1. INTRODUCTION

Most nuclear reactors presently operating throughout the world are water-cooled. The reactor core consists of numerous fuel bundles, each bundle containing a number of fuel pins. Each fuel pin contains a stack of ceramic, cylindrical UO_2 fuel pellets. The fuel pellets are contained within a metallic sheath or cladding having an outside diameter of approximately 0.5-inches.

The fuel forms for gas-cooled reactors are very different. Tiny kernels of UO_2 fuel are encapsulated within several layers of pyrolytic carbon (PyC) and a single layer of silicon carbide (SiC) to create a fuel particle having a diameter of approximately 1-mm as shown in Fig. 1-2. This fuel is called TRISO-coated particle fuel. Thousands of these particles are combined with a matrix material and pressed into spheres for pebble bed fuels or cylindrical or annular compacts for prismatic fuels. TRISO-coated particle fuel particles are intended to stay intact and effectively retain and contain fission products during normal operation as well as during postulated accidents.

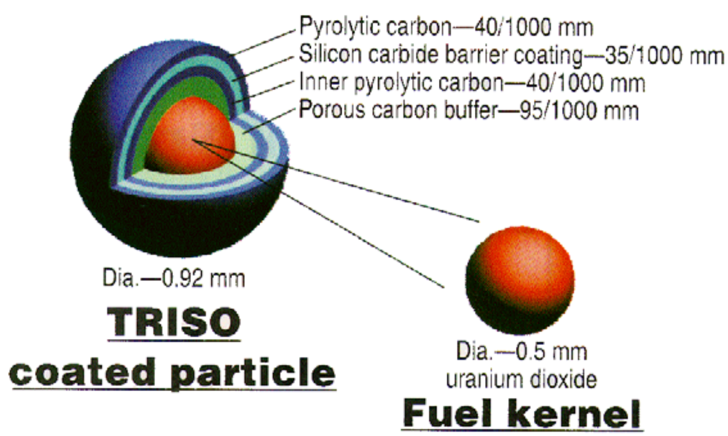

Figure 1-1 An example of a TRISO-coated particle fuel particle

TRISO-coated particle fuel has been used in several reactors in the past, e.g., the 330 MW(e) Ft. Saint Vrain reactor in the US and the 15 MW(e) AVR and 300 MW(e) THTR reactors in Germany. TRISO-coated particle fuel is being used in the10 MW(t) HTR-10 research reactor in China and the 30 MW(t) HTTR research reactor in Japan. The HTR-10 has a pebble bed core and the HTTR uses a prismatic compact fuel form. The total numbers of reactor years of TRISO-coated particle fuel operating experience are few relative to water reactor fuel.

In anticipation of future licensing applications for gas-cooled reactors, the NRC seeks to fully understand the significant features of TRISO-coated particle fuel design, manufacture, operation and accident behavior. To address this objective, the NRC established a Phenomena Identification and Ranking Table (PIRT) panel to identify and rank the factors, characteristics, and phenomena associated with the life-cycle phases of TRISO-coated particle fuel.

The panel considered four TRISO-coated particle fuel life-cycle phases or conditions: (1) design, (2) manufacturing, (3) normal operation, and (4) accidents. Four accident scenarios, namely depressurized heatup, reactivity insertion, intrusion of water vapor and intrusion of air were addressed. The panel identified the factors, characteristics and phenomena for each of the four life-cycle phases. The ranking portion of the PIRT process was completed for the manufacturing, normal operation, and accident life-cycle phases only.

1.1 Need for Identification and Ranking

The physical processes and phenomena that occur in nuclear reactors can be both complex and highly coupled. The ability to predict the behavior of nuclear reactors during normal operation as well as their response to accident conditions is of paramount importance. With predictability comes understanding. Both are required to ensure safe reactor operation.

Several fundamental elements form the basis for a safe design. First, the design itself is of paramount importance. An important recent trend in reactor design is the reliance on simplified, passive and/or inherent safety features to reduce the reliance on both active, complex hardware and systems and operator interventions. The ability to accurately predict the behavior of the design under operational and accident conditions using qualified analytical methods is essential.

Predictability, including an understanding of safety margins, is based upon both experiments in scaled component and integral facilities and calculations using analytical tools. It is not, however, feasible to build a full-scale test reactor and then expose that reactor to the aggressive conditions of all design basis accidents. Therefore, analyses based upon qualified analytical methods have become essential to confirming the safety basis for nuclear reactors. The development and qualification of transient and accident analysis methods is central to both designing and demonstrating the safety of a reactor design.

Recently, the NRC has issued a draft regulatory guide, DG-1120, for "Transient and Accident Analysis Methods" (Ref. 1-1). The regulatory guide articulates six basic principles of evaluation model development and assessment. The first principle is to "determine the requirements for the evaluation model." Central to this step is "identification of the . . . components, phenomena, physical processes, and parameters (hereafter collected under the general designation of 'phenomena') needed to evaluate event behavior relative to the figures of merit described in the Standard Review Plan and derived from the General Design Criteria in Appendix A to 10 CFR 50." This identification step is the first essential element of the Phenomena Identification and Ranking Table (PIRT) process. The second essential element is ranking each phenomenon relative to an evaluation criterion, also called a figure of merit. The ranking step is based upon the reality that plant behavior is not equally influenced by all processes and phenomena that occur during a transient or accident. The PIRT process reduces candidate phenomena to a manageable set by identifying and ranking the phenomena with respect to their influence on the figure of merit.

As stated in Ref. 1-1, the principal product of the process outlined above is a phenomena identification and ranking table. Evaluation model development and assessment should be based upon a credible PIRT. The PIRT should be used to determine the requirements for physical model development, scalability, validation, and sensitivities studies. Given these importance statements, it is important to recognize that “the PIRT is not an end in itself, but is rather a “tool” to be used to guide and focus subsequent efforts.

1.2 The PIRT Process

The PIRT process has evolved from its initial development and application (Refs. 1-2 1-3, 1-4) to its description as a generalized process (Ref. 1-5). The PIRT process is deterministic; it is not risk-informed. A PIRT can be used to support several important decision-making processes. For example, the information can be used to support either the definition of requirements for related experiments and analytical tools or the adequacy and applicability of existing experiments and analytical tools. This information is important because it is neither cost effective nor required to assess each feature of an experiment or analytical tool in a uniform fashion. The PIRT methodology brings into focus the phenomena that dominate, while identifying all plausible effects to demonstrate completeness.

A simplified description of the PIRT process, as applied to the development of the PIRT for TRISO-coated particle fuel, is illustrated in Fig. 1-2 and described as follows.

Step 1: Define the issue that is driving the need, e.g., licensing, operational, or programmatic. The definition may evolve as a hierarchy starting with federal regulations and descending to a consideration of key physical processes.

Step 2: Define the specific objectives of the PIRT. The PIRT objectives are usually specified by the sponsoring agency. A clear statement of PIRT objectives is important because it defines the focus, content, and intended applications of the PIRT product. The PIRT objectives should include a description of the final products to be prepared.

Step 3: Define the hardware, equipment and scenario for which the PIRT is to be prepared. Generally, a specific hardware configuration and specific scenario are specified. Usually, but not always, the scenario is divided into phases. This is done because the importance of a phenomenon often varies during the course of a scenario. In addition, some system components may not be activated throughout the scenario. Experience obtained from previous PIRT efforts indicates that any consideration of multiple hardware configurations or scenarios impedes PIRT development. After the baseline PIRT is completed for the specified hardware and scenario, the applicability of the PIRT to related hardware configurations and scenarios can be assessed.

Step 4: Define the primary evaluation criterion. The primary evaluation criterion is the key figure of merit used to judge the relative importance of each phenomenon. It must, therefore, be identified before proceeding with the ranking portion of the PIRT effort. It is extremely important that all PIRT panel members come to a common and clear understanding of the primary evaluation criterion and how it will be used in the ranking effort. The characteristics of a well-defined evaluation criterion are that it is: (1) directly related to the issue(s) being addressed, (2) directly related to the phenomena expected to occur during the scenario, (3) easily comprehended, (4) explicit, and (5) measurable. The primary evaluation criterion is generally derived from regulatory requirements.

Step 5: Compile and review the contents of a database that captures the relevant experimental and analytical knowledge relative to the physical processes and hardware for which the PIRT is being developed. Each panel member should review and become familiar with the information in the database.

Step 6: Identify all plausible phenomena i.e., PIRT elements. A primary objective of this step is completeness. In addition to preparing the list of phenomena, precise definitions of each phenomenon should be developed and made available to the PIRT panel to ensure that panel members have a common understanding of each phenomenon. In each PIRT effort, there is a phenomenological hierarchy beginning at the system level and proceeding in turn through the component level, local level, microscopic level, atomic levels and so on. Each PIRT panel must determine the appropriate phenomenological levels to include in its list of identified phenomena. Insights into the levels to be included can often be derived by considering the data needs for analytical methods and the level at which experimental data is collected. Usually, there is no need to proceed further down the phenomenological hierarchy than (a) the level at which physical processes modeled with analytical methods or (b) the level at which data, either direct or indirect, are acquired.

Step 7: Develop the importance ranking and rationale for each phenomenon. Importance is ranked relative to the primary evaluation criterion adopted in Step 4. Several ranking scales have been used in the past. However, consistent application of the scale is of equal importance as the specifics of the scale. A word-based scale, e.g., High, Medium or Low importance, has often been sufficient. Numerical scales, e.g., 1-5, have also been used. For example, an importance rank of 5 (equivalent to High in the word scale) might carry the explicit outcome that experimental simulations and analytical modeling with a high degree of accuracy are critical.

Step 8: Assess the level of knowledge regarding each phenomenon. This is a new step in the evolving PIRT process. It was not included, for example, in a recent generalized description of the PIRT process (Ref. 1-5). As with importance ranking, several scales have been used in the past. Again, a consistent application of the scale is of equal importance as the specifics of the scale. A word-based scale, e.g., Known, Partially Known or Unknown, has often been sufficient. A numerical scale, e.g., 1-5, which includes in its definitions a statement on uncertainty, has also been used. By explicitly addressing uncertainty due to a lack of knowledge, an observed defect of earlier PIRT efforts has been addressed, namely, the tendency of PIRT panel members to assign high importance to a phenomenon for which panel members concluded that there was significantly less than full knowledge and understanding.

A consistent outcome of PIRT efforts has been that phenomena found to be highly important relative to the primary evaluation criterion, but for which the knowledge level is insufficient, are carefully examined to determine if additional experimental or analytical efforts are warranted.

Step 9: Document the PIRT results. The primary objective of this step is to provide sufficient coverage and depth that a knowledgeable reader can understand what was done (process) and the outcomes (results). The essential results to be documented are the phenomena considered and their associated definitions, the importance of each phenomena and associated rationale for the judgment of importance, the level of

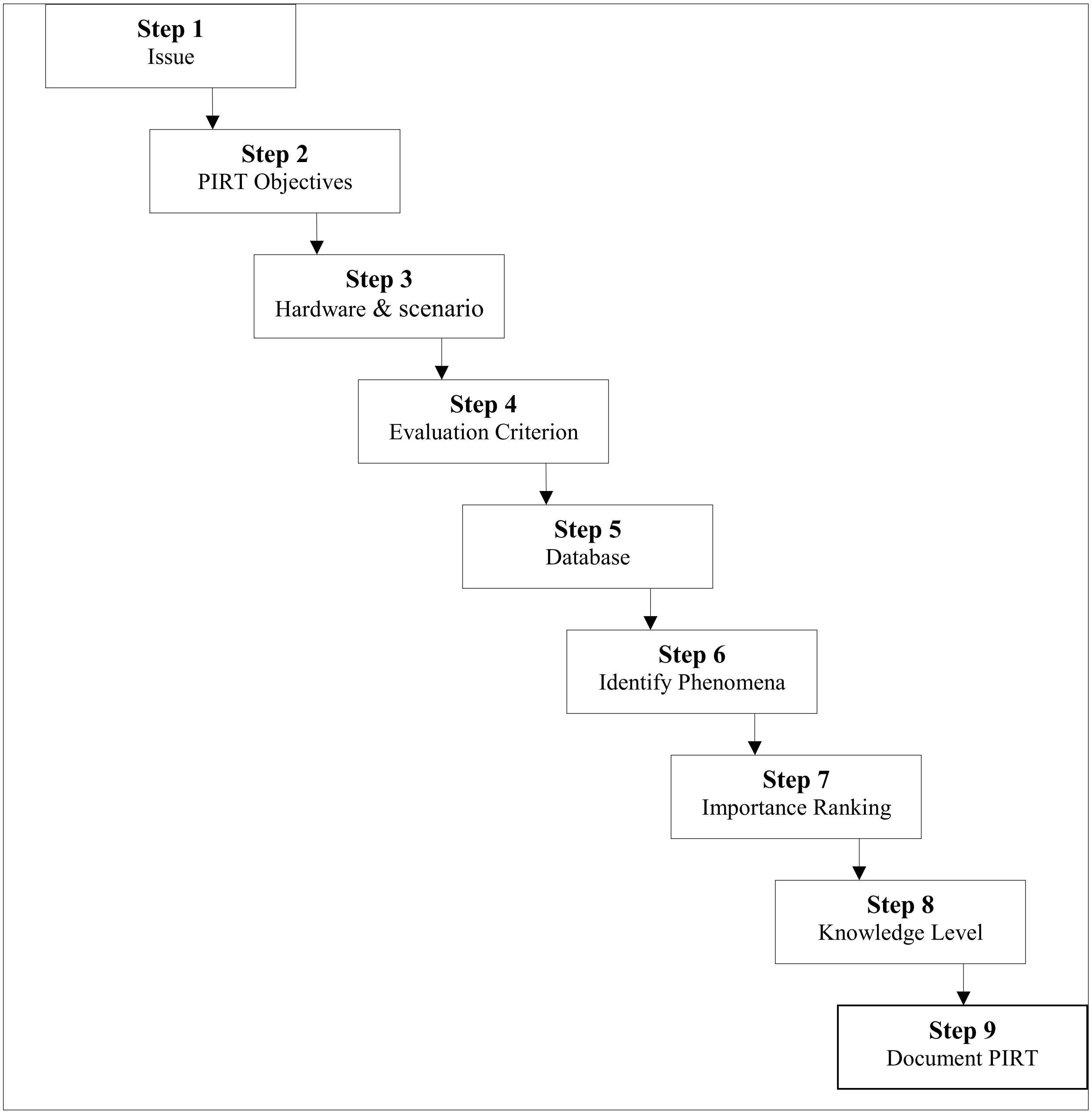

Figure 1-2 PIRT Process

knowledge or uncertainty regarding each phenomenon and associated rationale, and the results and rationales for any assessments of extended applicability for the baseline PIRT. Other information may be included as determined by the panel or requested by the sponsor. For the TRISO-coated particle fuel PIRT, the NRC requested that the panel members describe the research or other effort required to reach closure for a highly ranked phenomena for which only little or partial knowledge of the phenomenon was currently available.

As presented in Fig. 1-2, the PIRT process proceeds from start to end without iteration. In reality, however, the option to revisit any step is available and is often exercised during the PIRT development process.

1.3 PIRT Process Application for the TRISO-coated particle fuel PIRT

Although the PIRT process has been generalized, there are numerous details that must be addressed for each PIRT application. The initial PIRT application (Refs. 1-2 and 1-3) considered the response of a specific pressurized water reactor (PWR) design to a large-break loss of coolant accident. Such plants had been built and operated for a number of years and both the experimental and analytical databases for PWR designs were large. The current application focused on the TRISO-coated particle fuel particle and the fuel element within which the fuel particles are contained.

Numerous specific decisions were made during the development of the TRISO-coated particle fuel PIRT. These are summarized in the following for each PIRT process step described in Chapter 1.2.

Step 1 – Issue: In anticipation of future licensing applications for gas-cooled reactors, the NRC seeks to identify the significant features of TRISO-coated particle fuel design, manufacture, operation and accident behavior.

Step 2 - Objectives: The objectives of the PIRT for TRISO coated fuel particles were to (1) identify key attributes of HTGR fuel manufacture which may require regulatory oversight, (2) provide a valuable reference for the review of vendor HTGR fuel qualification plans and analytical methods, (3) provide insights for developing plans for fuel safety margin testing, (4) assist in defining test data needs for the development of fuel performance and fission product transport models, (5) inform decisions regarding the development of NRC's independent HTGR fuel performance code and fission product transport models, (6) support the development of NRC's independent models for source term calculations, and (7) provide insights for the review of vendor HTGR fuel safety analyses.

Objectives (1) through (4) are information and features included in the final PIRT report. Objectives (4) through (7) describe uses that will be made of the final PIRT report and the information provided therein.

The NRC requested that the TRISO-coated particle fuel PIRT panel identify the factors, characteristics, processes and phenomena, all of which are identified as phenomena for simplicity in the report, related to the design, manufacture, operation, and accident behavior of TRISO-coated particle fuel. The panel was asked to rank, with the exception of the design life-cycle phase, each phenomenon for importance relative to the evaluation criterion (figure of merit), assess the knowledge level for each phenomenon, and provide its rationale for both the importance and knowledge rankings. For those phenomena judged to be of high importance but not well understood, the panel was asked to describe the effort required to bring about closure, i.e., a sufficient level of knowledge regarding the phenomenon that it would be well understood.

Step 3 – Hardware & Scenario: For this step, there were significant variations relative to the generalized PIRT process. First, there are several forms of TRISO-coated particle fuel, with variations due to the kernel material, UO_2 or UCO; coating process as done, for example, in either the U.S. or Germany; and fuel form, either a spherical pebble or prismatic compact. Second, there are currently two candidate commercial power reactor designs being developed for potential NRC licensing, e.g., the Pebble Bed Modular Reactor (PBMR), which utilizes spherical fuel elements and the Gas-Turbine Modular Helium Reactor (GT-MHR), which utilizes prismatic fuel elements. The experimental and analytical databases for these two reactors are limited but these reactors are the most likely candidates for early NRC licensing reviews. Given these factors, the NRC, after discussion with the panel, specified the following hardware and scenario conditions for the baseline TRISO-coated particle fuel PIRT.

- UO_2 fuel. This fuel was selected because the experimental and operational database for this fuel is much larger than for UCO fuel.
- The fuel production process is similar to the German process, while allowing needed production changes consistent with modern UO_2 fuel. There is more information on the reference German process than the US process, which involved more variability.
- The fuel form is a spherical "pebble." As with the choice of UO_2 fuel, the database for pebbles is more extensive for this fuel form. Therefore, it was chosen as the fuel form for the baseline PIRT.
- Given the choice of pebble (spherical) fuel, the plant is considered to be a PBR and the operating conditions are consistent with that reactor type. There is one exception to this choice (see the description of the reactivity insertion scenario as described below)
- The panel did prepare incremental PIRTs relative to the baseline of UO_2 fuel produced by the German process and formed into pebbles. The panel identified and evaluated the importance rankings that would be altered for UCO fuel and prismatic fuel forms.

In a marked departure from highly plant- and scenario-specific specifications, the above specifications had a more general quality. The information needed to develop more detailed specifications were not available to the panel. Thus, the specifications were somewhat general but deemed sufficient to satisfy the NRC's stated objectives.

Another innovation was the development of a PIRT for the manufacturing phase of the TRISO-coated particle fuel life cycle. Clearly, the approach taken for manufacturing was, of necessity, somewhat different than for the operation and accident scenarios. The panel undertook to identify and rank numerous manufacturing factors and characteristics and assess the knowledge level associated with each. Therefore, the manufacturing PIRT should be considered as an extension of the PIRT process in that identification and ranking are performed on factors and characteristics that are related to the manufacturing process rather than "phenomena" arising with the transition of the plant through physical states associated with operation or accidents.

A PIRT was developed for plant operation. However, consistent with the evolving nature of the TRISO-coated particle fuel and gas-reactor designs, the features of the operational phase were only generally specified. For example, the panel did not explicitly consider a numeric burnup but did consider the fact that TRISO-coated particle fuel is taken to burnups higher than fuels in light water reactors.

Separate PIRT tables were prepared for four accident scenarios. With the exception of the air intrusion scenario, calculations for the remaining accident scenarios were not available. Therefore, the ranges of parameters occurring during the remaining accident scenarios were assumed. The accidents scenarios and a brief description follow.

Depressurized heatup scenario. Following a break in the reactor cooling system piping, the reactor depressurizes and heat is transferred from the core through the surrounding structures to the ground. This scenario has also been called the "conduction cooldown" scenario. All current reactor designs using TRISO-coated particle fuel are to be designed such that the fuel temperature will not exceed 1600 °C. This temperature is taken as a maximum allowable fuel temperature limit because the maximum accident fission product releases increase above this temperature. However, to address potential uncertainties and at the NRC's direction, a time versus fuel temperature curve was defined in which the fuel temperature reaches 1800 °C. The fuel temperature transient used in the PIRT evaluation is presented as the dashed line in Fig. 1-3.

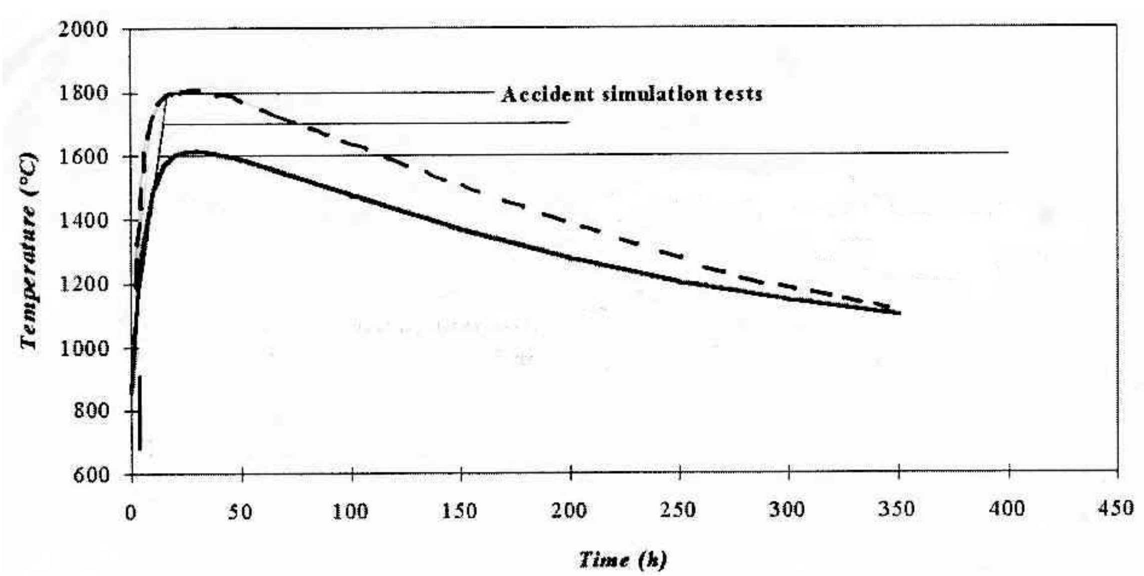

Figure 1-3 TRISO-coated particle fuel temperature transient for depressurized heatup scenario

- Reactivity insertion scenario: The potential reactivity additions for a pebble bed core undergoing a postulated control rod ejection accident are considered less challenging than for a prismatic reactor. For a pebble bed core, the reactivity accident would likely result in a fuel heatup event not dissimilar to the heatup event previously considered. Accordingly, the conditions arising from a potential reactivity scenario involving a postulated control rod ejection accident in a prismatic core design were selected as the basis for the postulated core conditions to develop the phenomena for this scenario and these conditions were applied to the pebble bed core.

- A power pulse occurs. This pulse is on the order of seconds, i.e., not milliseconds. A fraction of the TRISO-coated particle fuel particles fail. The kernel and buffer remain intact, as does the fuel element matrix, but the other layers are breached, i.e., the inner pyrolytic carbon (IPyC), silicon carbide (SiC) and outer pyrolytic carbon (OpyC). The remaining unfailed particles are considered to respond as in a heatup accident. For the purposes of the PIRT, the panel considered how fission product generation and transport would be affected for a rapidly failed particle.
- Depressurized heatup followed by water intrusion: The reactor is depressurized as in the conduction cooldown scenario. Water enters primary system and is vaporized but the amount of water vapor present is not sufficient to cool the core. The panel assumed 1% water vapor content in the core for the duration of the transient. Throughout the scenario, the core is assumed to be immersed in coolant having a composition of 1% water vapor and 99% helium. Carbon and steam react to produce reaction products. Some of these reaction products can also react with carbon. The panel did not consider phenomena associated with the interaction of these reaction products with carbon at high temperatures.
- Depressurized heatup followed by air intrusion: The reactor is depressurized as in the conduction cooldown scenario. The break location is assumed to be in the cross-over vessel between the reactor vessel and the power conversion system vessel. Initially, air can enter the primary system only by diffusion. Although this process proceeds slowly, sufficient air enters the primary system over time and moves to the core. When air reaches the core, natural circulation is initiated and the graphite structures in the flow path are exposed to increased flows of air. The results of this "base" scenario were analyzed using the MELCOR code. The results are presented in Appendix G. Sensitivity studies are also presented.

Step 4 – Evaluation Criterion: Each factor, characteristic, process or phenomenon was assessed relative to its importance to fission product release from the fuel or in a more licensing-specific term, the source term.

Step 5 – Database: The panel compiled and reviewed the contents of a database that captured the relevant experimental and analytical knowledge relative to the physical processes and hardware for which the PIRT was developed. Chapter 2 of this report, TRISO-Coated Fuel Particle Performance, describes the TRISO coated particle and fuel element; the design function of each part of the TRISO-coated particle fuel, e.g., kernel, buffer, pyrolytic carbon layers, silicon carbon layers, and fuel element; fabrication processes; fuel behavior during normal operation and fuel behavior during accident conditions. Chapter 3 discusses the potential phenomena responsible for the transport of fission products in TRISO-coated particle fuel. Finally, Appendices A-F present the individual panel member importance and knowledge rankings and rationales for each PIRT. Citations are provided for the importance and knowledge rankings for many of the more important phenomena.

Step 6 – Identify Phenomena: Over the course of the first TRISO-coated particle fuel PIRT panel meetings, the panel members first identified and then refined the phenomena lists. The "phenomena" definition for the manufacturing PIRT was broadened to include manufacturing factors and characteristics. The “phenomena” identified for the operation and accident scenarios were those of the more typical PIRT. Precise definitions of each phenomenon were developed and made available to the PIRT panel to ensure that panel members had a common understanding of each phenomenon. The identified “phenomena” and associated definitions are presented in the summary PIRT tables found in Chapter 4 of this report.

Although the objective of the identification step is to identify all pertinent phenomena, it is necessary for the PIRT panel to determine how deep down into the phenomenological hierarchy levels to proceed. For example, no useful purpose is served by defining phenomena at the “microscopic” level when the PIRT is being developed for the system-wide response of a reactor to a large-break loss-of-coolant-accident. However, phenomena occurring at such levels may be appropriate when the PIRT is focusing on a TRISO-coated particle fuel kernel with a diameter of approximately 1-mm, said particle consisting of multiple thin layers of various materials. The phenomena identified in the TRISO-coated particle fuel PIRT tables (See Chapters 2 and 4) reflect the panel’s awareness of the need to be complete but at a level of phenomenological detail appropriate for the end practical use of the PIRT by the NRC.

The panel first identified elements of the design life-cycle phase. Importance of the design elements was ranked and the knowledge level assessed. The panel did not further discuss the results of their individual PIRT findings, as was done with the other PIRTs documented in this report. The PIRT findings of each panel member are provided in Appendix H.

Next, the panel applied the following conditions on the manufacturing, operations, and accident phenomena to be included in each PIRT.

Manufacturing PIRT

- Identify and rank the factors, specifications, material properties and manufacturing processes related to fuels manufactured per specification.
- Consider the importance of fuel defects beyond those permitted by the specifications as deemed necessary.

Operations PIRT

- Assume fuel manufacture meets specifications, i.e., “good” fuel. Such fuel can have defects at levels allowed by the specifications but no additional defects.
- Identify and rank the impacts of operation on good fuel properly operated to the time of the accident.
- Address fuel defects beyond that allowed by specification only in the manufacturing phase

Accident PIRTs (heatup, reactivity insertion, water and air intrusion)

- Assume fuel is manufacture meets specifications. Such fuel can have defects at levels allowed by the specifications but no additional defects.
- Assume the fuel is operated as specified by the operating specifications.
- Identify and rank the impacts of accidents on good fuel properly operated up to the time of the accident.
- Address fuel defects beyond that allowed by specification only in the manufacturing phase

The construct of the PIRT tables was aligned with the various physical features of a TRISO-coated particle fuel particle, i.e., the kernel, porous carbon buffer layer, inner pyrolytic carbon layer, silicon carbide layer, outer pyrolytic carbon layer, and fuel element. The phenomena list was essentially replicated for each layer for like life-cycle phases, e.g., operation and the accidents[1]. As a consequence, the PIRT tables are large. Given the detailed PIRT information requested of the panel members, as documented in Appendices A-F, the effort required was very large.

Step 7 – Importance Ranking: The panel ranked each phenomenon in each table relative to the evaluation criterion, i.e., fission product release (See Step 4 of Chapter 1.4). A summary of the importance ranking assigned by each panel member (listed by institution) is found in Chapter 4. The rationale provided by each panel member for the importance ranking of each phenomenon is provided in the Appendices.

Each phenomenon was assigned an importance rank of "High," "Medium," or "Low." The definitions associated with each of these importance ranks are shown in the following table.

Table 1-1 Importance Ranks and Definitions

Importance Rank	Definition
Low (L)	Small influence on primary evaluation criterion
Medium (M)	Moderate influence on primary evaluation criterion
High (H)	Controlling influence on primary evaluation criterion

Each PIRT panel is challenged by the need to apply consistent thought processes when evaluating the importance of each phenomenon. PIRT panels have found that expressing the importance ranking issue as a question proves helpful. The TRISO-coated particle fuel PIRT panel used this approach for the manufacturing PIRT. Following are selected

[1] One panel member expressed the following concern: "This PIRT is based more on geometry than it is on phenomenology, despite the name. The PIRT seems to be attempting to identify the critical component of the coated particle fuel structure that deserves the most attention. This is done at the expense of identifying the critical phenomena that need to be understood to anticipate the behavior of the fuel in normal and off normal circumstances. As a result questions are asked repetitively about each of the major elements of the fuel perhaps to see if one or more of the elements are more vulnerable than others. The questions do not illuminate in any detail the type of information that must be derived for coated particle fuel or the types of testing that must be done to gather the information. For instance, lumped within the simple question of gas phase diffusion are bulk and Knudsen diffusion. Though the question is repeated for each layer even when the layers are very similar, such as inner and outer PyC, there is no request for details of the materials that would be essential to estimate Knudsen versus bulk diffusion such as porosity and tortuosity. There is no indication of whether tests of permeability need to be done for layers *in situ* or such data can be obtained from macroscopic samples of analog material. We do not know from the PIRT whether phenomena such as thermal diffusion require testing to be done in prototypic gradients or just known gradients. We do not know from the PIRT whether diffusion must be considered as approximately binary diffusion or has to be viewed as a multi-component process. This focus on the structure at the expense of phenomena limits the utility of the PIRT for the design of fuel models and experimental studies. Perhaps, the PIRT is more useful in other respects because of its focus on structure."

questions formulated by the panel as consistency guides. The first question applies to specifications and the second to other factors and characteristics.

Question 1: Which of the specifications are most important with respect to manufacturing fuel that will successfully perform in the reactor under normal operations and accident conditions?

Question 2: Which of the material properties, factors, or processes are most important with respect to manufacturing fuel that will successfully perform in the reactor under normal operations and accident conditions?

Step 8 – Knowledge Level: Each panel member assessed the current knowledge level for each phenomenon in each PIRT table. The knowledge level for each phenomenon was assessed rather than the level of knowledge of the impact of each phenomenon on the Primary Evaluation Criterion. Numbers between 1 and 9 were assigned to reflect the knowledge level with the associated definitions shown in the following table. A summary of the knowledge ranking assigned by each panel member (listed by institution) is found in Chapter 4. The rationale provided by each panel member for the knowledge ranking of each phenomenon is provided in the Appendices.

Table 1-2 Knowledge Levels and Definitions

Knowledge Level	Definition
7-9	Known: Approximately 70%-100% of complete knowledge and understanding
4-6	Partially Known: 30%-70% of complete knowledge and understanding
1-3	Unknown: 0%-30% of complete knowledge and understanding

Step 9 – Documentation: This document represents the realization of the documentation step. The general PIRT process and its specific application to the TRISO-coated particle fuel PIRT effort are documented in Chapter 1. A description of TRISO design, manufacturing, operation and accident factors is presented in Chapter 2. Potential phenomena responsible for the transport of fission products in TRISO-coated particle fuel are presented in Chapter 3. Summary PIRT tables with the identified phenomena, importance ranks, and knowledge ranks are presented in Chapter 4. Analysis of the results and conclusions are presented in Chapter 5. The detailed PIRT panel member importance and knowledge findings and the rationales for each are presented in the appendices, as are brief biographies for each panel member.

1.4 Report Organization

The report is organized into five chapters and contains nine supporting appendices.

- Chapter 1, Introduction, provides an overview of the general PIRT process, identifies modifications to the general approach for the TRISO-coated particle fuel PIRTs, provides a brief description of the TRISO-coated particle fuel life-cycle phases and, where appropriate, the scenarios considered. The objectives of the PIRT effort are identified and the members of the TRISO-coated particle fuel PIRT panel are identified.

- Chapter 2, TRISO-Coated Fuel Particle Performance, describes the TRISO coated particle and fuel element; the design function of each part of the TRISO-coated particle fuel, e.g., kernel, buffer, pyrolytic carbon layers, silicon carbon layers, and fuel element; fabrication processes; fuel behavior during normal operation and fuel behavior during accident conditions.
- Chapter 3, Fission Product Transport in TRISO-Coated Particle Fuels, discusses the potential phenomena responsible for the transport of fission products in TRISO-coated particle fuel as a means of further understanding the identified phenomena.
- Chapter 4, TRISO-Coated Particle Fuel Phenomena Identification and Ranking Tables (PIRTs), contains the summary PIRTs for (1) manufacturing, (2) normal operation, (3) depressurization heatup accidents, (4) reactivity insertion accidents, and (5) depressurization heatup accidents with water intrusion, and (6) depressurization heatup accidents with air intrusion.
- Chapter 5, TRISO-Coated Particle Fuel PIRT Analysis and Summary, contains an analysis of the PIRT information and identifies the factors, characteristics and phenomena for which high importance and low knowledge level rankings were assigned by the panel members.

Important detailed and supporting information is presented in the appendices.

- Appendix A contains the individual panel member importance and knowledge rankings and rationales for the manufacturing phase.
- Appendix B contains the individual panel member importance and knowledge rankings and rationales for the operation phase.
- Appendix C contains the individual panel member importance and knowledge rankings and rationales for a depressurization heatup accident.
- Appendix D contains the individual panel member importance and knowledge rankings and rationales for a reactivity insertion accident.
- Appendix E contains the individual panel member importance and knowledge rankings and rationales for a depressurization heatup accident with water intrusion.
- Appendix F contains the individual panel member importance and knowledge rankings and rationales for a depressurization heatup accident with air intrusion.
- Appendix G contains the results of MELCOR calculations performed for the air-intrusion accident scenario.
- Appendix H contains the individual panel member submittals for the TRISO-coated particle fuel life-cycle design phase. Initial submittals were received from the panel members early in the TRISO-coated particle fuel PIRT effort and are included for completeness. The PIRT process was not taken to completion for the design phase.
- Appendix I contains brief biographies for each member of the TRISO-coated particle fuel PIRT panel.

1.5 PIRT Panel Membership

The participants in the TRISO-coated particle fuel PIRT Panel were:

Robert Morris, Oak Ridge National Laboratory

David A. Petti, Idaho National Engineering and Environmental Laboratory

Dana A. Powers, Sandia National Laboratories

A three-member PIRT panel was considered the minimum size for effective coverage of the phenomena and processes associated with the entire life cycle of TRISO-coated particle fuel, including operation and accident conditions. However, extensive experience with TRISO-coated particle fuels also exists within the international community. The NRC will, therefore, submit this TRISO-coated particle fuel PIRT report for review by a group of international experts and other knowledgeable stakeholders. The international participants will review the information developed during the present TRISO-coated particle fuel PIRT effort and provide comments. The NRC will collect and compile the comments provided by the reviewers. The compiled peer review comments will be collected as a separate source of expert opinions on TRISO-coated particle fuel.

1.6 References

1-1. Draft Regulatory Guide 1120, "Transient and Accident Analysis Methods" (December 2002).

1-2. "Quantifying Reactor Safety Margins: Application of CSAU to a LBLOCA," EG&G Idaho, Inc., NUREG/CR-5249 (1989).

1-3. "Quantifying Reactor Safety Margins: Application of CSAU to a LBLOCA," B. E. Boyack et al., Part 1: An overview of the CSAU Evaluation Methodology; G. E. Wilson et al., Part 2: Characterization of Important Contributors to Uncertainty; W. Wulff et al., Part 3: Assessment and Ranging Parameters; C. S. Lellouche et al., Part 4: Uncertainty Evaluation of Analysis Based on TRAC-PF1/MOD1; N. Zuber et al., Part 5: Evaluation of Scale-Up Capabilities of Best Estimate Codes; I. Catton et al., Part 6: A Physically Based Method of Estimating PWR LBLOCA PCT, Nuclear Engineering and Design 119 (1990).

1-4. Shaw, R. A., T. K. Larson, and R. K. Dimenna, "Development of a Phenomena Identification and Ranking Table (PIRT) for Thermal-Hydraulic Phenomena During a PWR LBLOCA," EG&G Idaho, Inc., NUREG/CR-5074 (1988).

1-5. Wilson, G. E., and B. E. Boyack, "The Role of the PIRT Process in Experiments, Code Development, and Code Applications Associated with Reactor Safety Analysis," Nuclear Engineering and Design 186, 2-37 (1998).