes and regime transition criteria. However, this traditional approach has a number of shortcomings. First, the flow regime transition criteria are algebraic relations that do not fully reflect the true dynamic nature of changes in the interfacial structure. Hence the effects of the entrance or boundary cannot be taken into account correctly, nor can the gradual transition between regimes. Secondly, the method based on the flow regime transition criteria is a two-step method that requires the regime-dependent closure relations for the interfacial area effects. Normally, the effects of these are imbedded in the correlations implicitly; therefore, the compound errors from this approach can be significant.

RES will develop an interfacial area transport equation for the first-order characterization of interfacial structures. For good mechanistic modeling, it is necessary to study bubble coalescence and break-up criteria to get information on the maximum bubble size and bubble size distribution. These are important in the formation of a link between the flow-pattern transition and the characteristics of the interfacial structure, such as interfacial area concentration and void fraction distributions.

Bubble coalescence and break up processes are considered explicitly to develop a more mechanistic model. For this purpose, the use of an interfacial area transport equation for two-phase flow appears to be most suitable. The concept of the interfacial area transport equation was suggested by Ishii in 1975 and subsequently applied for annular mist flow by Kataoka and Ishii to predict the entrainment and deposition processes. The mechanism of the transition from bubbly to slug flow can be considered as the elimination of the dispersed phase by the coalescence mechanism, whereas in the annular to annular-mist flow transition the dispersed phase is created by the droplet entrainment process. The processes are almost completely in the opposite direction. Hence it can be concluded that once the rate processes of the coalescence and bubble breakup are modeled, the gradual transition from the bubbly to slug flow can be predicted through the interfacial area transport equation.

2.3.3.2 Pilot Code Development Using Interfacial Area Transport Equation

The effect of the interfacial area transport equation on the overall two-fluid model formulation and numerical solution method should be studied through a simple one-dimensional pilot code. This will give insight to the dynamic effects of the transport equation, stability of the differential equation system, accuracy of the constitutive relations, and efficiency of the numerical method.

2.3.3.3 Two-phase Flow Instability at Low Pressure

At low pressure, two-phase flow systems tend to be quite unstable because of several mechanisms. In particular, natural circulation two-phase flow at a low pressure is highly unstable because manometric, density wave, chugging, and flashing-induced instabilities. This is because of the flow and void generation are closely coupled in a natural circulation system. Furthermore, because of the large density ratio between liquid and vapor, small fluctuations in heat transfer result in significant void fluctuations. However, two-phase natural circulation is a key in most of the advanced LWR designs that use the automatic depressurization systems and depend on the gravity-induced flow. Most of the existing studies have been performed for a forced flow system at relatively high pressure, hence it is necessary to carry out some basic research to understand these instabilities.

2.3.3.4 Constitutive Relation Development

Constitutive relations and correlations are used in the two-fluid model to close the two sets of conservation equations of mass, momentum, and energy. In particular, the interfacial transfer terms couple the mass, momentum, and energy of phases. There are several areas in which improved constitutive relations can make a large difference in the accuracy and reliability of code predictions based on the two-fluid model formulation, as follows.

- Interfacial Heat Transfer at Low Pressure: The current algebraic heat transfer model for the interfacial energy transfer is too sensitive to the instantaneous changes in the system pressure through the use of the saturation temperature of the interface, particularly at low pressure. This leads to considerable fluctuating energy transfer between the liquid and vapor and leads to oscillatory void fraction predictions. The actual physical process involves the transient thermal boundary layer development, which should exhibit some effects of time delay. Either a time lag model that leads to a difference differential equation or an exponential relaxation model may be used to fix this problem.

- Interfacial Momentum Transfer: The constitutive relations for interfacial drag and shear for certain regimes require further study. These are (1) inverted flow regimes in the post-dry-out region, (2) annular flow at high pressure, and (3) developing flow where void distribution changes rapidly.

- Thermal Non-equilibrium Model: Significant thermal non-equilibrium occurs during flashing, direct contact condensation, and post-CHF heat transfer. Among these, flashing and direct contact condensation are particularly important for advanced LWRs. A mechanistic model of flashing based on the nucleation site density is in the early stage of the development; however, it has the potential to eliminate the large uncertainty in the existing empirical correlation and the shortcomings of the thermal equilibrium model. The condensation of large volumes of steam with noncondensable gas by injected subcooled water is another important problem, yet there are no reliable models or data. Similarly, the condensation of steam with noncondensable gases in a heat exchanger or in a pool of subcooled water is not well understood.

3. Experiments

Experiments simulating reactor plant designs and their components are necessary in order to:

- Perform independent confirmatory tests of an applicant's design to ensure that potential problems are fully explored

- Provide additional independent data in areas of particular importance for existing plants
- Provide additional data for thermal-hydraulic code validation.

These activities require that testing be conducted in scaled integral test facilities. When properly instrumented, these same integral facilities may be operated in a separate effect mode to provide more specific code assessment data and to help establish a data base for model development. It is necessary to continue staff involvement with integral facility experimental programs so that technical skills are not lost.

In 1976, the NRC created a Reactor Safety Data Bank to provide a central, readily accessible repository of qualified test results of tests performed in experimental facilities and reactors. These data were produced by experiments that took place over a period of several decades, in test facilities such as LOFT that cannot be replicated. It is therefore vital that the agency not lose either the data from the experiments or the information needed to accurately model the test facilities for code validation purposes. The staff is in the process of transferring the data bank, from INEL to an internal NRC computer system, and will ensure that both the data from the tests and the experimental facility configuration information are maintained for the use of agency thermal-hydraulic code developers and other code users.

3.1 Significance of the Problem

Large thermal-hydraulic experimental facilities are costly to maintain. There are several available around the world (e.g., in Japan, Switzerland, France) that could probably be used if the need arose for integral experiments. However, smaller scale, university-run facilities provide a more economical alternative with the added advantages of maintaining expertise in nuclear technology in universities and a stream of trained graduates. Gaps in the knowledge of two-phase flow need to be filled in order to conduct regulatory analyses; this can best be accomplished with small-scale facilities in a research environment such as exists at universities.

There are three facilities (OSU, Purdue, and UMD) that have experimental equipment as well as a team of thermal-hydraulic experts. In addition to providing support so that these facilities and on-site teams can be maintained, the NRC should provide an environment in which research teams from other institutions will have access both to these experimental facilities and to the necessary facility support staff. In this way, these three experimental facilities will be shared between on-site and visiting research teams.

3.2 Identified Needs

Code validation and a greater understanding of thermal-hydraulic phenomena depend on properly scaled, designed, instrumented, and conducted experiments. The data base used to develop and assess the existing thermal-hydraulic codes was developed in the 1970s. Because of their intrusive nature, and the long time delay, the instruments that were used were inadequate to provide sufficient data to develop models to represent the complex thermal-hydraulic phenomena. New, less intrusive instruments have been used successfully in other fields. Advanced instruments can be used to obtain reliable multi-phase mass flow measurements, void fractions, two-phase density, and other needed information to identify phase configurations and interfacial areas to improve basic modeling of the two-phase processes.

To develop a data base that is adequate for code validation and for developing of state-of-the-art models, the NRC must maintain the existing experimental facilities and upgrade their instrumentation as described above. These facilities can then be used to obtain separate effects test data both through university research and international collaboration.

3.3 Strategic Plan for Experiments

The strategic plan for experiments provides for maintaining the three existing integral test facilities (OSU, Purdue, and UMD). In addition, to enlarge the data base for code validation and model development, these facilities would be used to conduct separate effects tests.

For each of the three facilities under consideration, we have developed a preliminary list of experiments that could provide us with experimental information that is currently needed for future code development. We will continue to review this list as the development and maintenance efforts proceed, to ascertain whether new or different experiments are needed or whether the information is not needed or is available from other sources.

3.3.1 Separate Effect Tests: Purdue University's PUMA Facility

The PUMA facility at Purdue was originally designed for the confirmatory integral test for the GE SBWR design. This facility has a large number of instruments and includes the capability for local void measurements and flow visualization. Each of the components displays some fundamental characteristics of various two-phase flow systems. It is quite possible to run the PUMA facility for various separate effect tests to obtain fundamental data focused on particular phenomena. The separate effect tests that can be performed without any major geometrical modifications are listed here.

3.3.1.1 Reactor Pressure Vessel (RPV) and Automatic Depressurization System (ADS)

- Single Phase Natural Circulation Benchmark Test: Focused on the natural circulation rate, two- and three-dimensional energy distribution, and flows instability.

- Two-phase Quasi-steady Natural Circulation Test: Focused on void distribution, relative velocity, two-phase level, natural circulation rate, void generation by flashing, and various flow instabilities.

- Rapid Depressurization and Flashing Test: Focused on flashing phenomena and void generation, void distribution, relative velocity, transient behavior of void fraction, flow, temperature and two-phase level, and flow instabilities.

- Critical Flow at Low Pressure Test: Focused on break flow and its measurement for both large (MSL, DPV, and SRV break) and small breaks.

- Downcomer Mixing Test: Focused on cold water injection into the RPV through GDCS, IC, or FWL nozzles, mixing of subcooled water with saturated water and the two-phase mixture, void collapse, condensation, reestablishment of natural circulation, and transition between single phase and two-phase flow.

- Boiler-Condenser Mode Operation Test: Using the RPV and ICS, the steady boiler-condenser mode of core cooling is studied. With limited modifications, reflux condenser mode operation is also possible.

3.3.1.2 Drywell Phenomena

The major focus is steam mixing with noncondensable gas in the dry well. The inertia transition and plume regimes are studied separately. Another focus is the effect of the vacuum breaker operation on the noncondensable gas distribution.

3.3.2 Separate Effects Tests: Oregon State University APEX Facility

The APEX facility was specifically designed to obtain integral system thermal-hydraulic data for the proposed AP600 design. However, with improved instrumentation, separate effects data can be generated that would pertain to not only the AP600 design but to generic PWRs as well.

3.3.2.1 Flow Stability and Heat Transfer in Forced Flow and Gravity Driven System

- Steam Generator Heat Transfer: Steady state and transient tests to improve understanding and modeling of heat transfer processes from primary to secondary.

- Two-Phase Natural Circulation: Perform natural circulation tests for the primary loop and steam generator with reduced system inventory to identify the conditions for the onset of instability.

- Onset of Tube Voiding: Perform natural circulation tests with reduced primary pressure to study the onset of tube voiding and breaking of the natural circulation loop. The prediction of this phenomenon is important to the potential occurrence of thermal stratification in the cold legs for the AP600 and for PTS in existing PWRs.

3.3.2.2 Critical Flow in Valves and Orifices

Perform critical flow tests under multiple chocked flow conditions (resonance effects) in spargers and valves and under single choked flow condition such as breaks.

3.3.2.3 Thermal Stratification

Construct a thermal fluid mixing map which describes the primary loop conditions under which cold leg thermal stratification can occur.

3.3.2.4 Two-phase Fluid Flow Pattern and Flow Pattern Transition in Complex Reactor Components

- Counter-Current Flooding Limit (CCFL): Identify the conditions at which the pressurizer cannot drain because of the CCFL at the surge line during operation of safety relief valves or the ADS systems. Complement the system tests with air/water bench tests to permit flow visualization and characterization of flow patterns.

- Level Swell: Perform pressurizer blowdown tests to determine level swell and phase separation during flashing conditions.

3.3.2.5 Phase Separation in Tees

Perform flow visualization and phase separation tests suitable for assessment or development of off-take model for geometries typical of hot leg/surge line and hot leg/ADS-4 conditions.

3.3.2.6 Multi-dimensional Turbulent Mixing Induced by Tube Bundle Boiling

- Determine the heat transfer characteristics, both in-tube and pool-side, for a heat exchanger submerged in a pool.

- Investigate thermal plume behavior in and around the submerged bundle and develop data on thermal stratification at the pool surface.

3.3.3 THECA program at University of Maryland Facility

One of the characteristics of the thermal-hydraulic experiments for code assessments (THECA) program is the flexibility of the test facility, resulting in low operating costs that would allow performing extensive sequences of repeat tests. In addition, because of the proximity of the UMD to the NRC headquarters, we will be able to use the staff in executing the experiments, thus providing the staff with hands-on experience. The following are some of the tests to be investigated under the THECA program.

- Liquid thermal stratification under vapor space--conditions for stable existence and for an onset of rapid condensation

- Single Loop Interruption/Resumption Mode--associated with natural circulation behavior.

- Single Loop Condensation Controlled Mode--originating from condensation of two-phase flow entrained over the candy-cane (B&W hot leg).

- Cold Leg Downcomer Flow Distribution--related to multidimensional effects in nearly stagnated system important for pressurized thermal shock (PTS).

4. In-house Capability

It is essential for the NRC to sustain the highest level of research expertise in thermal-hydraulics and reactor safety and to continuously improve our capability to analyze plant transient. To this end, a new direction has been set, one in which challenging research activities will be conducted in-house or in close collaboration with a contractor. Not only is this better for the agency's long-term interests, it is necessitated by declining capabilities at national laboratories and the declining budget for research. Future thermal-hydraulic research activities will be focused primarily in three areas:

1. Reactor Safety Code Development: The next generation thermal-hydraulic code (see Section I of this appendix) will have strong involvement of the NRC staff, and in addition to providing the computational tool for the future, will provide the opportunity for our junior staff to become tomorrow's experts.

2. Reactor Analysis: The staff will use the current (and future) code to perform analyses of both plant transients and integral facility experiments, requiring the current staff training program to continue.

3. Thermal-Hydraulic Experiments: Although the experiments will not be conducted here, the staff will actively participate with university researchers to develop a data base sufficient for future model development (the fundamental tests described in Section II) and model assessment (the separate effect tests of Section III).

A stable long-term research budget is needed to accomplish the above, which will result not only in the development of computational tools and expanded data bases, but also in a research staff capable of meeting the agency's needs in the future.

4.1 Plan

One of the primary goals of this research plan is the development of a world class thermal-hydraulics research team within the NRC. To do this, core competency in thermal-hydraulic code development and reactor safety analysis needs to be rebuilt and subsequently retained. The expertise required is above and beyond that resulting from a university nuclear engineering curriculum and can only be developed through performing research with the aid and supervision of a suitable mentor. To this end, two new branch members have been recruited; one with experience in numerical methods to supplement the two-phase model development experience of a current senior staff member, and another with experience in reactor plant analysis. These three individuals will form the nucleus of code development and analysis teams.

Given the above goals and budgetary constraints, development of the next generation thermal-hydraulic code would be undertaken by a small, well-organized team with less expenditure of resources and would have the crucial benefit of allowing the staff to develop expertise for the future. This team would be organized along functional lines that could be pursued independently for example, physical model development, numerical solution, neutronics, data management and parallel processing, and development of a graphical user interface.

In functional areas in which the staff is expert, the lead role would be undertaken by the appropriate staff member. In other areas, when the expert individual is from industry or academia, an NRC staff member would work closely with consultants, not as a project manager, but in an "apprentice" role. Such apprenticeships are designed to ensure a "technology transfer" between the outside consultant and the staff, so that expertise in each critical functional area would be developed in-house.

As for plant transient analyses, the current staff retraining program will continue and will be expedited by the addition of the new staff member. The program in two-phase fundamental experiments will provide an opportunity for the staff to collaborate with university researchers and develop expertise in the area of two-phase flow physics.

4.2 Near Term Plan

1. Continue training the staff to run and interpret our computer codes.
2. Recruit one more code developer to supplement the existing one, and recruit a staff member with analysis experience. This part of the plan is complete.
3. Investigate the use of a commercial contractor to maintain RELAP5 and service the CAMP users (in lieu of a national laboratory) for improved cost and performance.
4. Move RAMONA maintenance in-house.
5. Continue to analyze the systems tests from ROSA, SPES, and OSU in-house.
6. Continue international interactions on codes and data, domestic and foreign. Organize OECD/CSNI Workshop on the requirement for transient thermal-hydraulic and neutronic codes (to be held in Annapolis, November 5-8, 1996).
7. Sponsor in-house courses and seminars and international workshops to hone and maintain skills.

4.3 Long Term Plan

To achieve a state-of-the-art plant transient code <u>and</u> the associated expertise within the NRC requires a commitment to a modest long-term program that would involve:

- Assignment of five to six branch members to the code development team on a full-time basis

- Placement of consulting contracts for about five outside experts for at least five years.

- Contractor support to perform tasks such as code configuration control, code maintenance, and user support.

Similarly, the programs in two-phase flow fundamentals and separate effects testing would require the staff to work closely with university professors to formulate and conduct experimental programs to obtain information on some phenomena or process or on some integral response. Management will ensure interaction on specifications for tests at an early stage between the staff and contractors responsible for model developments and those responsible for experiments. This interaction is to be coordinate how the facility is nodalized and how it is instrumented, as well as to ensure that measurements are sufficient for model development needs. In addition, we plan to:

1. Train staff to run and interpret the new thermal-hydraulic code.

2. Continue courses, seminars, and workshops to maintain expertise.

3. After evolving to one code, rely on NRC staff to develop additional models for the code. Use a contractor to maintain the code and to support code users.

4. Remain current on international experimental programs through cooperative efforts.

USNRC Code Consolidation and Development Program

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ABSTRACT

The United States Nuclear Regulatory Commission (USNRC) is currently consolidating the capabilities of its four thermal-hydraulic codes into a single code. The goal of the effort is to recover the functionality of the current suite of codes while reducing the maintenance and development burden. The user community will then be able to focus on one code instead of four, thereby enhancing the knowledge-base. A modernized and modularized TRAC-P code, now called TRAC-M, serves as the basis for the consolidation. The architecture has been revamped and the language migrated to FORTRAN90 to produce a more modular, readable, extendable and developer-friendly code. A neutronics package has been coupled to TRAC-M using PVM to provide a one-dimensional (1-D) and three-dimensional (3-D) kinetics model without having to add this functionality to the TRAC-M code itself. This allows the ability to improve the neutronics model or hydraulic model in TRAC-M independently. BWR components were incorporated into TRAC-M using the modeling philosophy of TRAC-B. In TRAC-B, these components were built based on generic 1-D components, such as pipes and tees. Special terms were added to the generic equations if a BWR component were being modeled. Since TRAC-M already models generic components, only the BWR component specific terms were migrated to TRAC-M. Therefore, the consolidated code is not a super-set of TRAC-B and TRAC-M. TRAC-M has the ability to read a TRAC-B input deck and these decks are being run as a means of identifying constitutive models that must be used by the BWR components to produce results that are consistent with TRAC-B and data. Throughout the consolidation effort, improvements have been made to the code. These include: a semi-implicit numerics scheme to be used as an alternative to SETS in order to reduce numerical diffusion; an exterior communication interface, which facilitates the coupling of TRAC-M to processes running outside of the TRAC-M code, such as a simplified accumulator model; and a faster sparse matrix solver to be used as an alternative for large 3-D matrices. Effort has also been spent in modifying TRAC-M to facilitate the conversion of RELAP5 input decks. This functionality will be provided by the graphical user interface currently under development for both TRAC-M and RELAP5. Once the consolidation of the BWR applications is completed, and the code has been fully assessed, USNRC will then determine the most efficient way to consolidate the functionality of RELAP5. This work will mainly involve assessing the codes against each other and data and modifying TRAC-M constitutive models to allow TRAC-M to

simulate phenomena associated with RELAP5 applications (PWR SBLOCA and transients) while preserving its simulation fidelity with respect to those of the other codes. However, USNRC will continue to maintain RELAP5 and make user-requested improvements, such as the minimization of mass error, flow oscillations, and time-step/platform dependency. Throughout this process, USNRC will ensure that user needs are accommodated and will provide a transition period during which the codes are maintained until the user community has acclimated to the consolidated code.

1. Introduction

The USNRC currently relies on four different thermal-hydraulic system analysis codes to audit vendor or licensee analyses of new or existing reactor designs, to establish and revise regulatory requirements, to study operating events, to anticipate problems of potential safety significance and to support risk-informed regulation by determining thermal-hydraulic success criteria. The codes have similar but not identical capabilities.

For PWRs, the RELAP5 code is primarily used for simulations of SBLOCAs and plant transients and provides a 1-D representation of the flow-field. Generally, RELAP5 was developed as a fast-running, more simplistic code for long-term transients. In contrast, TRAC-P was utilized for faster transients, such as LBLOCAs, and provided a more detailed description of the flow-field with a 3-D representation of the vessel. In recent years, this distinct separation of functionality has been eroded and the present capabilities of the two codes overlap. However, the codes often model the same phenomena with different constitutive packages and also employ different numerical schemes. Until recently, the reactor physics capabilities of the two codes were limited to point kinetics. As will be explained in detail in Section 4.3, a 3-D kinetics capability has been provided to both RELAP5 and the consolidated code (TRAC-M) with tight parallel coupling to an advanced three-dimensional kinetics package using Parallel Virtual Machine (PVM).

For BWRs, the situation is comparable. The RAMONA code treats the flow field as 1-D but incorporates a 3-D kinetics package. A 3-D representation of the flow field is provided by the TRAC-B code, but the neutronics model is limited to either point or 1-D. The TRAC-B code stemmed from the TRAC-P code and was developed in parallel specifically for BWRs. It incorporates BWR specific models, such as the jet pump and feedwater heater and also utilizes a different constitutive package and numerical scheme. The development of both TRAC codes proceeded independently.

The USNRC system analysis codes were developed in the 1970s and do not take advantage of today's abundant supply of inexpensive, fast memory. In addition, older programming languages did not readily provide a means for dynamic memory allocation. As a result, creative programming styles such as "bit packing" and "container arrays" were invoked to overcome these limitations. Unfortunately, these techniques produced cryptic coding and compromised readability (the ability to read the code), maintainability (the ability to fix errors in the code), extendibility (the ability to add new capabilities) and portability (the ability to run on different platforms). Presently, a great deal of effort is vested in deciphering these codes in order to fix bugs or improve the physical models or numerics. Since when the codes were first developed, less than optimal architecture was chosen in order to conserve memory, architecture modifications are now necessary to ameliorate these development difficulties.

Other issues exist in which code architecture is a secondary concern. Assessment studies have identified physical models that require improvement. Physical models requiring further development include those pertaining to the phenomena of phase separation at tees, subcooled boiling at low pressure, and reflood heat transfer. By initiating separate effects test programs, USNRC is in the process of supplementing the existing database in order to improve these models. More detailed or prototypic data are being generated to be used for assessment as well as model development. These test programs are further described in Section 5. If such codes are to be used to support risk-informed regulation, then in addition to improvements in physical models, numerical methods should be upgraded to enhance the speed and robustness of the code and to minimize numerical diffusion to preserve property gradients, which can be important in 3-D kinetics calculations. A well designed architecture makes revision or replacement of physical models and numerical methods much easier.

User convenience was not the highest priority when the codes were developed. The older technology relied on command line input, which did not provide the analyst a means of easily determining the configuration of the modeled system or which code options were used in the simulation. In addition to not being user-friendly, the codes had limited ability to minimize the user effect, aside from generating a text output summarizing user options. Therefore, development of a graphical user interface (GUI), which will facilitate use of the code and help minimize user effect, is necessary for each of the four codes.

Since each code requires modernization and would benefit from an improved user-interface and an upgrade in physical models and numerics, USNRC is consolidating the suite of codes into one, with an aim of minimizing the dilution of resources that occurs with the development of four separate codes. As a result, user needs will be accommodated more expediently, since effort will not be distributed amongst the four codes. Additionally and perhaps most importantly, the consolidation will enhance analysis capabilities, as the USNRC and user community can focus its attention on one code thereby developing collective expertise far more efficiently than is possible when four codes are utilized. Input deck construction will not be duplicative, as all transients for a plant would be performed with one code instead of two.

2. Consolidation Plan

When the USNRC set the general goals for the consolidated code, a choice was required for the starting point of the effort. The options were to write the consolidated code from scratch, or to evolve an existing code to the final desired state. The evolutionary approach was suggested by a panel of code development experts convened in 1997 by USNRC, and was adopted for the following reasons:

1) Ability to have a functional code at all stages of the development process;
2) Existence of a large set of input decks for code testing;
3) Ability to design a sequence of code changes so that most test problems match results to the last bit (null testing); and
4) Automatic reuse of subprograms or code segments that already meet new requirements.

TRAC-P was selected as the base version of the consolidation because its structure was more modular and object-oriented, making it more closely aligned with final design goals for the consolidated code. It has 3-D flow modeling capabilities not available in RELAP5, and was a better target for installation of special purpose BWR component models developed for the TRAC-B code series. Through the use of the Graphical User Interface (SNAP), currently under development, the consolidated code will have the ability to process all archival RELAP5, TRAC-P, TRAC-B input decks. Simply, SNAP was chosen to process input, and TRAC-P was selected as the starting point for the computational engine of the consolidated code.

Our experience thus far with the evolutionary approach has been very positive. The null testing capabilities have speeded development and increased our confidence in the resulting code. BWR capabilities have merged very smoothly into the original PWR code. The underlying architecture has evolved into a new, much more "developer friendly" environment. We have significantly enhanced extensibility, readability and in turn, maintainability over the predecessor codes. Optimization of the architecture to enhance these attributes continues to be the prime design goal, as future development and maintenance efforts will be accelerated and developer expertise gained more rapidly. The end result will be a code that can be adapted new user needs with far less effort than the current generation of safety analysis codes.

2.1. Consolidation Stages

Consolidation consists of three major stages. The first is creation of a modern architecture under which desired features can be implemented and maintained with minimal effort. The second is installation of the general modeling capabilities (mesh topology, system components, and physical processes) of the four predecessor codes. The third is assessment during which the best model or correlation from the predecessor codes will be installed, so that the consolidated code will generate results as good as the predecessor codes for the targeted applications. The first two of these stages have been completed and are described in Sections 3 and 4. The third stage is currently in progress. Figure 1 depicts a timeline of the consolidation activities and is described in Section 4.

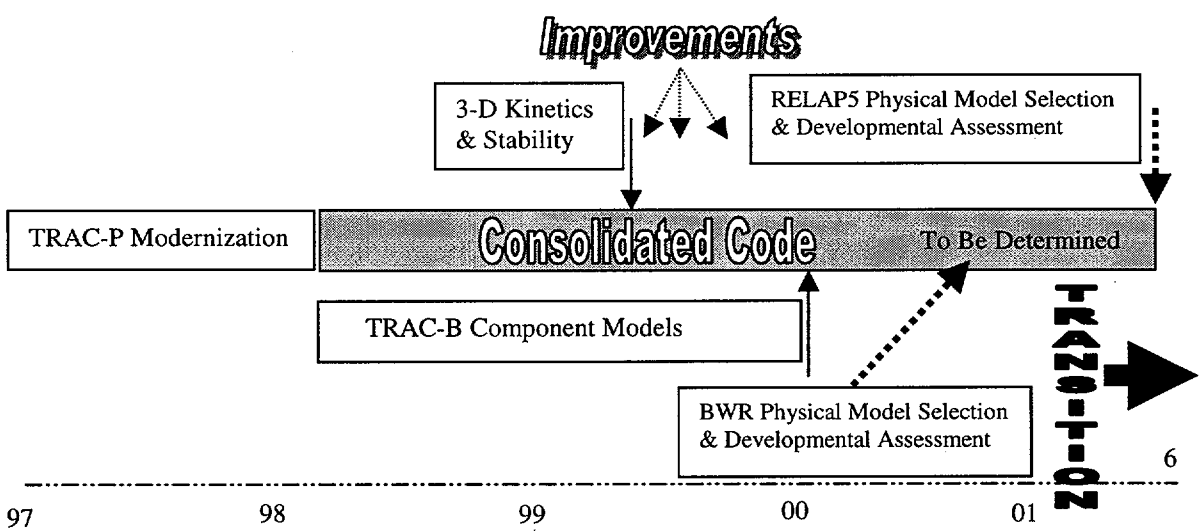

Figure 1: Consolidation Plan Timeline

2.2. Code Configuration and Software Quality Assurance

The plan of the consolidation stresses the importance of documentation and version control. To manage the versions created during the consolidation, USNRC has developed a configuration control system utilizing Concurrent Versions System (CVS) [http://www.sourcegear.com/CVS] and a development website. The development history is evident by perusing the "Build Page" of the website. The Build Page consists of a table with each row specific to a single version. Four columns contain: 1) the version number, which is a hypertext link to download the code; 2) links to the directory containing the modified files, test files and documentation; 3) a brief description of the modification; 4) the developer's name. By perusing the Build Page, a developer can quickly determine what changes have been made to the code. Future versions are also listed to enable developers working on potentially conflicting changes to resolve any problems. The website contains other pages, such as the Test Page, which provides links to download various test sets and describes what each test set covers, and a Troubles page which provides links into the Trouble Report Database, so that users can upload bug reports or developers can enter the resolution. When a report is filed, the user and developer are automatically E-mailed that the report has been assigned to a developer and the uploaded input deck has been received. When the bug fix is incorporated into the code, the user is E-mailed the resolution report and informed which code version, accessible from the Build Page, contains the fix. If a version on the Build Page was developed as a bug fix, then the Build Page entry describing the modification will contain a link to the Trouble Report Database.

The documentation uploaded depends on the type of code modification. If a bug fix is submitted, then an error correction report is filed and is accessible from the Build Page. The Trouble Report Database also contains this resolution description. If a more expansive change, such as a BWR component is uploaded, then full Software Quality Assurance (SQA) documentation is submitted. This documentation includes:

- Software Requirements Document- what does this component have to do?
- Software Design and Implementation Document- how is the functionality achieved in the code?
- Test Plan- what tests must be run to prove the requirements have been met?
- Completion Report- summary and results of the test plan

A summary document is also submitted. It is accessible from the Build Page by the links into the directory containing the uploaded files. The summary document describes the main points of the SQA documents, so that the full reports do not have to be read if another developer wants to get an overview of the change. When new functionality is added to the code, uploaded tests are run to ensure the requirements are satisfied, and then made accessible from the Test Page. An automated developmental assessment script allows the tests to be run for each version created, and stores the results by version number. Therefore, changes in code results are easily traced.

The CVS code repository, development website, automated testing, and Trouble Report database have resulted in an organized and efficient development process. The modifications made to the code during the development are described in following sections.

3. Architectural Improvements to TRAC-P

As depicted in Figure 1, the first stage in the consolidation is the creation of a modern architecture under which desired features can be implemented and maintained with minimal effort. The following sections summarize the new architecture and the modifications made to the TRAC-P code in its evolution to TRAC-M.

3.1. Code Language and Database Design

The base TRAC-P code was written in Fortran77 (F77) and utilized a container array and integer pointers as its form of home-spun dynamic memory allocation as well as common blocks to provide communication of the global data. The associated coding was difficult to decipher. Fortran restrictions that drove the original TRAC-P data structures, have been eliminated with the introduction of derived types, dynamically allocatable arrays, pointers, and modules in Fortran 90 (F90). Features new to F90 also eliminated portability issues common in F77 codes. As a first step in the evolution of the consolidated code, TRAC-PF1/MOD2 version 5.4.25 was converted into F90 and designated TRAC-M.

By utilizing F90 features, TRAC-M data integrity is preserved by limiting the use of common blocks and eradicating the container array. Subroutines only have access to data either passed through argument lists or through the use of modules. A module is a F90 program unit, which allows other program units to access variables, derived type definitions, and subprograms declared within it by the F90 USE association. The general use of F90 modules helps to protect data, compartmentalize functionality and data, and ensures data type consistency. F90 derived types serve as the primary mode of storage. A derived type allows the storage of several data types in one array. Therefore, integers, characters, reals and logicals can be contained in one data structure. As an example, general scalar variables associated with a system component (pipe, tee, etc.) are organized in the following derived type:

```
TYPE genTabT
  INTEGER(sik) :: num
  INTEGER(sik) :: ncell
  CHARACTER*8 :: type
   ...
END TYPE genTabT .
```

The derived type, containing the component number, the number of cells, and the component type (PIPE, TEE, ROD, etc...), is denoted genTab in reference to the fact that this information is common to all components and is "generic". Array data can also stored in derived types. Therefore, state information, such as phasic temperatures and velocities, void fraction, and pressure can also be stored in derived types. Each state variable is an element of the derived type and is an array with length equal to the number of cells in the component. These derived types are implemented as arrays with lengths equal to the total number of components. This makes location of information within a calculation very simple. As an example, the user specified ID for the fifth component in the input deck is stored in genTab(5)%num. The volume of the 3rd cell in this component would be obtained from g1DAr(5)%vol(3). g1DAr refers to the fact that this array data is generic to all 1-D components.

These derived types provide great flexibility in database design and allow the storage to be designed based on how the information will be used rather than by data type. The database restructuring capitalized on features of F90 such as dynamic memory allocation, module data protection, and derived types to meet the design goals of enhanced readability, portability, extensibility and maintainability.

3.2. Code Modularity

Originally TRAC-P was designed to contain component and functional modularity. Both the data and program structure were organized around modules in the physical system (e.g. pipes, pumps, vessels). Once the F90 conversion was completed, effort was expended to enhance the code modularity. Modularity was and continues to be a prime design goal, as it reduces conflicts between simultaneous development efforts, and also allows development expertise to be efficiently gained and utilized. For example, a developer working on the control system does not need to know the details of the heat structure coding. All that is necessary is an understanding of the communication service between the control system and heat structure database. Modularity also facilitates code re-use. If isolated tasks are performed by isolated program units, then in each instance the code only needs to call this particular function or subroutine instead of repeating the same logic in a variety of locations. Code repetition produces multiple maintenance points and adds complexity. Therefore, the goal of the modularization work was to provide a code structure with the minimum number of maintenance points, clean interaction points between component-types, separation of functionality at both a high and low level and also preservation of data integrity. In general, there are four basic forms of modularity in TRAC-M, including high and low level functional modularity and both interior and exterior component based modularity.

Functional modularity means that a subroutine or a set of subroutines collectively performs one function. TRAC-M is comprised of four general tasks: input processing, initialization, equation solution and output. These tasks are isolated by specific driver routines so that the code is structured to be functionally modular at a high level. This has been enhanced by improvements in data communication and isolation of equation solutions. In TRAC-P, the solution of linear systems was mixed with coding setting up terms in the flow equations, inhibiting the ability to adapt improved linear solvers to the code and parallelism. In TRAC-M terms in the finite volume equations are now evaluated and the matrix set up in a set of subroutines that are distinct from the subroutine that solves the matrix. This facilitated the incorporation of a new sparse matrix solver that reduces the run-time of the AP600 LBLOCA deck by 25%, while also enhancing parallelism. The new component data structure makes access to information adjacent to any given component very simple. However, direct access of one component's information by another component can disable parallelism within the code. As a result a system service was developed to manage the data communication between components. The service supports communication of information between fluid components, communication of fluid properties to heat structures, communication of heat flux information from heat structures to fluid components, and communication of information from any component to signal variables used by the control system. Most coding and computational effort associated with this service is contained in the initialization stage of a calculation. Timing tests on a 1-D model of LOFT produced identical results using 5% less time immediately after this transfer service was installed, while also enhancing code modularity.

High level modularity has also been impacted by the isolation of ASCII input deck processing into a separate program. This separation began by simply isolating old subroutines used to process native TRAC-P and TRAC-B input decks. The only input activities remaining in the consolidated code are associated with reading a binary restart file. Communication between input processor and the computational engine is via a platform independent binary (PIB) dump file, which contains all necessary initial conditions for the solution of the flow and conduction equations. This file enables the new graphical user interface, SNAP, to serve as the primary source of input for the consolidated code. SNAP will have the ability to generate PIB dump files for either RELAP5 or the new consolidated code. In normal mode the PIB files will be generated from user interaction with the GUI and a library of typical system configurations. To summarize, SNAP will have the ability to accept archival ASCII input decks for RELAP5, TRAC-P, or TRAC-B, permit user modifications via the GUI, and generate a PIB file to start the consolidated code.

Low level modularity enhances readability and facilitates bug fixes, as the functions of subroutines are clearly understood and simple enough for a developer to grasp and retain. Due to the obvious benefits of low-level functional modularity, some effort has been expended to enhance it. For example, the original TRAC-P code evaluated interfacial drag coefficients, developed terms in the 1-D momentum equations, and took steps to solve the equations in a single subroutine. This complicated any modifications to terms in the momentum equation or interfacial drag models, hindered replacement of the solver and hampered readability. This routine was streamlined and now one driver routine calls one subroutine for each physical model. Another driver routine calls the subroutine to set up terms in the momentum equation and calls another subroutine to handle the solution. This work facilitated the consolidation of the TRAC-B BWR components, as special terms were needed in the momentum equations to model the turbine and jet pump components. In our final stage of consolidation, isolation of the physical model evaluation will also expedite incorporating BWR component specific physical models, or generic RELAP5 correlations found to be superior to those in the current consolidated code.

4. General Modeling Capabilities

As depicted in Figure 1, the consolidation will recover all capabilities of the current suite of codes. This stage of the consolidation focuses on BWR applications and does not include RELAP5 capabilities. It is paramount that the following point be understood: USNRC is not simply lumping all of the code together and renaming it TRAC-M, since the consolidated code would be the same size as the current suite of codes, and it would still be necessary to know each of the four codes in order to use, maintain and develop it. In contrast, the consolidation involves using TRAC-B philosophy to develop BWR components out of TRAC-M components.

4.1. TRAC-B

BWR components/features that have been incorporated into TRAC-M to model BWRs include:

- Jet Pump

- Turbine
- Level Tracking (1-D and 3-D)
- CHAN (BWR fuel channel)
- Feedwater Heater
- Containment
- Separator/Dryer
- BWR Control Systems
- BWR Input Processing

Using the jet pump as an example, the consolidation method will be described. In TRAC-B the jet pump was based on a tee component. In order to accurately predict the pressure rise due to mixing of suction and drive line flows, TRAC-B applied a negative K-loss (derived from a properly formulated momentum source term) at the cell that models the mixing region of the jet pump. This was necessary in order to make this prediction consistent with an analytical result (obtained by assuming no pressure drop at the suction line flow) because the tee component momentum equation neglected the side leg momentum flux contribution. In contrast, TRAC-M uses a properly formulated momentum source term for tees, so that it was not necessary to add a negative loss coefficient for the jet pump in TRAC-M. It should be noted that the negative K-loss term was incorporated explicitly into the momentum equations, potentially limiting the maximum achievable time step size to avoid numerical instabilities, whereas the tee momentum source term in TRAC-M is implicit, imposing no limit on time step size.

Additionally, consistent with the TRAC-B modeling approach, the irreversible losses due to incomplete mixing of the high-velocity drive flow and the low-velocity suction flow and the unique geometry of the drive nozzle must be accounted for. The irreversible loss coefficients are based on the $1/6^{th}$ scale INEL jet pump test. So in summary, a user will specify a jet pump component and will input the geometry information for the jet pump but interior to TRAC-M standard tee routines will be used to calculate the terms in the finite volume equations with additional terms for the jet pump-specific irreversible losses. In addition to the output generated for a tee, the jet pump specific parameters are calculated and printed out, such as jet pump efficiencies (M and N ratios).

This example demonstrates that the tee-specific coding was not simply copied from TRAC-B and merged with TRAC-M, since TRAC-M already can model a tee. Instead, only the additional features required to model a jet pump were incorporated into TRAC-M. This same approach was used for all the TRAC-B components although more discussion is necessary to explain the CHAN component.

In TRAC-B, the CHAN component represents the BWR fuel channels. In a TRAC-B BWR plant model, this component provides a 1-D flow path over the fuel rods and a leak path that allows some fluid flow from the fuel channel to the bypass volume between the channels in the vessel. In TRAC-B, the CHAN component is based on a pipe, a standard 1-D component, which can only be connected to other components at its ends. TRAC-B developers could have used a tee component to model the CHAN- the primary flow path through the core in the channel box would have been the tee primary leg, and the tee side leg would have allowed the primary leg to be connected to the vessel. They did not use a tee because the side leg would have had at least one cell volume, which is not an exact representation of the geometry of the leak path in a BWR core. Instead, a pipe was used and the source terms of mass, energy and momentum coming from the CHAN and flowing into the vessel (or vice versa) were modeled explicitly, i.e. explicit leak path model. Therefore, these terms were added to the right hand side (the known quantities) of the vessel and subtracted from the right hand side of the pipe.

During the consolidation, a decision was made to improve the hydraulic model of the CHAN component when it was incorporated into TRAC-M. An implicit rather than explicit leak path is provided in TRAC-M, to prevent instabilities that had been caused by TRAC-B's explicit connection of the CHAN to the vessel bypass. This improvement could be accomplished only by developing a new component, called a single junction. This junction has no volume and allows the cell of the CHAN pipe to be connected to a cell in the vessel implicitly (at new time). Additional work was needed in the code to allow this new type of connection, which modifies the structure of the matrices (the left-hand side quantities, evaluated at new time).

Using a single junction component will also aid RELAP5 input deck conversion, since in RELAP5 1-D components do not have end junctions built into the components, and single junctions must be used to connect them. The single junction component will also help alleviate differences in the way pumps and valves are modeled in the codes.

In order to preserve TRAC-B input decks, TRAC-M has been modified to process TRAC-B input decks. Due to the input separation task previously described in Section 3.2, this was done cleanly and did not hamper the readability of the code. In the future, SNAP will provide the ability to process RELAP5 input decks, so that the investment in legacy input decks will be recovered.

As depicted in Figure 1, the next stage in the consolidation process is developmental assessment. The TRAC-B, RAMONA, and TRAC-P functionality will be tested using a developmental assessment matrix, which is being developed. This assessment matrix is developed based on existing PIRTS, CSNI test matrices and each of the codes' developmental assessment matrices. To be more systematic, scaled test data and code simulations were used to generate the ranges of conditions over which the ranked phenomena operate during the transients the consolidated code is tasked to simulate. These tests will be run to ensure that the consolidated code simulation fidelity is acceptable for all applications. The current constitutive relationships in TRAC-M may not be suited well for simulating the flow conditions common in BWRs. Whenever necessary, the TRAC-B specific constitutive relations will be incorporated into TRAC-M. For example, currently in TRAC-M the CHAN component uses interfacial drag for a pipe, since it is based on a TRAC-M pipe. Therefore, the TRAC-B interfacial drag model for rod bundles will have to be incorporated for use only when the PIPE component represents a rod bundle. Otherwise, the PIPE component will continue to use the original TRAC-M model for the pipe. The improvements to the code architecture, such as component based modularity, has facilitated this effort.

4.2. Stability

Semi-Implicit numerics scheme was added to TRAC-M, so that an alternative technique could be used in place of the standard TRAC-M SETS method (stability-enhancing two-step method) in situations where it is necessary to limit numerical diffusion, such as stability analysis. This work was made more efficient because of the numerical solution modularization effort, previously described in Section 3.2.

4.3. 3-D Kinetics

3-D kinetics and 1-D kinetics have been consolidated by coupling TRAC-M to a neutronics package through PVM (Parallel Virtual Machine). The benefit of this coupling methodology is that the codes remain isolated and communicate across a well-defined interface. Essentially, each code runs as a separate process. PARCS receives thermal-hydraulic data from TRAC-M, such as void fraction, phasic densities, temperatures, boron concentration, and fuel temperatures and returns the power back to TRAC-M. Therefore, a developer in TRAC-M is not required to have knowledge of the details of the neutronics package when trying to either debug a problem or add a capability. Only the knowledge of what needs to be passed and what is returned during the solution procedure is necessary. This methodology also allows upgrades to the neutronics package to take place without hindrance from TRAC-M development.

4.4. RELAP5 Capabilities

Once the consolidated code has been fully assessed for the TRAC-B and RAMONA and TRAC-P applications, USNRC will then determine the most efficient way to consolidate the functionality of RELAP5. This work will mainly involve assessing the codes against each other and data and modifying TRAC-M constitutive models to allow TRAC-M to simulate phenomena associated with RELAP5 applications (PWR SBLOCA and transients), while preserving its simulation fidelity with respect to those of the other codes. The single junction component added to TRAC-M in support of the TRAC-B CHAN component consolidation, enabling the semi-implicit numerical scheme and other improvements made to TRAC-M, discussed in Section 5, will facilitate this effort as well as the translation of RELAP5 input decks. However, USNRC will continue to maintain RELAP5 and make user-requested improvements, such as the minimization of mass error, flow oscillations, and time-step/platform dependency. Throughout this process, USNRC will ensure that user needs are accommodated and will provide a transition period during which the codes are maintained until the user community has acclimated to the consolidated code. This approach is depicted in Figure 1. The dashed lines indicate that the schedule has not yet been determined and is only estimated.

5. Code Improvements

Throughout the consolidation, improvements have been made to the TRAC-M code and merged whenever logistically feasible (Figure 1). The following section describes these modifications.

5.1. Graphical User Interface

As alluded to in Section 3.2, work is in process to extend the graphical user interface, SNAP, to TRAC-M in an effort to enhance the user friendliness of the code. The SNAP front end will replace current text-based input deck preparation and will assist the analyst in executing the model. Expert systems will provide default nodalization and other user conveniences. Component templates will be available to simplify the construction of plant models. Analysts will only have to make plant specific modifications to system loss coefficients or other geometric details. Furthermore, the user effect will be minimized, as SNAP will report any modeling practices that are not recommended. The SNAP back end will serve as the visualization tool. The back end capabilities will include a 3-D representation of the piping system and components, a simulator-like mask of the system with animation (colors represent temperatures, trips enunciated, strip charts depicting time traces of system parameters, etc...), and run-time control system linkage. The latter feature will allow the user to interact with the model/execution of the code as is common with simulators, thereby having the capability to change things such as positions of valves, pump speeds, and trip settings during run-time. The back-end will also have multiple masks, allowing the analyst to run and display different models simultaneously with the ability to pause and resume each calculation.

5.2. Exterior Communication Interface

As the user community requests additional code capabilities in response to increases in available computing power, the danger exists to complicate the code and its architecture, hindering further development and maintenance. To prevent this, USNRC has adopted the design strategy of coupling the code across a well-defined interface. This strategy was utilized in providing the code with a 3-D kinetics capability. To allow this logic to be extended to other functional models and to make its implementation consistent in each case, an exterior communication interface has been developed. As a proof of principle, a RELAP5 accumulator model has been coupled to TRAC-M utilizing this interface. Currently in TRAC-M, an accumulator is simply an option in a pipe that has a very low interfacial drag at the interface to provide phasic stratification. Since an accumulator is more physically modeled by simple perfect gas expansion and does not require full two-fluid model solution, the RELAP5 accumulator model can replace the current TRAC-M approach. The exterior communication interface will also be utilized to allow the GUI back-end to communicate with the TRAC-M control system, so that TRAC-M can be run in "simulator-like" mode. The exterior communication interface will also facilitate coupling to other codes, such as CFD codes, sub-channel analysis codes or more detailed containment codes.

5.3. Model Development

Since code deficiencies have been identified, USNRC has initiated work to ameliorate these limitations. These new features will be merged with the consolidated code when available and when logistically feasible. This approach was adopted, since it was necessary to supplement the currently available database before some models could be developed. Therefore, four separate effects tests are being run in an attempt to minimize the time required before these deficiencies can be improved.

5.3.1. Subcooled Boiling at Low Pressure

In two-fluid codes, only one temperature is specified for each phase in a cell. Therefore, in order to predict boiling on the heated surface when the volume averaged temperature is subcooled, a special model is required to predict vaporization in the superheated near wall region. RELAP5 use a modified Lahey subcooled boiling model (1978) to determine the fraction of the wall heat flux that results in vapor generation. This model utilizes a liquid to vapor density ratio to account for buoyancy induced "pumping" that mixes the near wall region and suppresses nucleation. At low pressures, the density ratio is huge (0.2 MPa, the ratio is 1300 vs. a ratio of 6 at 15 MPa) and the net vapor generation is dramatically under-predicted. The AP600 analysis proved that the subcooled boiling model at low pressure requires improvement.

5.3.2. Interfacial Area Transport

TRAC-M and most two-fluid codes use interfacial area to determine the total force between phases for heat transfer and drag. Currently the codes use static flow regime maps and deduce the representative interfacial area. As mass flux and void fraction change, the flow regimes change instantaneously with no regard of the physical time and length scale of flow regime development. This approach causes instabilities and limits code accuracy. An alternative approach is to use a transport equation for interfacial area with source and sink terms representing the actual processes that govern the change in interfacial area. A preliminary model has been incorporated a test version of the code to predict the development of interfacial area in a vertical pipe. Good agreement with data was achieved.

5.3.3. Phase Separation at Tees

During depressurization, phase separation at tees can dominate the course of a transient, since the effluent quality determines how fast the system depressurizes and the liquid inventory. Perfect separation will maximize depressurization while minimizing the loss of inventory, resulting in a non-conservative result. Underprediction may be conservative but may limit design in cases of low inventory, such as beyond design base accident scenarios. During AP600 analysis, the phase separation at tee model in RELAP5 was proven to be of limited applicability, since data only covered a limited range of conditions. USNRC is currently supplementing this database and reviewing existing models with an aim of either developing or identifying applicable models over all ranges of conditions prototypic of nuclear reactor operation.

5.3.4. Rod Bundle Heat Transfer Program

The goal of this effort is to develop a more mechanistic model for reflood heat transfer. The test facility will generate data in a manner that will help isolate each of the many phenomena that affect reflood. For example, data on convection heat transfer alone will be taken, as well as the effects of drops (induced turbulence, distributed heat sink, etc...) and radiation only. The facility will also measure detailed data on drop size distribution, drop velocity, vapor superheat, void distribution in froth region to help identify the effect of void fraction on heat transfer, and will have instrumented spacer grids to measure rewetting and droplet break-up. The current database lacks this information, which is expected to help minimize the uncertainty in current reflood models.

6. Conclusions

The goal of the consolidation is to recover the functionality of the current suite of codes, while reducing the maintenance and development burden so that the capabilities can be extended more efficiently and the knowledge-based developed more rapidly. The first stage of the effort was improving the architecture of TRAC-P to serve as the basis of consolidated code. The architecture was revamped and the language migrated to FORTRAN90 to produce a more modular, readable, extendable and developer-friendly code. TRAC-B and RAMONA capabilities have been incorporated into the code while adhering to the new modular architecture concepts. Therefore, the TRAC-B and TRAC-P finite volume equations were compared and only those additional terms required to model the BWR components were consolidated. To enhance modularity, 1-D and 3-D kinetics were coupled to the code across a well-defined interface. This coupling strategy has been extended into an exterior communication interface, which will facilitate coupling other codes in the future. A RELAP5 accumulator model has been coupled in this manner to prove the feasibility of the approach. The graphical user interface, SNAP, has also been extended to provide the input processing for the consolidated code. SNAP will also allow the consolidated code to process RELAP5 input decks, so that the code will be able to read TRAC-B, TRAC-P and RELAP5 decks. Currently, work focuses on assessing the consolidated code in order to identify the TRAC-B constitutive models must be incorporated into TRAC-M in order to achieve the simulation fidelity of TRAC-B for the BWR applications. These BWR component specific constitutive models will be used only with the BWR components so as not to hamper the ability of the code to model PWRs.

Once this assessment is completed, USNRC will then determine the most efficient approach to recover the RELAP5 capabilities. To achieve this goal, this work will mainly focus on assessment, since aside from some component options, like heat structure boundary condition specification, and the thermal front tracking flow process model, TRAC-M has the same functionality as RELAP5. During the TRAC-B consolidation code modifications were made to TRAC-M that has reduced the work involved in the RELAP5 consolidation. These modifications include enabling a semi-implicit numerical scheme, development of a single junction component and a RELAP5 accumulator model and extending the GUI to TRAC-M, achieving the first stages of input deck translation. Therefore, the bulk of the work remaining involves assessing TRAC-M against RELAP5 and data for the RELAP5 applications and modifying the TRAC-M constitutive models so that TRAC-M can simulate PWR SBLOCAs and transients while also preserving the simulation fidelity with respect to its current applications.

Once completed, the consolidation effort will produce a code that recovers the functionality of the current suite of codes. Throughout the effort, RELAP5 will be developed and maintained to accommodate user needs. A transition period will also be provided to allow the user community to acclimate to the consolidated code. With one code, the knowledge-base will be enhanced as the user and developer community can focus on one code instead of four and code improvements will be made more efficiently.

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DRAFT REGULATORY GUIDE DG-1096

TRANSIENT AND ACCIDENT ANALYSIS METHODS

A. INTRODUCTION

Section 50.34, "Contents of Applications; technical information" of 10CFR Part 50, "Domestic Licensing of Production and Utilization Facilities," requires that:

1. Safety Analysis Reports be submitted that analyze the design and performance of structures, systems and components provided for the prevention of accidents and the mitigation of the consequences of accidents,

2. Analysis and evaluation of ECCS cooling performance following postulated loss-of-coolant accidents (LOCAs) shall be performed in accordance with the requirements of Section 50.46, and

3. The technical specifications for the facility (Section 50.36) be based on the safety analysis.

This regulatory guide describes a process that is acceptable to the NRC staff for the development and assessment of evaluation models used to analyze transient and accident behavior described in Chapter 15 of the Standard Review Plan (SRP)(NUREG-0800) and in the Standard Format and Content Guide (Regulatory Guide 1.70). These Chapter 15 events (transients and accidents) are a sub-set of those required in 10 CFR 50.34. It includes those events presented in sub-Chapters 15.1 through 15.6, except for the fuel assembly misloading event and all radiological consequence analyses. An appendix to this regulatory guide is provided for ECCS analysis. As appropriate, other appendices will be developed for other specific classes of events, that are described in SRP sub-chapters 15.1 through 15.6. The purpose of these appendices is to address phenomena, assessment, uncertainty analyses, and other factors important or unique to a particular class of events.

This regulatory guide is aimed at providing realistic accident analysis. This provides a more reliable framework for risk informed regulation. It also provides a basis for estimating the uncertainty in understanding transient and accident behavior.

SRP section 15.0.1 provides guidance to NRC reviewers of transient and accident analysis methods. This regulatory guide and SRP section 15.0.1 cover the same subject material and are meant to be complementary documents, with section 15.0.1 providing guidance to reviewers and this guide providing practices and principles for the benefit of methods developers.

The information collections contained in this draft regulatory guide are covered by the requirements of 10 CFR Part 50, which were approved by the Office of Management and Budget, approval number 3150-   . The NRC may not conduct or sponsor, and a person is not required to respond to, a collection of information unless it displays a currently valid OMB control number.

B. DISCUSSION

This discussion addresses two fundamental features of transient and accident analysis methods: (1) the evaluation model concept and (2) basic principles important for the development, assessment, and review of those methods.

1. EVALUATION MODEL CONCEPT

The basis for analysis methods used to analyze a particular event or class of events is contained in the evaluation model concept. This concept is described in 10 CFR 50.46 for LOCA analysis but can be generalized to all analyzed events described in Chapter 15. An evaluation model (EM) is the calculational framework for evaluating the behavior of the reactor system during a postulated transient or design basis accident. It may include one or more computer programs, special models and all other information necessary for application of the calculational framework to a specific event, such as:

1. procedures for treating the input and output information, particularly the code input arising from the plant geometry, assumed plant state at transient initiation,
2. specification of those portions of the analysis not included in the computer programs, for which alternative approaches are used, and
3. all other information necessary to specify the calculational procedure.

It is the entirety of an evaluation model that ultimately determines that the results are in compliance with applicable regulations. Therefore, the entire evaluation model must be considered during the development, assessment, and review process.

In this regulatory guide, the term "model" is also used and should be distinguished from the "evaluation model" or "EM." In contrast to "EM" as defined here, "model" without the "evaluation" modifier is used in the more traditional sense to describe the representation of a particular physical phenomenon within a computer code or procedure.

Most evaluation models used to analyze SRP Chapter 15 events rely on a "systems code " that describes the transport of fluid mass, momentum, and energy throughout the reactor coolant systems. The extent and complexity of the physical models needed in the systems code are strongly dependent on the reactor design and the transient being analyzed. For a particular transient, a subsidiary device like a sub-channel analysis code may actually be more complex than the systems code. Regardless of its complexity, the systems code plays a key role in organizing and controlling other aspects of the transient analysis. Each computer code, analytical tool or calculational procedure that compose the evaluation model is referred to as a "calculational device" in this guide.

In some cases as many as 7 or 8 calculational devices may be used to define an evaluation model for a particular event. Although the trend today is to integrate as many of these components into a smaller set of computer codes, usually within the framework of the systems code.

Sometimes, a general purpose systems code may be developed to address similar phenomenological aspects of several diverse classes of transients. This presents unique challenges in the definition, development, assessment, and review of those codes as they apply to a particular transient evaluation model. A separate section of the Regulatory Position is devoted to the issues involved with general purpose computer codes.

2. BASIC PRINCIPLES OF EVALUATION MODEL DEVELOPMENT AND ASSESSMENT

Recent reviews have shown the need to provide guidance to applicants and licensees regarding transient and accident analysis methods. By providing such guidance, the review process should be streamlined by reducing the frequency and extent of iterations between the methods developers and NRC staff reviewers. To produce a viable product, certain principles should be addressed during the model development and assessment process.

There are six basic principles that have been identified as important to follow in the process of evaluation model development and assessment. They are:

1. ***Determine requirements for the evaluation model*** - The purpose of this principle is to provide a focus throughout the evaluation model development and assessment process (EMDAP). An important outcome should be the identification of mathematical modeling methods, components, phenomena, physical processes and parameters needed to evaluate the event behavior relative to the figures of merit described in Chapter 15 of the SRP and derived from the General Design Criteria (GDC)(Appendix A of 10 CFR Part 50). The phenomena assessment process is central to assuring that the evaluation model can analyze the particular event appropriately and that the validation process addresses key phenomena for that event.
2. ***Develop an assessment base consistent with the determined requirements*** - Since an evaluation model can only approximate physical behavior for postulated events, it is important to validate the calculational devices, individually and collectively, using an appropriate assessment base. The data base may consist of already existing experiments, or it may require the performance of new experiments depending on the results of the requirements determination.
3. ***Evaluation model development*** - The calculational devices needed to analyze the events in accordance with the requirements determined in the first principle, should be selected or developed. To define an evaluation model for a particular plant and event, it is also necessary to select proper code options, boundary conditions, and the temporal and spatial relationship among the component devices.
4. ***Assess the adequacy of the evaluation model*** - Based on the application of the first principle, especially the phenomena importance determination, an assessment should be made regarding the inherent capability of the evaluation model to achieve the desired results relative to the GDC derived figures of merit. Some of this assessment is best made during the early phase of code development to minimize the need for corrective actions later. A key feature of the adequacy assessment is the ability of the evaluation model or its component devices to predict appropriate experimental behavior. Once again, the focus should be on the ability to predict key phenomena as described in the first principle. To a large degree, the calculational

devices are collections of models and correlations that are empirical in nature. Therefore, it is important to assure that they are used within the range of their assessment.

5. ***Follow an appropriate quality assurance protocol during the EMDAP*** - Quality assurance standards, as required in Appendix B of 10 CFR Part 50, are a key feature of the development and assessment process. When complex computer codes are involved, peer review by independent experts should be an integral part of the quality assurance process.

6. ***Provide comprehensive, accurate, up-to-date documentation*** - This is an obvious requirement for a credible NRC review. It is also clearly needed for the peer review described in the fifth principle. Since the development and assessment process may lead to changes in the importance determination, it is most important that documentation of this activity be developed early and kept current.

The principles of an EMDAP were developed and applied in the study titled "Quantifying Reactor Safety Margins" (Reference 1). In that report, the Code Scaling, Applicability, and Uncertainty (CSAU) evaluation methodology was applied to a large break LOCA. The purpose of that study was to demonstrate a method that could be used to quantify uncertainties as required by the best-estimate option described in the 1988 revision to the ECCS Rule (10 CFR 50.46). While the goal was related to code uncertainty evaluation, the principles derived to achieve that goal involved the entire process of evaluation model development and assessment. Thus many of the same principles would apply even if a formal uncertainty evaluation was not the specific goal. Since the publication of Reference 1, there have been several applications of the CSAU process with modifications to fit each particular circumstance (See References 2-10).

In References 2 and 3, a process was developed using an integrated structure and scaling methodology for severe accident technical issue resolution (ISTIR). ISTIR defined separate components for experimentation and code development. Although a code development component is included in ISTIR, the ISTIR demonstration did not include code development. An important feature of Reference 2 is the use of hierarchical system decomposition methods to analyze complex systems. In the ISTIR demonstration (Reference 2), the methods were used to investigate experimental scaling, but they are also well suited to providing structure in the identification of evaluation model fundamentals.

Reference 4 was an adequacy evaluation of RELAP5 for simulating AP600 SBLOCAs. Most of that effort focused on demonstrating the applicability and assessment of a developed code for a new application.

The subjects addressed in References 1-4 are complex, and the structures used to address these subjects are very detailed. The EMDAP described in this guide is also detailed, so that it can be applied to the complex events described in SRP Chapter 15. This is particularly true if the application is new or the methods proposed are new. The risk importance of the event or the complexity of the problem should determine the level of detail needed to develop and assess an evaluation model. For simpler events, many of the steps in the process may only need to be addressed briefly. Also, if a new evaluation model only involves an incremental change to an existing evaluation model, the process may also be shortened, as long as the effect of the change is thoroughly addressed.

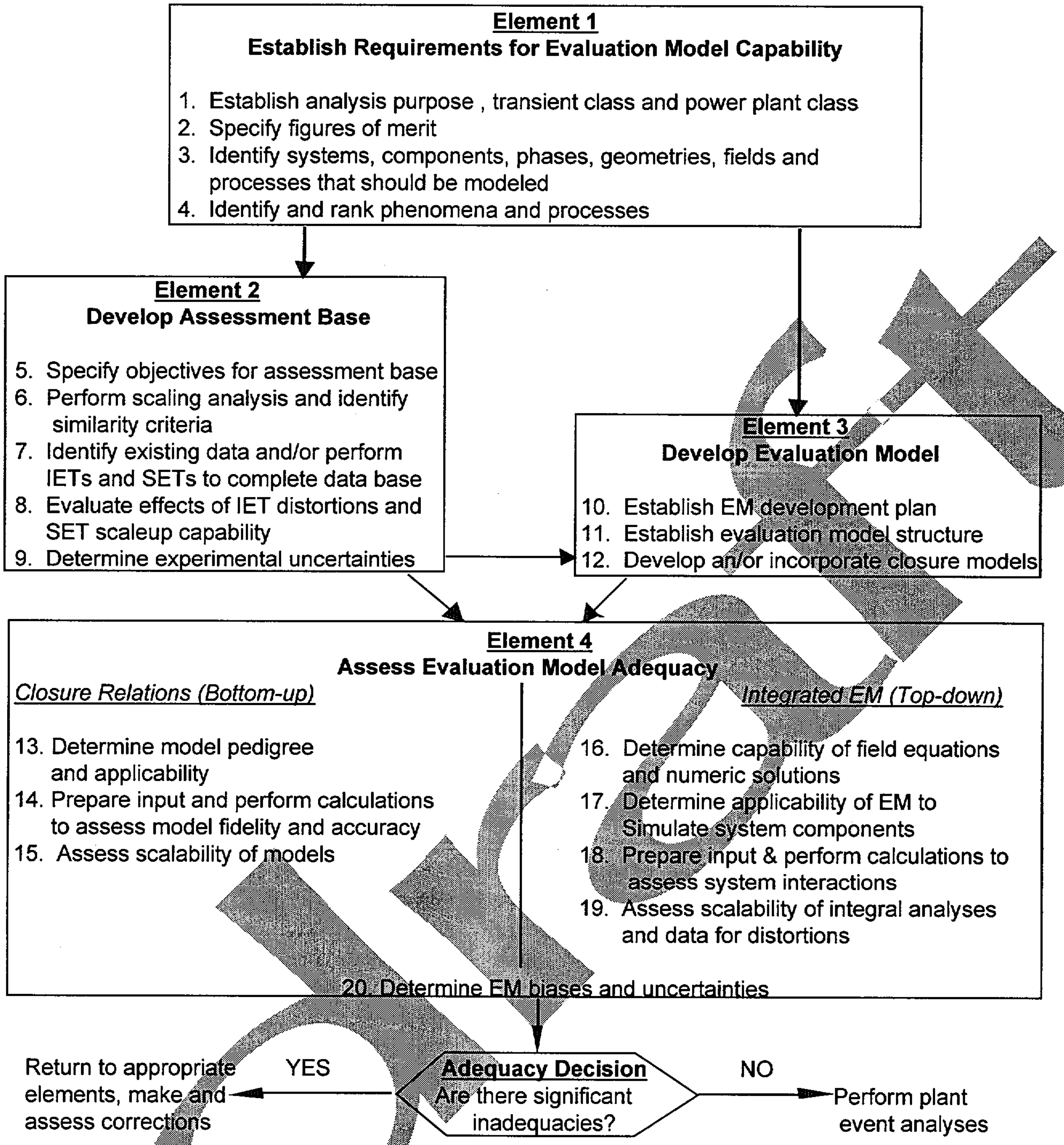

Figure 1. Elements of Evaluation Model Development and Assessment Process (EMDAP)

An overall diagram of the EMDAP process and the relationship of its elements is shown above in Figure 1.

Guidance on methods for calculating transient and accident behavior is provided in the following Regulatory Position. Appendix A provides additional information important to ECCS analysis.

C. REGULATORY POSITION

This regulatory position addresses four related aspects of evaluation model development and assessment. They are:

1. Description of the four elements and included steps in the EMDAP based on the first four principles described above and shown in Figure 1.
2. The relationship of accepted quality assurance practices to this process and the incorporation of peer review as described in the fifth principle.
3. A description of what should be included in evaluation model documentation to be consistent with the sixth principle.
4. The unique aspects of general purpose computer programs.

1. EVALUATION MODEL DEVELOPMENT AND ASSESSMENT PROCESS (EMDAP)

The basic elements developed to describe an EMDAP directly address the first four principles described in Section B.2 and are shown in Figure 1.

The next five sections address the four elements and the adequacy decision shown in Figure 1. Adherence to EMDAP for new applications or a completely new evaluation models could involve significant iterations within the process. However, the same process applies even if the new evaluation model is the result of relatively simple modifications to an existing evaluation model. "Feedback" loops are not shown. Rather, this is addressed in the adequacy decision described in Section 1.5.

1.1 Element 1 - Establish Requirements for Evaluation Model Capability

It is very important to determine at the beginning, the exact application envelope for the evaluation model and to identify and agree upon the importance of constituent phenomena, processes, and key parameters within that envelope. Figure 2 illustrates the steps within this element.

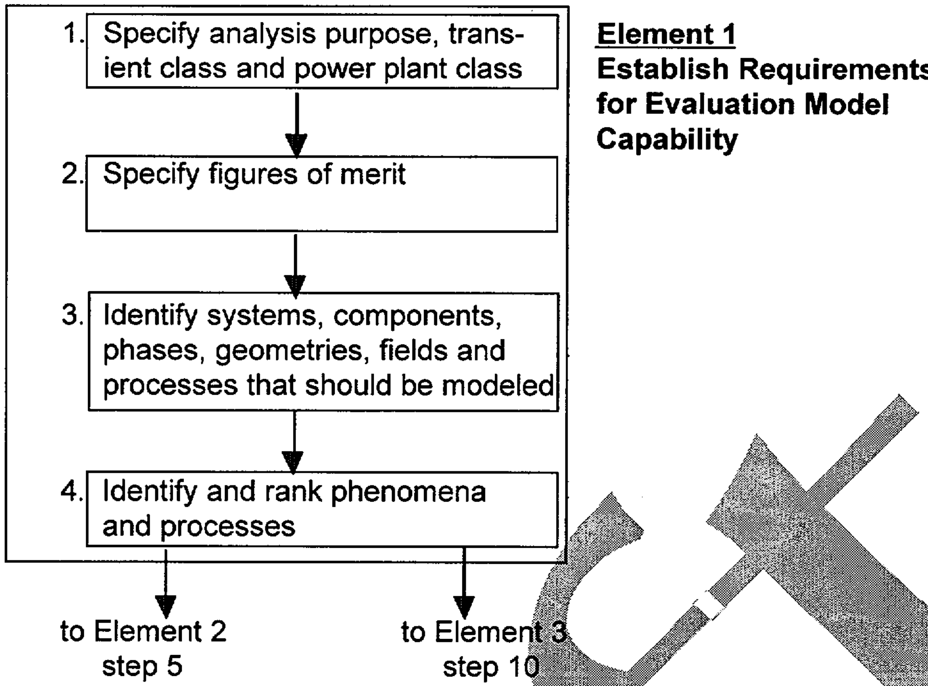

Figure 2. Steps in Element 1

1.1.1 Step 1 - Specify Analysis Purpose, Transient Class and Power Plant Class

The first step in establishing evaluation model requirements and capabilities, is specification of the analysis purpose, and identification of the class of plants and class of transients to be analyzed. Specification of purpose is important because any specific transient may be analyzed for different reasons. For instance, a small break LOCA maybe analyzed for assessment of pressurized thermal shock (PTS) potential or for compliance with 50.46. The statement of purpose influences the entire process of development, assessment, and analysis. Evaluation model applicability is scenario dependent because the dominant processes, safety parameters and acceptance criteria change from one scenario to another. The transient scenario therefore dictates the processes that must be addressed. A complete scenario definition is plant specific, because the dominant phenomena and their interactions differ in varying degrees with the reactor design.

For events described in Chapter 15, this steps should be straightforward. The purpose is compliance with the GDC, while the events and event classes are described in Chapter 15. The licensee/applicant and evaluation model developer should then specify applicability to plants and plant types. As examples, fuel design, core loading, number and design of steam generators, number and design of coolant loops, safety injection system design, and control systems can differ significantly from plant to plant and will significantly influence scenario behavior.

1.1.2 Step 2 - Specify Figures of Merit

Figures of merit are those quantitative standards of acceptance that are used to define acceptable answers for a safety analysis. The GDC (10 CFR 50 Appendix A) describe general requirements for maintaining the reactor in a safe condition during normal operation and during transients and accidents. SRP Chapter 15 further defines these criteria in terms of quantitative fuel and reactor system design limits (DNBR limits, fuel temperatures, etc.) for the events of interest. For ECCS design, five specific criteria described in 10 CFR 50.46 must be met for LOCA analysis. Thus for Chapter 15 events, figures of merit are generally synonymous with criteria directly associated with the regulations, and their selection is usually a simple matter. There may be times during evaluation model development and assessment when a temporary "surrogate" figure of merit is of value in evaluating the importance of phenomena and processes. Section 2.5 of Reference 5 describes a hierarchy of criteria that was used in SBLOCA assessment. In that case, vessel inventory was judged to be more valuable in defining and assessing code capability. Justification for using a surrogate figure of merit should be provided.

1.1.3 Step 3 - Identify Systems, Components, Phases, Geometries, Fields and Processes That Must Be Modeled

The purpose of this step is to establish the evaluation model characteristics. In References 2 and 3, hierarchical system decomposition methods are used to investigate scaling in complex systems. These methods can also be valuable in the identification of evaluation model characteristics. The ingredients at each hierarchical level described in References 2 and 3 are, in order from top to bottom:

1. *System* - The entire system that must be analyzed for the proposed application.

2. *Sub-systems* - Major components that must be considered in the analysis. For some applications this would include the primary system, secondary system, and containment. For other applications only the primary system would need to be considered.

3. *Modules* - Physical components within the sub-system, i.e., reactor vessel, steam generator, pressurizer, piping run, etc..

4. *Constituents* - Chemical form of substance, e.g., water, nitrogen, air, boron, etc..

5. *Phases* - Solid, liquid or vapor.

6. *Geometrical Configurations* - The geometrical shape that is defined for a transfer process, e.g., pool, drop, bubble, film, etc..

7. *Fields* - The properties that are being transported (mass, momentum, energy).

8. *Processes* - Mechanisms that move properties through the system.

Ingredients at each hierarchical level can be decomposed into the ingredients at the next level down. In references 2 and 3, this process is described in the following way:

1. Each system can be divided into interacting subsystems.
2. Each subsystem can be divided into interacting modules.
3. Each module can be divided into interacting constituents.
4. Each constituent can be divided into interacting phases.
5. Each phase can be can be characterized by one or more geometrical configurations.
6. Each geometrical configuration can be described by three field equations, that is, by conservation equations for mass, energy and momentum.
7. Each field can be characterized by several processes.

By carefully defining the number and type of each ingredient at each level, the evaluation model developer should be able to establish the basic characteristics of the evaluation model. An important principle to note, is that if a deficiency exists at a higher level, it is usually not possible to resolve it by fixing ingredients at lower levels. For relatively simple transients, the decomposition process should also be simple.

1.1.4 Step 4 - Identify and Rank Key Phenomena and Processes

Process identification is the last step in the decomposition described above and provides the logical beginning to this step. Plant behavior is not equally influenced by all processes and phenomena that occur during a transient. An optimum analysis reduces candidate phenomena to a manageable set by identifying and ranking the phenomena with respect to their influence on figures of merit. Each phase of the transient scenario and system components are separately investigated. The processes and phenomena associated with each component are examined. Cause and effect are differentiated. After the processes and phenomena have been identified, their importance should be determined with respect to their effect on the relevant figures of merit.

The importance determination should also be applied to high level system processes, which may be missed if the focus is solely on components. High level system processes, such as depressurization and inventory reduction are often very closely related to figures of merit. Focus on such processes can also help to identify the importance of individual component behavior.

As noted in Step 2, it may be possible to show that a figure of merit other than the applicable Chapter 15 acceptance criterion is more appropriate as a standard for identifying and ranking phenomena. This is acceptable as long as it can be shown that for all of the scenarios being considered for the specific ranking and identification activity, the alternate figure of merit is consistent with plant safety.

The principal product of the process outlined above is a phenomena identification and ranking table (PIRT)(See References 1, 4,7 and 10). Evaluation model development and assessment should be based on a credible and scrutable PIRT. The PIRT should be used to determine the requirements for physical model development, scalability, validation, and sensitivities studies. Ultimately, the PIRT is used to guide any uncertainty analysis or in the assessment of overall evaluation model adequacy. The PIRT is not an end in itself, but is rather a tool to provide guidance for the subsequent steps.

The processes and phenomena that evaluation models should simulate are found by examining experimental data, experience and code simulations related to the specific scenario. Independent techniques to accomplish the ranking include expert opinion, selected calculations, and decision making methods {such as the Analytical Hierarchical Process (AHP)}. Examples of the first two are found in Reference 10, and an example of the last is found in Reference 11. Comparison of the results of these techniques provides assurance of the accuracy and sufficiency of the process.

The initial phases of the PIRT process described in this step can rely heavily on expert opinion, which can be subjective. Therefore, iteration of the PIRT based on experimentation and analysis is important. Although the experience is limited, development of other less subjective importance determination methods is encouraged.

Sensitivity studies can help determine the relative influence of phenomena identified early in the PIRT development and for final validation of the PIRT as the EMDAP is iterated. Examples of sensitivity studies used for this purpose are provided in References 1, 4, 7, 9 and 10.

The identification of processes and phenomena proceeds as follows:

1. The scenario is divided into operationally characteristic time periods in which the dominant processes and phenomena remain essentially constant.

2. For each time period, processes and phenomena are identified for each component following a closed circuit throughout the system. This is done to differentiate cause from effect.

3. Starting with the first time period, the activities continue component by component, until all potentially significant processes have been identified.

4. The procedure is repeated sequentially from time period to time period, until the end of the scenario.

Once the identification has been completed, the ranking process begins. The reason to numerically rank the processes and phenomena is based on the need to provide a systematic and consistent approach to all of the subsequent EMDAP activities.

Sufficient documentation should accompany the PIRT to adequately guide the entire EMDAP. Development and assessment activities may be revisited during the process, including the identification and ranking. In the end, however, the evaluation model, the PIRT, and all documentation should be "frozen" to provide the basis for a proper review. With well defined ranking of important processes, evaluation model capabilities, and calculated results, the prioritization of further modeling improvements can be made more easily. An important principle is the recognition that the more highly ranked phenomena and processes require modeling with greater fidelity. References 4 and 5 describe the role of the PIRT process in experiments, code development and code applications associated with reactor safety analysis.

1.2 Element 2 - Develop Assessment Base

The second component of ISTIR (References 2 & 3) is a scaling methodology which includes acquiring appropriate experimental data relevant to the scenario being considered, and assuring that the experimental scaling is suitable. In References 2 and 3, the relationship of the SASM component to code development is shown but not emphasized in the SASM demonstration. For the EMDAP, the purpose is to provide the basis for development and assessment as shown previously in Figure 1. Figure 3 shows the steps in this element and their relationship. It should be noted that for simple transients or transients where the scaling issues and assessment are well characterized, the implementation of this element should also be simple. The numbering of steps in this and subsequent elements continues from each previous element.

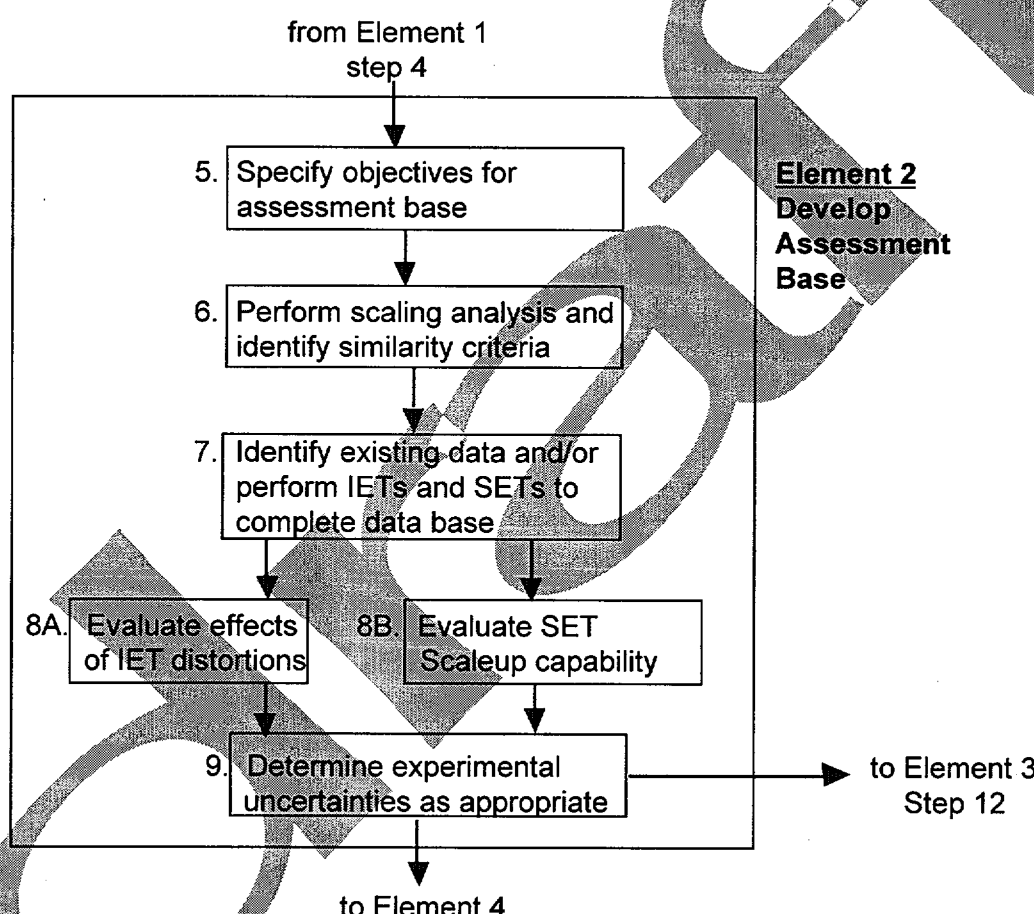

Figure 3. Steps in Element 2

1.2.1 Step 5 - Specify Objectives for Assessment Base

For analysis of Chapter 15 events the principle need for a data base is to assess the evaluation model and if needed to develop correlations. The selection of the data base is a direct result of the requirements established in Element 1. The data base should include:

1. separate effects experiments needed to develop and assess empirical correlations and other closure models,
2. integral systems tests to assess system interactions and global code capability,
3. benchmarks with other codes (optional),
4. plant transient data (if available),
5. and simple test problems to illustrate fundamental calculational device capability.

It should be noted that items 3 and 5 in the above list are not meant to be substitutions for obtaining appropriate experimental and/or plant transient data for evaluation model assessment.

1.2.2 Step 6 - Perform Scaling Analysis and Identify Similarity Criteria

All experiments are compromises with full scale plant systems. Even nominally full scale experiments do not include complete similitude. Scaling analyses should be conducted to insure that the data and the models based on the data, will be applicable to the full scale analysis of the plant transient. Scaling compromises that are identified here should ultimately be addressed in the bias and uncertainty evaluation in Element 4. Scaling analyses are employed to demonstrate the relevancy and sufficiency of the collective experimental data base for representing the behavior expected during the postulated transient and to investigate the scalability of the evaluation model and its component codes for representing the important phenomena. The scope of these analyses is much broader than for the scalability evaluations described in Element 4 relating individual models and correlations or scaling-related findings from the code assessments. Here, the need is to demonstrate that the experimental data base is sufficiently diverse, so that the expected plant-specific response is bounded and that the evaluation model calculations are comparable to the corresponding tests in non-dimensional space. This demonstration allows extending the conclusions relating to code capabilities, drawn from assessments comparing calculated and measured test data (Element 4), to the prediction of plant specific transient behavior.

The scaling analyses employ both "top-down" and "bottom-up" approaches. The "top-down" scaling approach evaluates the global system behavior and systems interactions from integral test facilities that can be shown to represent the plant specific design under consideration. A "top-down" scaling methodology is developed and applied in which:

1. the non-dimensional groups governing similitude between facilities are derived,

2. these groups are shown to scale the results among the experimental facilities, and

3. it is determined whether the ranges of the group values provided by the experiment set encompass the corresponding plant and transient specific values.

The "bottom-up" scaling analyses address issues raised in the plant and transient specific PIRT relating to localized behavior. These analyses are used to explain differences among tests in different experimental facilities and to use these explanations to infer the expected plant behavior and determine whether the experiments provide adequate plant specific representation. Application of this scaling process is described in Section 5.3 of Reference 4.

In most applications, especially those with a large number of processes and parameters, it is difficult, if not impossible, to design test facilities that preserve total similitude between the experiment and the NPP. Therefore, based on the important phenomena and processes identified in Step 4 and the scaling analysis described above, the optimum similarity criteria should be identified, and the associated scaling rationales developed for selecting existing data or designing and operating experimental facilities.

1.2.3 Step 7 - Identify Existing Data and/or Perform IETs and SETs to Complete Data Base

Based on the results of the previous steps in this element, it should be possible to complete the data base by selection and experimentation. To complete the assessment matrix, the PIRT developed in Step 4 is used to select experiments and data that best address the important phenomena and components. In selecting experiments, a range of tests should be employed to demonstrate that the calculational device or phenomenological model has not been tuned to a single test. A correlation derived from a particular data set may be identified for inclusion in the evaluation model. In such cases, an effort should be made to obtain additional data sets which may be used to assess the correlation. For integral behavior assessment, counterpart tests (similar scenarios and transient conditions) in different experimental facilities at different scales should be selected. Assessments using such tests lead to information concerning scale effects on the models used for a particular calculational device.

1.2.4 Step 8 - Evaluate Effects of IET Distortion and SET Scaleup Capability

8A - IET Distortions - Distortions in the integral experimental data base may arise from scaling compromises (missing and/or atypical phenomena) in sub-scale facilities and/or atypical initial and boundary conditions in all facilities. The effects of the distortions should be evaluated in the context of the experimental objectives determined in Step 5. If the effects are important, a return to Step 7 is probably needed.

8B - SET Scaleup - As noted in Step 7, correlations should be based on SETs at various scales. In the case of poor scaleup capability, it may be necessary to return to Step 6. Appendix C of Reference 1 describes rationale and techniques associated with evaluation of scaleup capabilities of computer codes and their supporting experimental data bases.

1.2.7 Step 9 - Determine Experimental Uncertainties as Appropriate

It is important to know the uncertainties in the data base. These uncertainties arise from such items as measurement errors and experimental distortions. If the quantified experimental uncertainties are too large compared to the requirements for evaluation model assessment, then the particular data set or correlation should be rejected.

1.3 Element 3 - Develop Evaluation Model

As discussed in Section B, an evaluation model is a collection of calculational devices (codes and procedures) developed and organized to meet the requirements established in Element 1. The steps for developing the desired evaluation model are shown in Figure 4.

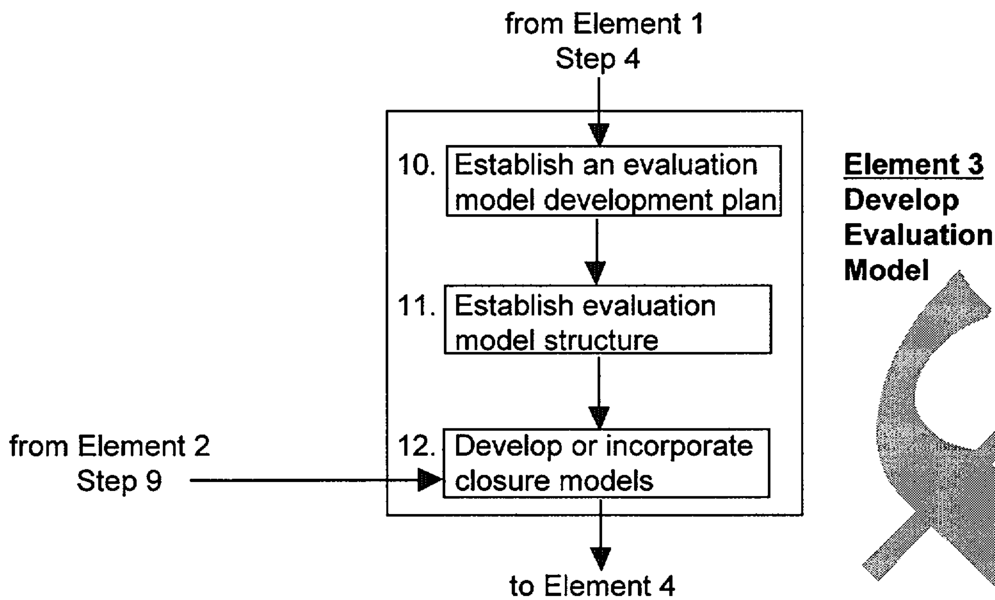

Figure 4. Steps in Element 3

1.3.1 Step 10 - Establish an Evaluation Model Development Plan

Based on the requirements established in Element 1, a development plan should be devised that includes development standards and procedures that will apply during the development activity. Specific areas of focus should include:

1. calculational device design specifications,
2. documentation requirements (See section C.3 of this guide),
3. programming standards and procedures,
4. transportability requirements,
5. quality assurance procedures (See section C.2 of this guide), and
6. configuration control procedures

1.3.2 Step 11 - Establish Evaluation Model Structure

The evaluation model structure includes the structure of the individual component calculational devices, and the structure that combines the devices into the total evaluation model. This structure is based on the principles of Element 1, especially Step 3.

The structure for an individual device or code consists of:

1. *Systems and components* - A structure should be present which can analyze the behavior of all the systems and components that play a role in the targeted application.
2. *Constituents and phases* - The code structure should be able to analyze the behavior of all constituents and phases relevant to the targeted application.
3. *Field equations* - are equations which are solved to determine the transport of the quantity of interest (usually mass, energy and momentum).
4. *Closure relations* - are correlations and equations which provide code capability to model and scale particular processes, and are needed to model the terms in the field equations.
5. *Numerics* - provide code capability to perform efficient and reliable calculations.
6. *Additional features* - address code capability to model boundary conditions and control systems.

Of course, the code structure should be based on the requirements established in Element 1 and Step 10. Because of the importance of selecting proper closure relationships for the governing equations, these models are treated separately in Step 12. The six ingredients described above should be successfully integrated and optimized if a completed code is to is to meet its objectives determined in Step 10.

There are special concerns related to the integration of the component calculational devices into a complete evaluation model. This is frequently referred to as the evaluation model methodology. The way in which the devices are connected spatially and temporally should be described. How close the coupling needs to be would in part be determined based on the results of the analysis done in Step 3, but is determined by the magnitude and direction of transfer processes between devices. The hierarchical decomposition described in References 2 and 3 would apply to how transfer processes are analyzed between devices. Since most devices include user options, all selections made should be justified as appropriate for the evaluation model.

1.3.3 Step 12 - Develop and/or Incorporate Closure Models

Models or closure relations that describe a specific process are developed using SET data. This includes models which can be used in a stand alone mode or correlations which can be incorporated in a calculational device (usually a computer code). On rare occasions, sufficient experimental detail may be available to develop correlations from IET experiments. The scalability and range of applicability of a correlation may not be known a priori the first time it is developed or selected for use in this step. An iteration of scaleup evaluation (Step 8) and adequacy assessment (Element 4) may be needed to ensure correlation applicability. It should be noted that a path is shown from Element 2 to this step, since correlations may be selected from the existing data base literature.

Models developed here are key to successful evaluation model development. The basis, range of applicability and accuracy of incorporated phenomenological models should be known and traceable. Justification should be provided for extension of any models beyond their original basis.

1.4 Element 4 - Assess Evaluation Model Adequacy

Evaluation model adequacy can be assessed once the previous elements have been established and the evaluation model capability has been documented. Figure 5 is a diagram of Element 4.

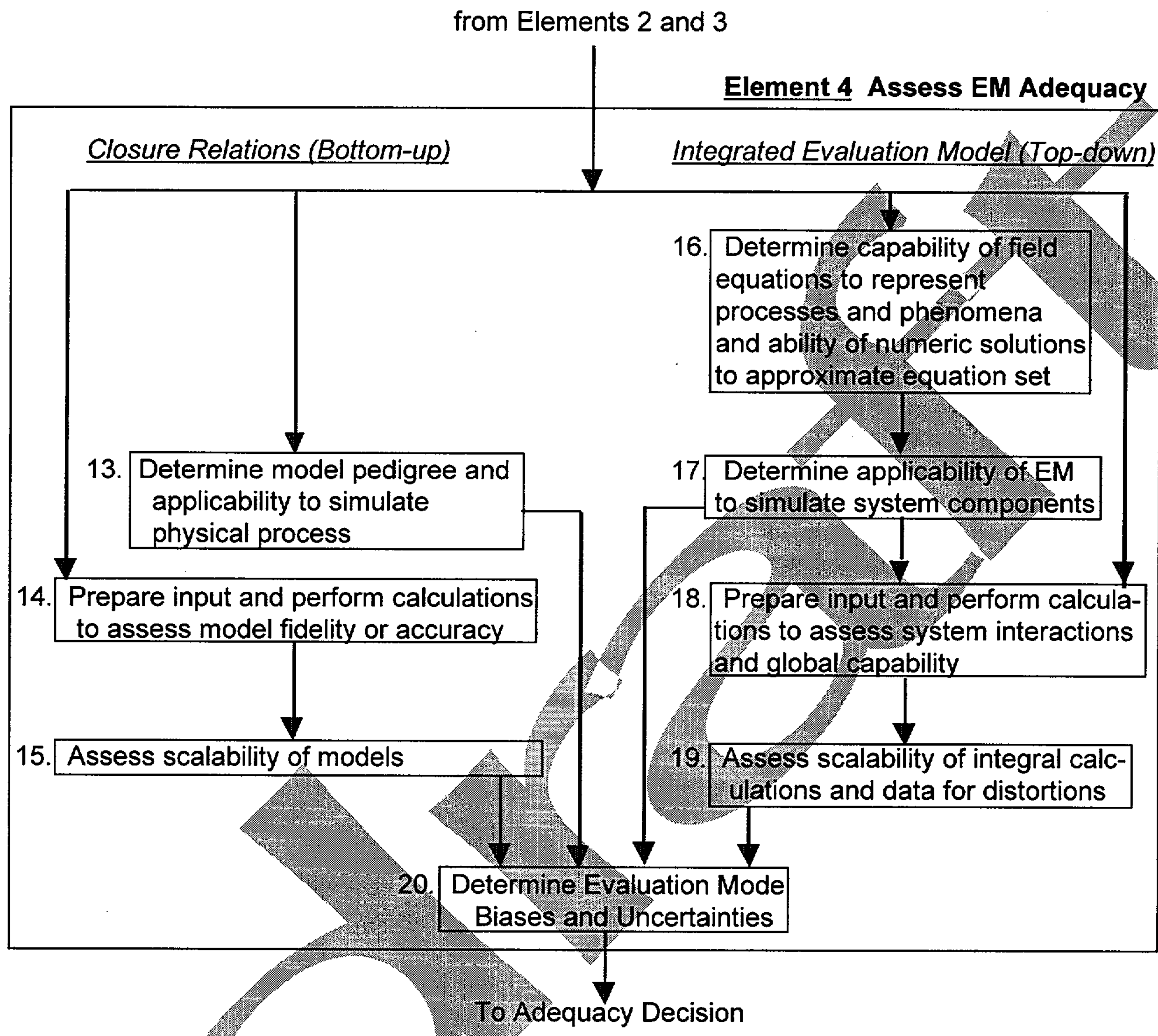

Figure 5. Steps in Element 4

The evaluation model assessment is divided into two parts as shown in Figure 5. The first part (Steps 13 through 15) pertains to the "bottom-up" evaluation of the closure relations for each code. The second part (Steps 16 through 19) pertains to the "top-down" evaluations of code governing equations, numerics, the integrated performance of each code and the integrated performance of the total evaluation model.

It is important to note that any changes to an evaluation model should then include at least a partial assessment to assure that these changes do not produce unintended results in the code predictive capability.

Evaluation of Closure Relations (Bottom-up)

In the first part, important closure models and correlations are examined by considering their pedigree, applicability, fidelity to appropriate fundamental or separate effects test data, and scalability. The term "bottom-up" is used because the review focuses on the fundamental building blocks of the code.

1.4.1 Step 13 - Determine Model Pedigree and Applicability to Simulate Physical Processes

The pedigree evaluation is related to the physical basis of a closure model, assumptions and limitations attributed to the model, and details of the adequacy characterization at the time the model was developed. The applicability evaluation is related to whether the model, as implemented in the code, is consistent with its pedigree or whether use over a broader range of conditions is justified.

1.4.2 Step 14 - Prepare Input and Perform Calculations to Assess Model Fidelity or Accuracy

The fidelity evaluation is related to the existence and completeness of validation efforts (through comparison to data) or benchmarking efforts (through comparison to other standards, for example, a closed form solution or results obtained with another code), or some combination of these comparisons.

SET input for component devices used in model assessment (usually computer codes) should be prepared to represent the phenomena and test facility being modeled and the characteristics of the NPP design. In particular, nodalization and option selection should be consistent between the experimental facility and similar components in the NPP. When the calculations of the SETs are completed, the differences between calculated results and experimental data for important phenomena should be quantified for bias and deviation.

1.4.3 Step 15 - Assess Scalability of Models

The scalability evaluation here is limited to whether the specific model or correlation is appropriate for applying to the configuration and conditions of the plant and transient under evaluation. Reference 3 and 14-18 document recent approaches to scaling, ranging from theoretical methods to specific applications that are of particular interest here.

Integrated Evaluation Model Assessment (Top-down)

In the second part of the assessment, the evaluation model is evaluated by examining the field equations, numerics, applicability, fidelity to component or integral effects data and scalability. This part of the assessment effort is called the "top-down" review because it focuses on capabilities and performance of the evaluation model.

1.4.4 Step 16 - Determine Capability of Field Equations to Represent Processes and Phenomena and the Ability of Numeric Solutions to Approximate Equation Set

The field equation evaluation considers the acceptability of the equations. An assessment of the governing equations in each of the component codes, should consider their pedigree and the key concepts and processes culminating in the equation set solved by the code. The objective of this assessment is to characterize the relevance of the governing equations for the chosen application.

The numeric solution evaluation considers convergence, property conservation and stability of code calculations to a solution of the original equations when applied to the target application. The objective of this review is to summarize information regarding the domain of applicability of the numerical techniques and user options that may impact the accuracy, stability and convergence features of each component code.

A complete assessment within this step can only be performed after a sufficient foundation of assessment analyses are complete. Section 3 and Appendix A of Reference 4 provides an example application of this step.

1.4.5 Step 17 - Determine Applicability of Evaluation Model to Simulate Systems and Components

This applicability evaluation considers whether the integrated code is capable of modeling the plant systems and components. Before integrated analyses are performed, it should be determined that the various evaluation model options, special models and input have the inherent capability to model the major systems and subsystems required for the particular application.

1.4.6 Step 18 - Prepare Input and Perform Calculations to Assess System Interactions and Global Capability

The fidelity evaluation considers the comparison of evaluation model-calculated and measured test data from component and integral test data and where possible plant transient data. For these calculations, the entire evaluation model or its major components are used to compare against the integral data base selected in Element 2.

As was done in Step 14 for the SET assessments, the evaluation model input for IETs should best represent the facilities, and should represent the characteristics of the NPP design. As before, nodalization and option selection should be consistent between experiment and NPP. When the IET simulations are complete, the differences between calculated results and experimental data for important processes and phenomena should be quantified for bias and deviation. The ability of the evaluation model to model system interactions should also be evaluated in this step. Section 5 of Reference 4 provides an example application of this step.

In this step, plant input decks should also be prepared for the target applications. Sufficient analyses should be performed to determine parameter ranges expected in the NPP. These input decks also provide the groundwork for the analyses performed in Step 20.

1.4.7 Step 19 - Assess Scalability of Integral Calculations and Data for Distortions

The scalability evaluation here is limited to whether the assessment calculations and experiments exhibit otherwise unexplainable differences among facilities, or between the calculated and measured data for the same facility, that indicate experimental or code scaling distortions.

1.4.8 Step 20 - Determine Evaluation Model Biases and Uncertainties

The analysis purpose established in Step 1 and the transient complexity, will determine the substance of this step. For best estimate LOCA analysis , uncertainty determination description and guidance are described in Reference 1, Regulatory Guide 1.157 and in Appendix A of this document. In these examples, the uncertainty analyses discussed have the ultimate objective of providing a singular statement of uncertainty with respect to the 10 CFR 50.46 acceptance criteria when using the best estimate option in that rule. This singular uncertainty statement is accomplished when the individual uncertainty contributions are determined (See Regulatory Guide 1.157).

For other Chapter 15 events a complete uncertainty analysis is not required. However, in most cases the SRP guidance is to use "suitably conservative" input parameters. This suitability determination may involve a limited assessment of biases and uncertainties and is closely related to the analyses performed in Step 16. Based on the results of Step 4, individual device models can be chosen from those obtained in Step 9. The individual uncertainty (in terms of range and distribution) of each key contributor is determined from the experimental data (Step 11), input to the NPP model, and the effect on appropriate figures of merit evaluated by performing separate NPP calculations. The figures of merit and devices chosen should be consistent. In most cases the analysis would involve the entire evaluation model. The last part of this step is to determine if the degree of overall conservatism or analytical uncertainty is appropriate for the entire evaluation model. This is done in the context of the analysis purpose (Step 1) and the regulatory requirements.

1.5 Adequacy Decision

The evaluation model adequacy decision is the culmination of the EMDAP described in sections 1.1 through 1.4. Throughout the EMDAP, questions concerning the adequacy of the evaluation model should be asked. At the end of the process they should be asked again to assure that all of the answers are satisfactory, and that intervening activities have not invalidated previous acceptable responses. If unacceptable responses indicate significant evaluation model inadequacies, the code deficiency is corrected and the appropriate steps in the EMDAP are repeated to evaluate the deficiency correction. The process continues until the ultimate question regarding adequacy can be answered positively. Of course, the documentation as described in

Section C.3 should be updated as code improvements and assessment are accomplished during the process. Analysis, assessment and any sensitivity studies can also lead to a re-assessment of the phenomena identification and ranking. Therefore, that documentation should also be revised as appropriate.

It is helpful to develop list of questions to be asked during the process and again at the end. To answer these questions, standards should be established by which the capabilities of the evaluation model and its composite codes and models can be judged. Section 2.2.2 of Reference 4 provides an example of the development of such standards.

2. QUALITY ASSURANCE

Much of what is described throughout this regulatory guide relates to good quality assurance practices. For that reason it is important to establish, early in the development and assessment process, appropriate quality assurance protocol. The development, assessment and application are all activities that are related to the requirements of 10CFR50 Appendix B. Section III of Appendix B is a key requirement for this activity and requires that design control measures be applied to reactor physics, thermal, hydraulic, and accident analyses. Section III states that:

> "The design control measures shall provide for verifying or checking the adequacy of design, such as by performance of design reviews, by the use of alternate or simplified calculational methods, or by the performance of a suitable testing program."

Section III also states that design changes should be subject to appropriate design control measures.

It is important to note that other parts of Appendix B are also relevant, such as Section V (requiring documented instructions, e.g., user guidance; Section XVI (corrective actions, e.g.,error control, identification and correction); and Section VI and XVII, which address document control and records retention.

To capture the spirit and intent of Appendix B, independent peer review should be performed at key steps in the process, such as at the end of a major pass through an element..

In the early stages of evaluation model development, it is recommended that a review team be convened to review evaluation model requirements as developed in Element 1. Peer review should also be employed at the later stages during major inquiries associated with the adequacy decision.

In addition to programmers, developers, and end users, it is recommended that the peer review team have independent members with recognized expertise in relevant engineering and science disciplines, code numerics, and computer programming. Expert peer review team members, who were not directly involved in the evaluation model development and assessment, can enhance the robustness of the evaluation models. Further, they can be of value in identifying deficiencies that are common to large system analysis codes.

Throughout the development process, configuration control practices should be adopted that protect program integrity and allow traceability of the development of both the: code version and the plant input deck used to instruct the code in how to represent the facility or NPP. Configuration control of the code version and the plant input deck are separate, but related elements of the evaluation model development and require the same degree of quality assurance. Responsibility for these functions should be clearly established. At the end of the process, only the approved, identified code version and plant input deck should be used for licensing calculations.

3. DOCUMENTATION

Proper documentation allows appraisal of the evaluation model application to the postulated scenario. The documentation for the evaluation model should cover all the elements of the EMDAP process and should include:

1. Evaluation Model requirements document
2. Evaluation Model methodology document
3. Code description manual(s)
4. User's manual(s) and user guidelines
5. Scaling reports
6. Assessment reports
7. Uncertainty analysis reports

3.1 Requirements Document

The requirements determined in Element 1 should be documented so the evaluation model can be assessed against known guidelines. In particular, a documented, current PIRT is important in deciding whether a particular evaluation model feature should be modified before the evaluation model can be applied with confidence.

3.2 Methodology Document

Methodology documentation should include the inter-relationship of all the computational devices used for the plant transient being analyzed including the description of input and output. This should also include a complete description and specification of those portions of the evaluation model not included in the computer programs. A description of all other information necessary to specify the calculational procedure should also be included. A very useful part of this description would be a diagram to illustrate how the various programs and procedures are related, both in time and in function. This methodology description is needed to know exactly how the transient will be analyzed in its entirety.

3.3 Computational Device Description Manual(s)

A description manual is needed for each computational device that is contained in the evaluation model. There are several important components to the Manual. The first is a description of the modeling theory and associated numerical schemes and solution models. It should include a description of the architecture, hydrodynamics, heat structure heat transfer models, trip systems and control systems, reactor kinetics models, and fuel behavior models.

A key ingredient of the documentation is a Models and Correlations Quality Evaluation (MC/QE) report. The MC/QE report provides a basis for the traceability of the models and detailed information on the closure relations. Information on correlation and model sources, data bases, accuracy, scale-up capability, and applicability to specific plant and transient conditions is also documented. The MC/QE report represents a quality evaluation document that provides a blueprint as to what is in the computational device, how it got there, and where it came from.

The MC/QE document has three objectives:

1. To provide information on the sources and quality of closure equations, that is on correlations and models and/or other criteria used.

2. To describe how these closure relations are coded in the device and to assure that the descriptions in the manual conform to the coding, and the coding conforms to the source from which the closure relations were derived.

3. To provide a technical rationale and justification for using these closure relations. That is, to confirm the dominant parameters (pressure, temperature, etc.) represented by the models and correlations reflect the ranges expected in the plant and transient of interest.

Consequently, for correlations, models, and criteria used, the MC/QE should:

1. Provide information on the original source, the supporting data base, the accuracy and applicability to the plant specific transient conditions.

2. Provide an assessment of effects if used outside the supporting data base. A description of and justification for the extrapolation method should be provided. For certain applications, recommendations may be given to use options other than the default options. In such cases, instructions should be provided to assure that appropriate validation is performed for the non-standard option.

3. Describe the implementation in the device (i.e., actual coding structure).

4. Describe any modifications required to overcome computational difficulties.

5. Provide an assessment of effects due to implementation (item 3) and/or due to modifications (item 4) on the overall code applicability and accuracy.

References 12 and 13 are examples of the MC/QE documents generated to meet the requirements listed above.

3.4 Users Manual And User Guidelines

The user's manual should be a complete description of how to prepare all required and optional input. The user guidelines should describe recommended practices for preparation of all relevant input. To minimize the risk of inappropriate program use the guidelines should include:

1. The proper use of the program for the particular plant specific transient or accident being considered,

2. The range of applicability for the transient or accident being analyzed,

3. The code limitations for such transients and accidents,

4. Recommended modeling options for the transient being considered, the equipment required, and choice of nodalization schemes. Plant nodalization should be consistent with nodalization used in assessment cases.

3.5 Scaling Reports

Reports should be provided for all scaling analyses used to support the viability of the experimental data base, the scalability of models and correlations and the scalability of the complete evaluation model. Section 5.3 of Reference 4 provides an example and references of scaling analysis done to support adequacy evaluations.

3.6 Assessment Reports

Assessment Reports are generally of three types:

1. Developmental Assessment
2. Component Assessment
3. Integral Effects Test Assessment

Most developmental assessment (DA) reports should be a set of code analyses that focus on a limited set of ranked phenomena. That is, the code or other device should analyze experiments or plant data that demonstrate in a separate effects manner the capability to calculate individual phenomena and processes determined to be important by the PIRT for the specific scenario and plant type.

There may be equipment which a code or other device may model in a special way. For these components, assessment calculations should be performed.

Integral effects tests (IET) should show the evaluation model's integral capability by comparison to relevant integral effects experiments or plant data. Some IET assessments may be general in nature but for evaluation model consideration, the IET assessment cases should include a variety of scaled facilities applicable to the plant design and transient.

For some plants and transients, code-to-code comparisons can be very helpful. In particular, if a new code or device is intended to have a limited application, the results may be compared to calculations using a previous code. However, the previous code should be well assessed to integral or plant data for the plant type and transient being considered for the new device. Differences in key input such as system nodalization should be explained so favorable comparisons are providing the right answers for the right reasons. Such benchmark calculations would not be a replacement for assessment of the new code.

A significant amount of evaluation model assessment may be performed prior to selection of the plant specific transient to be analyzed. In other cases the assessment may be done outside the context of the plant and transient specific evaluation model. In still other cases the assessment may be done by organizations other than those responsible for the plant specific analysis. If it is desired to credit these assessments to the plant and transient under consideration, great care should be taken in evaluating the applicability of those assessments. The applicability to the present case should be thoroughly evaluated and documented.

To gain confidence in evaluation model predictive capability when applied to a plant specific event, it is important for assessment reports to:

1. Assess calculational device capability and quantify accuracy to calculate various parameters of interest, in particular those described in the PIRT.

2. Determine whether or not the calculated results are due to compensating errors by performing an appropriate scaling analysis and sensitivity analyses.

3. Assess whether or not the calculated results are self-consistent and present a cohesive set of information that is technically rational and acceptable.

4. Assess whether the timing of events calculated by the evaluation model are in agreement with the experimental data.

5. Assess the evaluation model capability to scale to the prototypical NPP. Almost without exception such assessment also addresses the experimental data base used in development and/or validation of the evaluation model.

6. Explain any unexpected or, at first glance, strange results calculated by the evaluation model or component devices. This is particularly important when experimental measurements are not available to give credence to the calculated results. In such cases, rational technical explanations will greatly support generation of credibility and confidence in the evaluation model.

Furthermore, whenever there is a disagreement between calculated results and experimental data, it is necessary to:

7. Identify and explain the cause for the discrepancy, that is, to identify and discuss the deficiency in the device (or, if necessary, to discuss the inaccuracy of experimental measurements).

8. Address the question of how important the deficiency is to the overall results, that is to parameters and issues of interest.

9. Explain why a deficiency may not have an important effect on a particular scenario.

With respect to a calculational device input model and sensitivity studies, it is necessary for assessment reports to:

10. Provide a nodalization diagram along with a discussion of the nodalization rationale.

11. Specify and discuss the boundary and initial conditions, as well as the operational conditions for the calculations.

12. Present and discuss results of sensitivity studies (if performed) on closure relations or other parameters.

13. Discuss modifications to the input model (nodalization, boundary, initial and/or operational conditions) resulting from sensitivity studies (if performed).

14. Provide Guidelines for performing similar analyses.

3.7 Uncertainty Analysis Reports

Documentation should be provided for any uncertainty analyses performed as part of Step 20 of the EMDAP.

4. GENERAL PURPOSE COMPUTER PROGRAMS

Very often a general purpose transient analysis computer program, such as RELAP5, TRAC, or RETRAN, is developed to analyze a number of different events for a wide variety of plants. These codes can constitute the major portion of an evaluation model for a particular plant and event. Generic reviews are often performed for these codes to minimize the amount of work required for plant and event specific reviews. A certain amount of generic assessment may be performed for such a code as part of the generic code development. The EMDAP, on the other hand starts with identification of plant, event, and directly related phenomena. This process, as previously described, may indicate that a generic assessment does not include all of the appropriate geometry, phenomena or the necessary range of variables to demonstrate code adequacy for some of the proposed plant specific event analyses. Evidence of this is the fact that safety evaluations for generic code reviews often contain a large number of qualifications on the use of the code. To avoid such problems, it is important to qualify the applicability of the generic code, including its models and correlations, and the applicability of any "generic" assessment that accompanies the code.

D. IMPLEMENTATION

The purpose of this section is to provide information to applicants and licensees regarding the NRC staff's plans for using this regulatory guide.

Licensees and applicants may propose means other than those specified by the provisions of the Regulatory Position of this guide for meeting applicable regulations. This guide has been approved for use by the NRC staff as an acceptable means of complying with the Commission's regulations and for evaluating submittals in the following categories:

1. Construction permit applicants that must meet the design bases description requirements of 10CFR50.34 and the relation of the design bases to the principal design criteria described in Appendix A of 10CFR Part 50. Chapter 15 of the Standard Review Plan (NUREG-0800) describes the transients and accidents that the NRC staff reviews as part of the application, and those criteria of Appendix A which specifically apply to each class of transients and accidents. Chapter 15 also states that acceptable evaluation models should be used to analyze these transients and accidents.

2. Operating license applicants that must meet the design bases description requirements of 10CFR50.34 and the relation of the design bases to the principal design criteria described in Appendix A of 10CFR Part 50. Chapter 15 of the Standard Review Plan (NUREG-0800) describes the transients and accidents that the NRC staff reviews as part of the application, and those criteria of Appendix A which specifically apply to each class of transients and accidents. Chapter 15 also states that acceptable evaluation models should be used to analyze these transients and accidents.

3. Operating reactor licensees will not be evaluated against this guide unless a licensee proposes a new evaluation model and the NRC staff undertakes to review that model.

4. Chapter 15 of the revised Standard Review Plan (SRP) recommends that approved evaluation models or codes be used for the analysis of most identified events. The SRP suggests that evaluation model reviews be initiated whenever an approved model for a specified plant event does not exist. If the applicant or licensee proposes to use a new model, an evaluation model review should be initiated.

NOMENCLATURE AND DEFINITIONS

All definitions are in the context of the objectives of this reg. guide and may not be generic to other uses.

AHP	Analytical Hierarchical Process - *An analytical and software based methodology used to combine experimental data with expert judgement to efficiently rank the relative importance of phenomena and processes to the response of an NPP to an accident or other transient in a consistent and traceable manner.*
AP600	Advanced Passive 600 Mwe PWR designed by Westinghouse Electric Co.
"bottom-up"	The approach to a safety related analysis similar to "top-down"(see below), but in which the key feature is to treat all phenomena and processes, including all those associated with the analysis tool(s) modeling, as equally important to the facility/NPP response to an accident or transient and, therefore, quantified in depth.
calculational devices	Computer codes or other calculational procedures that compose an evaluation model.
Chapter 15 Events	In this regulatory guide, Chapter 15 events refer to those transients and accidents that are defined in Chapter 15 of NUREG-0800 to be analyzed to meet the requirements of the General Design Criteria (GDC), except for the fuel assembly misloading event and all radiological consequence analyses.
CFR	Code of Federal Regulations
closure relations	Equations and correlations required to supplement the field equations that are solved to obtain the required results. This includes physical property definitions and correlations of transport phenomena.
constituents	Chemical form of any material being transported, e.g., water, air, boron, etc..
CSAU	Code Scaling, Applicability and Uncertainty - *A process to determine the applicability, scalability, and uncertainty of a computer code in simulating an accident or other transient. A PIRT process is normally imbedded within a CSAU process. See Reference 1.*
DA	Developmental Assessment - *Calculations performed using the entire evaluation model or its individual calculational devices to validate its capability for the target application.*
DNBR	Departure from nucleate boiling ratio
EMDAP	Evaluation Model Development and Assessment Process

ECCS	Emergency Core Cooling System
evaluation model (EM)	Calculational framework for evaluating the behavior of the reactor system during a postulated Chapter 15 event, which includes one or more computer programs and all other information needed for use in the target application.
Fields	The properties that are being transported (mass, momentum, energy).
field equations	Equations that are solved to determine the transport of mass, energy and momentum throughout the system.
"frozen"	*The condition whereby the analytical tool(s) and associated facility input decks remain unchanged (and under configuration control) throughout a safety analysis thereby ensuring traceability of, and consistency in, the final results.*
GDC	General Design Criteria - *Design criteria described in Appendix A to 10 CFR Part 50.*
Geometrical Configurations	The geometrical shape that is defined for a transfer process, e.g., pool, drop, bubble, film, etc..
H2TS	*Hierarchical, Two-Tiered Scaling* - Methodology that uses hierarchical systems analysis methods to evaluate experimental scaling, and described in References 2 and 3.
IET	Integral Effects Test - *An experiment in which the primary focus is on the global system behavior and the interactions between parameters and processes.*
ISTIR	Integrated Structure for Technical Issue Resolution - *Methodology derived for severe accident issue resolution described in References 2 and 3.*
LB	Large Break
LOCA	Loss of Coolant Accident
LWR	Light Water Reactor
MC/QE	Models and Correlations Quality Evaluation - *A report documenting what is in a computer code, the sources used to develop the code, and conditions under which the original source of information was developed.*
model	(without "evaluation" modifier) - *Equation or set of equations that represents a particular physical phenomenon within a calculational device.*

modules	Physical components within the sub-system, i.e., reactor vessel, steam generator, pressurizer, piping run, etc.
MYISA	Maine Yankee Independent Safety Assessment
NPP	Nuclear Power Plant
phase	State of matter involved in transport process, usually liquid or gas. Notable exception is heat conduction through solids.
PIRT	Phenomena Identification and Ranking Table - *May refer to a table, or to a process depending on context of use. The process relates to determining the relative importance of phenomena (and/or physical processes) to the behavior of an NPP following the initiation of an accident or other transient. A PIRT table is a listing of the results of application of the process.*
Processes	Mechanisms that move properties through the system
QA	Quality Assurance
SB	Small Break
scalability (scaling)	The process in which the results from a subscale facility (relative to an NPP) and/or the modeling features of a calculational device are evaluated to determine the degree to which they represent an NPP.
scenario	Description and time sequence of events
sensitivity studies	*The term is generic to several types of analyses; however, the definition of most interest here relates to those studies associated with the PIRT process and used to determine the relative importance of phenomena/ processes. This may also involve analysis of experimental data that are a source of information used in the PIRT process.*
SET	Separate Effects Test - *An experiment in which the primary focus is on an single physical phenomena or process.*
SRP	Standard Review Plan - *Acceptable plan for NRC reviewers described in NUREG-0800.*
system	The entire system that must be analyzed for the proposed application
systems code	Principle computer code of an evaluation model that describes the transport of mass, momentum and energy throughout the reactor coolant systems.
sub-systems	Major components that must be considered in the analysis. For some applications this would include the primary system, secondary system, and

containment. For other applications only the primary system would need to be considered.

target application — safety analysis for which specific purpose, transient type and NPP type has been specified.

"top-down" — The approach to a safety related analysis in which one sequentially determines or performs: 1) the exact objective of the analysis (regulatory action, licensing action, desired product, etc.), 2) the analysis envelope (facility or NPP, transient(s), analysis code(s), facility/NPP imposed geometric and operational boundary conditions, etc.), 3) all plausible phenomena or processes that have some influence on the facility/NPP behavior, 4) a PIRT process, 5) applicability and scalability of the analysis tool(s), and 6) the influence of various uncertainties embedded in the analysis on the end product. A key feature of the top-down approach is to address those parts of the safety analysis associated with 5) and 6) in a graduated manner based on the relative importance determined in 4). *The approach elements 1) through 5)* are analysis tool(s) independent. Elements 5) and 6) require the approach to become analysis tool(s) dependent.

uncertainty (bands) — There are two separate, but related definitions of primary interest:
a. The inaccuracy in experimentally derived data typically generated by the inaccuracy of measurement systems.
b. The inaccuracy of calculating primary safety criteria or related figures of merit typically originating in the experimental data and/or assumptions used to develop the analytical tools. The analytical inaccuracies are related to approximations and uncertainties involved with solving the equations and constitutive relations.

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Appendix A

ADDITIONAL CONSIDERATIONS IN THE USE OF THIS REGULATORY GUIDE FOR ECCS ANALYSIS

A.1 BACKGROUND

Section 50.46 of 10 CFR Part 50, as it existed prior to September 1988, provided the requirements for domestic licensing of production and utilization facilities using conservative analysis methods. Section 50.46, Paragraph (b) listed the acceptance criteria for peak clad temperature, cladding oxidation, hydrogen generation and long-term decay heat removal. Appendix K to 10 CFR Part 50 provided specific requirements related to ECCS evaluation models. 50.46 also notes that the requirements of that section are in addition to the requirements of Criterion 35 of 10 CFR Part 50 Appendix A (GDC 35). GDC 35 states requirements for electric power and equipment redundancy for ECCS systems. Chapter 15.6.5. of NUREG-0800, "Standard Review Plan" describes for reviewers the scope of review, acceptance criteria, review procedures and findings relevant to ECCS analyses submitted by licensees. Chapter 15.0.1 of NUREG-0800 is the companion SRP section to this regulatory guide.

In September 1988, the NRC amended the requirements of Section 50.46 and Appendix K so that the regulations reflected the improved understanding of ECCS performance during reactor transients that was obtained through extensive research performed between the promulgation of the original requirements in January 1974 and September 1988. Examples of that body of research can be found in Reference A-1. Further guidance to licensees or applicants was provided in May 1989 via Regulatory Guide 1.157, "Best-Estimate Calculations of ECCS Performance". The 10 CFR 50 amendment and Regulatory Guide 1.157 now permits licensees or applicants to use either the Appendix K conservative analysis methods or a realistic evaluation model (commonly referred to as best estimate plus uncertainty analysis methods). That is, the uncertainty in the best estimate analysis must be quantified and considered when comparing the results of the calculations with the applicable limits in Paragraph 50.46(b) so that there is a high probability that the criteria will not be exceeded. It may be noted the acceptance criteria for PCT, cladding oxidation, hydrogen generation and long-term decay heat removal did not change with the September 1988 amendment.

A.2 NEED FOR REGULATORY GUIDANCE UPDATE FOR ECCS ANALYSIS

The regulatory structure described above was strongly founded on the supporting work documented in Reference A-2. Therefore, it is important to provide a regulatory structure update that reflects the last eleven years of advancement in best estimate plus uncertainty analysis methods. Examples of the extension of evolving best estimate plus uncertainty analysis methods to the both the old and new advanced reactor designs can be found in References A-3 through A-8 of this appendix and Reference 12 of the main body of this regulatory guide.

A.3 UNCERTAINTY METHODOLOGY

The best estimate option in 10CFR50.46 allowed since 1988, requires that:

> "uncertainties in the analysis method and inputs must be identified and assessed so that the uncertainties 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 this section, there is a high level of probability that the criteria would not be exceeded."

To support the revised 1988 ECCS rule, the NRC and its contractors and consultants developed and demonstrated an uncertainty evaluation methodology called code scaling, applicability, and uncertainty (CSAU) (Reference A-2). While this regulatory guide is oriented towards the CSAU approach, including its embedded PIRT process, it is recognized other approaches exist. Since the CSAU demonstration was not a plant specific application, evaluation of input uncertainties related to plant operation was not emphasized. Proprietary methodologies have been submitted and approved by the NRC which fully address uncertainties in analysis methods and input. Thus, other approaches to determining the combined uncertainty in the safety analysis are recognized as having potential advantages, as long as the evaluation model documentation provides the necessary validation of its approach.

The safety criteria (PCT, H_2 generation, etc.) specified in 10 CFR 50.46 remains unchanged regardless of the uncertainty methodology used in a licensing/regulatory submittal. Similarly, the same is true for the general guidelines provided in Regulatory Guide 1.157 with regards to the phenomena and components, and computer models thereof described in that regulatory guide. Thus, the focus of the remainder of this section is those considerations primarily related to determining the:

- relative importance of phenomena/processes and components, and thereby those that should be included in the uncertainty analysis,
- method of establishing the individual phenomenon/process contribution to the total uncertainty in the safety criteria, and
- method to combine the individual contributions to uncertainty into the total uncertainty in the safety criteria.

CSAU and other methods address the relative importance of phenomena/processes, the difference being in the approach. CSAU uses the PIRT process in which relative importance is established by an appropriate group of experts based on experience, experimental evidence and/or computer based sensitivity studies. Once finalized, the resulting PIRTs guide the degree of effort to determine the individual phenomenon/process uncertainty in the safety criteria. The PIRT process results also guide the method used to combine the individual contributions into an estimate of the total uncertainty in the safety analysis. Commonly, but not required, a response surface is developed to act as a surrogate for the computer code(s) used in estimating the total uncertainty. The response surface can then be extensively Monte Carlo sampled to determine the total uncertainty. The use of limited computer calculations to develop an accurate response surface is followed by sufficient Monte Carlo sampling of the response surface in an effort to be as thorough as necessary yet as economical as possible. Therefore the major cost of the CSAU methodology is related to the extensive expert man-hours normally required by the expert panel to perform the PIRT process. Additional advantages of the CSAU are that it has been used by the USNRC, and the details of the methodology have been well documented (Reference A-2).

A potential disadvantage is related to the dependency of the number of computer simulations on the number of phenomena/processes determined in the PIRT which may be needed to estimate the total uncertainty. That is, at least two "single parameter change" runs must be made for each required phenomenon/process. In addition, cross-product runs must be made when several of the phenomena/processes have significant covariance. The cross-product runs may involve "two parameter, three parameter and four parameter" change runs to adequately determine the effect of non-independent phenomena/processes.

In contrast, other methods (Reference A-7) may use a panel or individual experience only to determine what phenomena/processes may contribute to the total uncertainty in the safety criteria, and adequate estimates of the variability of those phenomena/processes. Similar to CSAU, the estimates of the individual parameter variations are based on expert experience, experimental data, and available sensitive studies. The required computer simulations may be a large number because the number of computer calculations needed to determine the total uncertainty is independent of the number of contributors. That is, the number of computer simulations is dependent only on the probability and confidence limits desirable in the final results. For example 95%/95% limits require something in the order of 90 simulations regardless of the number of phenomena/processes selected as contributors. This feature is achieved through the use of unique statistical assumptions with respect to how the individual contributor uncertainty domain is sampled. There is not a strong non-proprietary precedence that could be used a priori by the USNRC in approving such a licensing/regulatory submittal to evaluate overall uncertainty. Accordingly, such submittals would initially require significant validation of the methodology. The same is considered to be true of uncertainty methodologies described in Reference A-7 that might be used.

An uncertainty methodology is not required for the original conservative option in Section 50.46. Rather, the required features of Appendix K provide sufficient conservatism without the need for an uncertainty analysis. It should be noted that Appendix K does require that:

"To the extent practicable, prediction of the evaluation model, or portions thereof, shall be compared to applicable experimental information."

Thus for Appendix K, comparisons to data similar to those required for the best estimate option are also required, but without the need for an uncertainty analysis. However, poor comparisons with applicable data, may prevent NRC acceptance of the Appendix K model.

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