TRISO-Coated Particle Fuel Phenomenon Identification and Ranking Tables (PIRTs) for Fission Product Transport Due to Manufacturing, Operations, and Accidents

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ABSTRACT

TRISO-coated particle fuel is to be used in the next generation of gas-cooled reactors. In anticipation of future licensing applications for gas-cooled reactors, the United States Nuclear Regulatory Commission (NRC) seeks to fully understand the significant features of TRISO-coated particle fuel design, manufacture, and operation, as well as behavior during accidents. The objectives of the TRISO Phenomena Identification and Ranking Table (PIRT) program are to (1) identify key attributes of gas-cooled reactor fuel manufacture which may require regulatory oversight, (2) provide a valuable reference for the review of vendor fuel qualification plans, (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 reactor 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 fuel safety analyses. To support these objectives, the NRC commissioned a PIRT panel to identify and rank the factors, characteristics, and phenomena associated with TRISO-coated particle fuel. PIRTs were developed for (1) Manufacturing, (2) Operations, (3) a Depressurized Heatup Accident, (4) a Reactivity Accident, (5) a Depressurization Accident with Water Ingress, and (6) a Depressurization Accident with Air Ingress.

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EXECUTIVE SUMMARY

Most nuclear power reactors presently operating throughout the world are water-cooled. The core of these reactors consists of arrays of fuel bundles, each bundle containing a number of fuel pins. Each fuel pin contains a stack of cylindrical, ceramic UO_2 fuel pellets contained within a sheath of metallic cladding.

The fuel forms for gas-cooled reactors are very different. The TRISO-coated fuel particle is a spherical layered composite about 1 mm in diameter. It consists of a kernel of uranium dioxide surrounded by a porous graphite buffer layer. Surrounding the buffer layer are a layer of dense pyrolytic carbon, a SiC layer, and a dense outer pyrolytic carbon layer. These three isotropic layers are termed the TRISO coating. Thousands of these particles are combined with a matrix material and pressed into either spherical forms for pebble bed fuels or cylindrical or annular compacts for prismatic fuels.

In anticipation of future licensing applications for gas-cooled reactors, the United States Nuclear Regulatory Commission (NRC) seeks to fully understand the significant features of TRISO-coated particle fuel design, manufacture, and operation, as well as behavior during accidents. To address this objective, the NRC has commissioned the formation of a panel of experts to identify and rank the factors, characteristics, and phenomena associated with the life-cycle phases of TRISO-coated particle fuel. The products of the panel are Phenomena Identification and Ranking Tables (PIRTs) and the associated documentation.

The objectives of the PIRT program on TRISO-coated particle fuel are to (1) identify key attributes of gas-cooled reactor fuel manufacture which may require regulatory oversight, (2) provide a valuable reference for the review of vendor gas-cooled reactor fuel qualification plans, (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 gas-cooled reactor 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 gas-cooled fuel safety analyses.

A three-member panel of experts developed the phenomena identification and ranking tables (PIRTs) presented in this document. The charter of this small PIRT panel was to develop TRISO-coated particle fuel PIRTs, i.e., structured PIRT tables and accompanying rationales. This report will be provided to international experts and other knowledgeable stakeholders for review and comment. 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.

Six phenomena identification and ranking tables (PIRTs) were developed by the panel and are presented in this document. They are: (1) Manufacturing, (2) Operations, (3) Depressurized Heatup Accident, (4) Reactivity Accident, (5) Depressurization Accident with Water Ingress, and (6) Depressurization Accident with Air Ingress.

This report contains significant additional content.

The general PIRT process is described in Chapter 1 as well as a detailed discussion of the application of the general process for the TRISO-coated particle fuel PIRT program.

Chapter 2 presents an extensive discussion of the design function of each component of TRISO-coated particle fuel, i.e., the kernel, buffer layer, inner PyC layer, SiC layer, outer PyC layer, and the fuel element. Manufacturing practices, fuel particle performance throughout the operational life of the fuel and also under accident conditions, and fuel failure mechanisms are also discussed.

Chapter 3 presents a detailed discussion of fission product transport in TRISO-coated fuel particles in each component of TRISO-coated particle fuel. The physical processes comprising fission product transport are described, as are data and the potential analytical approaches to modeling fission product transport.

Summary PIRT tables for manufacturing, operations, depressurized heatup accident, reactivity accident, depressurization accident with water ingress, and depressurization accident with air ingress are provided in Chapter 4.

Chapter 5 presents an analysis and summary of the TRISO-coated particle fuel PIRTs. General technical findings from the TRISO-coated particle fuel PIRTs are presented. Analyses and summaries for each of the six PIRTs are also presented. A total of 327 factors, characteristics and phenomena were identified in the six PIRT tables. The importance of each factor, characteristic, process or phenomenon was assessed relative to the magnitude of its influence on fission product release or in a more accident consequence-related term, the source term. One hundred-ten (110) factors, characteristics and phenomena were assigned an importance rank of "High" by each of the three panel members. The panel concluded that these 110 factors, characteristics and phenomena had the most significant impact on fission product release. Each panel member prepared a written rationale supporting the importance rank assigned to each highly ranked factor, characteristic or phenomenon. The rationales are presented in Appendices A through F.

In addition to ranking importance, the panel members assessed the level of scientific knowledge and understanding of the factor, characteristic or phenomenon. Each panel member also prepared a written rationale supporting the knowledge level assigned to each highly ranked factor, characteristic, or phenomenon. The rationales for the knowledge level assessed by each panel member are also presented in Appendices A through F.

There were some factors, characteristics, or phenomena for which a consensus was not reached regarding importance or knowledge level. There were, for example, instances where two panel members assessed the importance as "High" and the remaining panel member ranked importance as "Medium" or "Low." There were also instances where importance was assessed as "High" by one panel member, "Medium" by the second panel member, and "Low" by the third panel member. Similar differences also arose in the assessment of knowledge level. The TRISO-coated particle fuel PIRT provides a comprehensive and current view of the significant phenomena that affect TRISO-coated particle fuel performance and fission. It is anticipated that the international peer review of the TRISO fuel PIRT report will provide additional insights and perspectives on the identified phenomena, as well as on the importance and the level of knowledge of these phenomena.

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