5. TRISO-COATED PARTICLE FUEL PIRT ANALYSES AND SUMMARY

The PIRT analysis and summary information presented in this chapter is based on two sources. The first source is the summary TRISO-coated particle fuel PIRT tables presented for Manufacturing, Operations, Depressurized Heatup Accident, Reactivity Accident, Depressurization Accident With Water Ingress, and Depressurization Accident With Air Ingress PIRT Analysis presented in Chapter 4. The second source is the detailed PIRT inputs submitted by the TRISO-coated particle fuel PIRT panel members as found in Appendices A-F. A PIRT effort was started for the Design phase of the TRISO-coated particle fuel life cycle but it was not continued to completion. Preliminary panel findings on the Design PIRT are provided in Appendix H.

General technical findings from the TRISO-coated particle fuel PIRTs are presented in Section 5.1. Analyses of the findings for each individual PIRT are provided in Sections 5.2 through 5.7. As with each PIRT effort, lessons are learned that may prove beneficial to subsequent PIRT efforts. Programmatic lessons learned from the TRISO-coated particle fuel PIRT effort are provided in Section 5.8.

5.1 General TRISO-Coated Particle Fuel PIRT Findings

In this section, key findings of the TRISO-coated particle fuel PIRT panel are identified, analyzed and summarized.

Each of the six summary PIRTs presented in Chapter 4 were examined and each factor, characteristic or phenomenon determined to be of High importance by all PIRT panel members was identified. The resulting consensus TRISO-coated particle fuel factors, characteristics, and phenomena ranked high are presented in Table 5-1.

The factors, characteristics or phenomena entered in Table 5-1 for Manufacturing do not appear in any of the remaining five PIRT tables.

The Depressurization Heatup Accident with Air Ingress was characterized by a large number of highly ranked phenomena (25). Approximately one-half of these were directly related to phenomena associated with the interaction of air with the various components of TRISO-coated particle fuel. Interactions of air with the kernel and buffer layer were not ranked high by the PIRT panel. However, changes in the chemical form of fission products, kinetics, and temperature distributions associated with a chemical attack by air were ranked High for the remaining layers of the TRISO-coated particle fuel. Two of the panel members generally concluded that the knowledge level regarding these phenomena were either Low or Mid-range while the third panel member concluded the knowledge level was High. Phenomena associated with interactions of air with the TRISO-coated particle fuel may require additional research effort if the majority perspective on importance is confirmed.

Similar conclusions apply for the Depressurization Accident with Water Ingress. The primary difference is that phenomena associated with the interaction of water with the various components of TRISO-coated particle fuel are only ranked High for the fuel element and outer PyC layers. As with air ingress, two of the panel members generally concluded that the knowledge level regarding these phenomena were either Low or Mid-range while the third panel member concluded the knowledge level was High. Phenomena associated with interactions of water with the TRISO-coated particle fuel may require additional research effort if the Depressurization Accident with Water Ingress is to be included among events considered within the licensing basis or as a severe core damage accident.

In addition to the observations regarding the air- and water-ingress accidents, the factors, characteristics and phenomena in Table 5-1 were further evaluated using several screening criteria. Although helpful in focusing attention on specific factors, characteristics and phenomena, the criteria are, in fact, arbitrary. Those who plan to utilize the TRISO-coated particle fuel PIRT should examine each of the factors, characteristics and phenomena carrying a consensus importance ranking of High and those factors, characteristics, and phenomena viewed by a majority of the panel members as having High importance. Table 5-1 identifies only those factors, characteristics, and phenomena viewed by all panel members as having High importance. These screening criteria identify additional factors, characteristics and phenomena of potential importance.

The first screening criterion was a consensus importance ranking of High in three or more of the six conditions considered. The first screening aggregated the results for each component of the TRISO-coated particle fuel, i.e., kernel, buffer layer, inner pyrolytic carbon (PyC) layer, silicon carbide (SiC) layer, Outer PyC layer, and fuel element. Ten factors, characteristics and phenomena were identified by this screening criterion. The knowledge level assessed by the PIRT panel for each of the ten was then considered. The resulting analyses for the ten factors identified by the first screening criterion are presented below.

1. Temperature related phenomena in the kernel, i.e., maximum fuel temperature and temperature versus time transient conditions, were judged to be important for each of the four accident conditions considered. The knowledge level was judged to be High by two of the panel members while the third judged it to be at the upper end of the Mid-range. These two factors do not require additional research efforts.

2. The thermodynamic state of the fission products in the kernel was judged to be important for each of the four accident conditions considered. The knowledge level was judged to be Mid-range by two of the panel members while the third judged it to be High. This factor may require additional research for the water- and air-ingress accidents, if these events are to be included among the events considered within the licensing basis or as a severe core damage accident.

3. The knowledge level for cracking of the inner PyC layer was judged by all panel members to be either in the Low or Mid-range. Research to achieve better understanding of this phenomenon, i.e., increased knowledge level, is needed for this phenomenon.

4. The knowledge level for gas phase diffusion through the inner PyC layer was judged to be High by two of the panel members for the different conditions and Mid-range or Low by the other panel member. This phenomenon may require additional research.

Table 5-1 TRISO-Coated Particle Fuel Factors, Characteristics, and Phenomena Ranked High

Factor, Characteristic or Phenomenon	Condition: Manufacture	Operation	Depressur-ization Accident	Reactivity Accident	Water Ingress Accident	Air Ingress Accident
Kernel: CO production		X				
Kernel: Condensed-phase diffusion			X	X		
Kernel: Energy deposition (total)				X		
Kernel: Gas-phase diffusion			X			
Kernel: Maximum fuel temperature			X	X	X	X
Kernel: Temperature vs. time transient conditions			X	X	X	X
Kernel: Thermodynamic state of fission products			X	X	X	X
Buffer Layer: Cracking		X				
Buffer Layer: Gas-phase diffusion			X	X		
Buffer Layer: Pressure		X				
Buffer Layer: Response to kernel swelling				X		
Buffer Layer: Temperature gradient		X				
Buffer Layer: Thin or missing	X					
Inner PyC Layer: Chemical attack by air or water – Changes in chemical form of fission products					X	X
Inner PyC Layer: Chemical attack by air or water – Kinetics					X	X
Inner PyC Layer: Chemical attack by air or water – Temperature distributions					X	X
Inner PyC layer: Condensed phase diffusion		X				
Inner PyC layer: Cracking		X	X		X	X
Inner PyC layer: Gas phase diffusion		X	X	X		X
Inner PyC Layer: Layer oxidation					X	X
Inner PyC Layer: Pressure loading (Carbon monoxide)			X	X	X	
Inner PyC Layer: Pressure loading (Fission products)				X		
Inner PyC layer: Anisotropy (initial)	X					
Inner PyC layer: Bonding strength (inner PyC to SiC)	X					

Table 5-1 TRISO-Coated Particle Fuel Factors, Characteristics, and Phenomena Ranked High (continued)

Factor, Characteristic or Phenomenon	Condition					
	Manufacture	Operation	Depressur-ization Accident	Reactivity Accident	Water Ingress Accident	Air Ingress Accident
SiC Layer: Chemical attack by air or water– Changes in chemical form of fission products					X	X
SiC Layer: Chemical attack by air or water – Kinetics						X
SiC Layer: Chemical attack by air or water – Temperature distributions					X	X
SiC layer: Condensed phase diffusion		X				
SiC layer: Cracking		X				
SiC layer: Defects	X					
SiC layer: Density	X					
SiC layer: Fission product corrosion		X				
SiC Layer: Fission product release through failures, e.g., cracking			X	X	X	X
SiC Layer: Fission product release through undetected defects			X			
SiC layer: Fracture strength	X					
SiC layer: Gas phase diffusion		X	X		X	X
SiC layer: Grain size and microstructure, e.g., alignment	X					
SiC layer: Stoichiometry	X					
SiC Layer: Thermodynamics of the SiC-fission product system			X			
Outer PyC layer: Anisotropy (initial)	X					
Outer PyC Layer: Chemical attack by air or water – Changes in chemical form of fission products					X	X
Outer PyC Layer: Chemical attack by air or water – Kinetics					X	X
Outer PyC Layer: Chemical attack by air or water – Temperature distributions					X	X
Outer PyC Layer: Cracking			X			
Outer PyC layer: Gas phase diffusion		X	X			X
Outer PyC Layer: Layer oxidation					X	X

Table 5-1 TRISO-Coated Particle Fuel Factors, Characteristics, and Phenomena Ranked High (continued)

Factor, Characteristic or Phenomenon	Condition: Manufacture	Operation	Depressur-ization Accident	Reactivity Accident	Water Ingress Accident	Air Ingress Accident
Fuel Element: Chemical attack by air or water – Changes in chemical form of fission products					X	X
Fuel Element: Chemical attack by air or water – Changes in graphite properties						X
Fuel Element: Chemical attack by air or water – Kinetics					X	X
Fuel Element: Chemical attack by air or water – Temperature distributions					X	X
Fuel Element: Compacting	X					
Fuel element: Condensed phase diffusion		X				
Fuel Element: Gas-phase diffusion				X	X	X
Fuel Element: Impurities Control	X					
Fuel Element: Initial particle defect fraction due to manufacture	X					
Fuel Element: Irradiation history			X			
Fuel Element: Matrix and Binder	X					
Fuel Element: Particle overcoating (fuel form dependent)	X					
Fuel Element: Strength	X					
Fuel Element: Tramp Uranium	X					
Fuel Element: Transport of metallic fission products– Chemical form			X		X	X

Layer coating process specifications: Ratio of gases	X
Layer coating process specifications: Temperature	X
Layer coating process specifications: Coating Rate	X
Layer coating process specifications: Coater Size	X
Layer coating process	X
Process control:	X

5. The importance of pressure loading of the inner PyC layer by carbon monoxide was judged to be High by two of the panel members and Low by the other panel member.
6. The panel members assessed the knowledge level for fission product release through SiC layer failures as primarily Mid-range or High.
7. The knowledge level for gas phase diffusion through the SiC layer was judged to be Mid-range or High by the panel members.
8. The knowledge level for gas phase diffusion through the fuel element as assessed by the panel members spanned the range from Low to High. This phenomenon may require additional research.
9. The panel members assessed the knowledge level for the chemical form of the metallic fission products transported through the fuel element to primarily be in Mid-range. A better understanding of this phenomenon, (i.e., increased knowledge level), is needed for this phenomenon.

The second screening criterion was the appearance of a phenomenon three or more times in Table 5-1 when considering all conditions and all components of the TRISO-coated particle fuel. This screening criterion identified four phenomena. The knowledge level assessed by the PIRT panel for each of the four was then considered. The resulting analyses for the four factors identified by the first screening criterion are presented below.

1. Condensed-phase diffusion appeared four times in Table 5-1. With one exception, the knowledge level for condensed-phase diffusion was judged to be Mid-range or High by the panel members. Three of the four rankings of High importance were associated with Operations. This phenomenon appears to be most important during the operational phase of the TRISO-coated particle fuel life cycle.
2. Gas-phase diffusion appeared 15 times in Table 5-1. Gas-phase diffusion is considered an important phenomenon that must be well understood. Knowledge levels were generally assessed as either Mid-range or High but there were instances where the knowledge level was assessed as low. This phenomenon may require additional research effort.
3. Particle layer cracking appeared 10 times in Table 5-1. Layer cracking is considered an important phenomenon that must be well understood. Knowledge levels were generally assessed as either Low or Mid-range. Seven of the ten cracking entries in Table 5-1 were associated with the inner PyC and SiC layers. Research to achieve a better understanding of this phenomenon, (i.e., increased knowledge level), appears to be needed for this phenomenon.
4. Pressure or pressure loading on particle layers appeared five times in Table 5-1. Pressure loading is considered a phenomenon that must be well understood. Knowledge levels were generally assessed as either Mid-range or High but there were instances where the knowledge level was assessed as low. The pressure-related entries in Table 5-1 were primarily associated with the inner PyC layer. This phenomenon may require additional research.

5.2 Manufacturing PIRT Analysis

The Manufacturing PIRT presented in this section differs in several important ways from the remaining PIRTs presented in Sections 5.3 – 5.7. First, several process specifications were identified and ranked for importance and the level of knowledge assessed. Second, several process or process control factors were identified and ranked for importance and the level of knowledge assessed. Third, only two members of the PIRT panel provided input for the Manufacturing PIRT, the remaining panel member declining due to a lack of manufacturing experience.

Several summary statistics regarding the manufacturing of TRISO-coated particle fuel are provided in Table 5-2. The statistical summary is presented to draw attention to (1) the number of factors identified by consensus to be of High importance relative to the total number of factors, (2) the number of factors identified to be of High importance by a majority of the panel, and (3) the number of factors identified by a majority, but not consensus, to be of High importance, and (4) the number of factors for which the range of importance assessed by the panel members was so large that the PIRT findings are inconclusive. The factors in each of the above categories are listed following Table 5-2.

Table 5-2 Significant Importance and Knowledge Level Statistics for Manufacturing

Total Number of Factors [1]	35

[1] Factor: factor, characteristic, or phenomenon identified for Manufacturing

Consensus Assessment [2]	High Importance	Knowledge Level		
		Low 1-3	Mid-range 4-6	High 7-9
Not applicable	22	0	8	9

[2] Consensus Assessment: All panel members had identical assessment of importance and knowledge level.

Majority Assessment [3]	High Importance	Knowledge Level
		Low or mid-range 1-6
	Not Applicable	Not Applicable

[3] Majority Assessment: Two members of the three-member panel

Divergent Assessment [4]	Importance [5]	Knowledge Level [4]
All fuel temperatures	5	

[4] Divergent Assessment: A range of High to Low importance assessed by individual panel members.
[5] Knowledge level deemed secondary to the divergent importance rankings amongst the panel members.

The two participating panel members concluded that 22 of the 35 Manufacturing factors, characteristics and phenomena are of "High" importance. The fraction of factors ranked High for Manufacturing is larger than for the other five PIRTs. One reason may be that the panel identified only important or near important factors when it created the PIRT table. Of the 22 High-importance factors, characteristics and phenomena, these panel members agreed that the knowledge levels of nine are High (7-9). These nine items follow.

Kernel	None
Buffer layer	Thin or missing
Inner pyrolytic carbon layer	None
SiC layer	Density
Outer PyC layer	None
Fuel element	Particle overcoating (fuel form dependent) Compacting Impurities control Tramp uranium Strength
Other	Layer coating process specifications – ratio of gases Layer coating process specifications – temperature

Of the 22 High-importance factors, characteristics and phenomena, the two participating panel members agreed that the knowledge levels of eight are Mid-range (4-6). These eight items follow.

Kernel	None
Buffer layer	None
Inner PyC layer	Anisotropy (initial)
SiC layer	Fracture strength Stoichiometry Defects
Outer PyC layer	Anisotropy (initial)
Fuel element	None
Other	Layer coating process specifications – coater size Layer coating process Process control

The two participating panel members agreed that there are no factors, characteristics, or phenomena for which the importance is High and the knowledge level Low (1-3).

There are no factors, characteristics, or phenomena for which one of the two participating panel members ranked the importance High and one as Low.

5.3 Operations PIRT Analysis

Several summary statistics regarding the Operation of TRISO-coated particle fuel are provided in Table 5-3. A brief discussion of each is provided following Table 5-3.

Table 5-3 Significant Importance and Knowledge Level Statistics for Operations

Total Number of Factors [1]	46

[1] Factor: factor, characteristic, or phenomenon identified for Operations

Consensus Assessment [2]	**High Importance**	**Knowledge Level**		
		Low 1-3	**Mid-range 4-6**	**High 7-9**
	13	0	3	0

[2] Consensus Assessment: All panel members had identical assessment of importance and knowledge level.

Majority Assessment [3]	High Importance	Knowledge Level
		Low or mid-range 1-6
	3	3

[3] Majority Assessment: Two members of the three-member panel

Divergent Assessment [4]	Importance [5]	Knowledge Level [4]
All fuel temperatures	8	

[4] Divergent Assessment: A range of High to Low importance assessed by individual panel members.
[5] Knowledge level deemed secondary to the divergent importance rankings amongst the panel members.

The panel determined that 13 of the 46 Operation factors, characteristics and phenomena are of "High" importance. The thirteen factors are:

Kernel	Carbon monoxide production
Buffer layer	Pressure Cracking Temperature gradient
Inner PyC layer	Cracking Condensed phase diffusion Gas phase diffusion
SiC layer	Fission product corrosion Cracking Condensed phase diffusion Gas phase diffusion
Outer PyC layer	Gas phase diffusion
Fuel element	Condensed phase diffusion

There is a consensus among the panel members that the level of knowledge is Mid-range (4-6) for buffer layer pressure, SiC layer fission product corrosion, and fuel element condensed phase diffusion.

There is one factor, characteristic or phenomenon ranked of High importance by a majority of the panel (two members) and the knowledge level assessed as either Low or Mid-Range. The factor is radiation induced creep in the inner PyC layer.

There are nine factors, characteristics, or phenomena for which the range of panel importance assessments varies from High to Low. These nine items should be the focus of particular attention by the international peer review group, with the objective of developing a clear majority assessment of importance. The nine items are:

Kernel	Burnup Microstructure changes Fission product chemical form Kernel-buffer interaction Fission product generation Temperature gradient
Buffer layer	Carbonyl vapor species
Inner PyC layer	Anisotropy

	Radiation induced creep
SiC layer	None
Outer PyC layer	None
Fuel element	None

5.4 Depressurization Heatup Accident PIRT Analysis

Several summary statistics regarding the Depressurization Heatup Accident PIRT results for two temperature ranges, i.e., fuel temperatures $T_{fuel} \leq 1600$ °C and $T_{fuel} > 1600$ °C, are provided in Table 5-4. A brief discussion of each is provided following Table 5-4.

Table 5-4 Significant Importance and Knowledge Level Statistics for the Depressurization Heatup Accident

Total Number of Factors [1]	46

[1] Factor: factor, characteristic, or phenomenon identified for Depressurization Heatup Accident

Consensus Assessment [2]	**High Importance**	**Knowledge Level**		
		Low 1-3	**Mid-range 4-6**	**High 7-9**
All fuel temperatures	17	0	0	0

[2] Consensus Assessment: All panel members had identical assessment of importance and knowledge level.

Majority Assessment [3]	**High Importance**	**Knowledge Level**
		Low or mid-range 1-6
$T_{fuel} \leq 1600$ °C	8	8

[3] Majority Assessment: Two members of the three-member panel

Majority Assessment [4]	**High Importance**	**Knowledge Level**
		Low or mid-range 1-6
$T_{fuel} > 1600$ °C	12	12

[4] Majority Assessment: Two members of the three-member panel

Divergent Assessment [5]	**Importance** [6]	**Knowledge Level** [5]
All fuel temperatures	6	

[5] Divergent Assessment: A range of High to Low importance assessed by individual panel members.
[6] Knowledge level deemed secondary to the divergent importance rankings amongst the panel members.

The panel determined that 17 of the 46 Depressurization Heatup Accident factors, characteristics and phenomena are of High importance. The seventeen factors are:

Kernel	Condensed phase diffusion Gas-phase diffusion Maximum fuel temperature Temperature vs. time transient conditions Thermodynamic state of fission products
Buffer layer	Gas-phase diffusion
Inner PyC layer	Cracking Gas phase diffusion Pressure loading (carbon monoxide0
SiC layer	Fission product release through failures, e.g., cracking Fission product release through undetected failures Gas-phase diffusion Thermodynamics of the SiC fission product system
Outer PyC layer	Cracking Gas phase diffusion
Fuel element	Irradiation history Transport of metallic fission products – chemical form

There is no consensus agreement among the panel members on the level of knowledge for any of the 17 High-ranked factors, characteristics and phenomena. However, there are four factors, characteristics and phenomena for which all three panel members agreed that the knowledge level is Low or Mid-range for $T_{fuel} \leq 1600$ °C (Fuel Element: Transport of metallic FPs through fuel element – Chemical form, Outer PyC Layer: Cracking, SiC Layer: Fission product release through undetected defects, and Inner PyC Layer: Cracking) and six factors, characteristics and phenomena for $T_{fuel} > 1600$ °C (Fuel Element: Irradiation history, Fuel Element: Transport of metallic FPs through fuel element – Chemical form, Outer PyC Layer: Cracking, SiC Layer: Fission product release through undetected defects, SiC Layer: Fission product release through failures, e.g., cracking, and Inner PyC Layer: Cracking).

There are two factors, characteristics or phenomena ranked of High importance by a majority of the panel (two members) and the knowledge level is assessed as either Low or Mid-Range for fuel temperatures ≤ 1600 °C and four factors, characteristics and phenomena for which the knowledge level assessed as either Low or Mid-Range for fuel temperatures > 1600 °C. The factors are:

	$T_{fuel} \leq 1600$ °C	$T_{fuel} > 1600$ °C
Kernel	Buffer carbon-kernel interaction	Buffer carbon-kernel interaction
Buffer layer	Layer oxidation	Layer oxidation
Inner PyC layer	None	None
SiC layer		Thermal deterioration or decomposition Fission product corrosion
Outer PyC layer	None	None
Fuel element	None	None

There are six factors, characteristics, or phenomena for which the range of panel importance assessments varies from High to Low. These six items should be the focus of particular attention by the international peer review group, with the objective of developing a clear majority assessment of importance. The six items are:

Kernel	Oxygen flux Buffer carbon-kernel interaction
Buffer layer	Condensed phase diffusion Layer oxidation Thermal gradient
Inner PyC layer	None
SiC layer	Fission product corrosion
Outer PyC layer	None
Fuel element	None

5.5 Reactivity Accident PIRT Analysis

Several summary statistics regarding the Reactivity Accident PIRT results are provided in Table 5-5. A brief discussion of each is provided following Table 5-5.

Table 5-5 Significant Importance and Knowledge Level Statistics for the Reactivity Accident

Total Number of Factors [1]	45

[1] Factor: factor, characteristic, or phenomenon identified for Reactivity Accident

Consensus Assessment [2]	**High Importance**	**Knowledge Level**		
		Low 1-3	**Mid-range 4-6**	**High 7-9**
	12	0	1	1

[2] Consensus Assessment: All panel members had identical assessment of importance and knowledge level.

Majority Assessment [3]	**High Importance**	**Knowledge Level**
		Low or mid-range 1-6
	4	4

[3] Majority Assessment: Two members of the three-member panel

Divergent Assessment [4]	**Importance** [5]	**Knowledge Level** [4]
All fuel temperatures	5	

[4] Divergent Assessment: A range of High to Low importance assessed by individual panel members.
[5] Knowledge level deemed secondary to the divergent importance rankings amongst the panel members.

The panel determined that 12 of the 46 Reactivity Accident factors, characteristics and phenomena are of "High" importance. The twelve factors are:

Kernel	Temperature vs. time transient conditions Condensed phase diffusion Maximum fuel temperature Energy deposition (total) Thermodynamic state of fission products

Buffer layer	Gas phase diffusion Response to kernel swelling
Inner PyC layer	Gas phase diffusion Pressure loading (fission products) Pressure loading (carbon monoxide)
SiC layer	Fission product release through failures, e.g., cracking
Outer PyC layer	None
Fuel element	Gas phase diffusion

There is a consensus among the panel members that the level of knowledge is High (7-9) for kernel temperature vs. time transient conditions and Mid-range (4-6) for kernel condensed phase diffusion.

There are no factors, characteristics and phenomena for which all three panel members agreed that the knowledge level is Low or Mid-range.

There are four factors, characteristics and phenomena ranked of High importance by a majority of the panel (two members) and the knowledge level assessed as either Low or Mid-Range. The four factors are:

Kernel	Gas phase diffusion Energy transport: conduction within the kernel
Buffer layer	Maximum fuel gaseous fission product uptake
Inner PyC layer	None
SiC layer	None
Outer PyC layer	None
Fuel element	Condensed phase diffusion

There were five factors, characteristics, or phenomena for which the range of panel importance assessments varies from High to Low. These five items should be the focus of particular attention by the international peer review group, with the objective of developing a clear majority assessment of importance. The five items are:

Kernel	Buffer carbon-kernel interaction
Buffer layer	Condensed phase diffusion Thermal gradient
Inner PyC layer	Stress state (compression/tension)
SiC layer	None
Outer PyC layer	Gas-phase diffusion
Fuel element	None

5.6 Depressurization Accident With Water Ingress PIRT Analysis

Several summary statistics regarding the Depressurization Accident with Water Intrusion PIRT results are provided in Table 5-6. A brief discussion of each is provided following Table 5-6.

Table 5-6 Significant Importance and Knowledge Level Statistics for the Depressurization Accident With Water Ingress

Total Number of Factors [1]	77

[1] Factor: factor, characteristic, or phenomenon identified for Depressurization Accident With Water Ingress

Consensus Assessment [2]	High Importance	Knowledge Level		
		Low 1-3	Mid-range 4-6	High 7-9
	22	1	1	0

[2] Consensus Assessment: All panel members had identical assessment of importance and knowledge level.

Majority Assessment [3]	High Importance	Knowledge Level
		Low or mid-range 1-6
	7	7

[3] Majority Assessment: Two members of the three-member panel

Divergent Assessment [4]	Importance [5]	Knowledge Level [4]
All fuel temperatures	12	

[4] Divergent Assessment: A range of High to Low importance assessed by individual panel members.
[5] Knowledge level deemed secondary to the divergent importance rankings amongst the panel members.

The panel determined that 22 of the 77 Water Intrusion Accident factors, characteristics and phenomena are of "High" importance. The twenty-two factors are:

Kernel	Temperature vs. time transient conditions Maximum fuel temperature Thermodynamic state of fission products
Buffer layer	None
Inner PyC layer	Oxidation Cracking Pressure loading (carbon monoxide) Chemical attack by water: kinetics Chemical attack by water: changes in chemical form of fission products Chemical attack by water: temperature distributions
SiC layer	Gas-phase diffusion Fission product release through failures, e.g., cracking Chemical attack by water: changes in chemical form of fission products Chemical attack by water: temperature distributions
Outer PyC layer	Layer oxidation Chemical attack by water: kinetics Chemical attack by water: temperature distributions Chemical attack by water: changes in chemical form of fission products
Fuel element	Gas phase diffusion Transport of metallic fission products through fuel element – chemical form

	Chemical attack by water: kinetics Chemical attack by water: changes in chemical form of fission products Chemical attack by water: temperature distributions

There is a consensus among the panel members that the level of knowledge is Mid-range (4-6) for fuel element chemical attack by water: kinetics and Low (1-3) for inner PyC layer oxidation.

There is one phenomenon for which all three panel members agreed that the importance is High and the knowledge level is Low or Mid-range (Inner PyC Layer: Cracking).

There are seven factors, characteristics and phenomena ranked of High importance by a majority of the panel (two members) and the knowledge level assessed as either Low or Mid-Range. The factors are:

Kernel	Buffer carbon-kernel interaction
Buffer layer	Layer oxidation
Inner PyC layer	Gas phase diffusion
SiC layer	Chemical attack by water - kinetics
Outer PyC layer	Cracking
Fuel element	Condensed phase diffusion Chemical attack by water – changes in graphite properties

There are twelve factors, characteristics, or phenomena for which the ranges of panel importance assessments vary from High to Low. These twelve items should be the focus of particular attention by the international peer review group, with the objective of developing a clear majority assessment of importance. The twelve items are:

Kernel	Chemical attack by water: kinetics Chemical attack by water: changes in chemical form of fission products
Buffer layer	Gas phase diffusion Condensed phase diffusion Maximum fuel gaseous fission product uptake Thermal gradient
Inner PyC layer	Pressure loading (fission products) Stress state (compression/tension) Chemical attack by water: changes in graphite properties
SiC layer	Layer oxidation
Outer PyC layer	Chemical attack by water: changes in graphite properties
Fuel element	Chemical attack by water: holdup reversals

5.7 Depressurization Accident With Air Ingress PIRT Analysis

Several summary statistics regarding the Depressurization Accident with Air Ingress PIRT results are provided in Table 5-7. A brief discussion of each is provided following Table 5-7.

Table 5-7 Significant Importance and Knowledge Level Statistics for the Depressurization Accident With Air Ingress

Total Number of Factors [1]	77

[1] Factor: factor, characteristic, or phenomenon identified for Depressurization Accident With Air Ingress

Consensus Assessment [2]	High Importance	Knowledge Level		
		Low 1-3	Mid-range 4-6	High 7-9
	25	1	4	0

[2] Consensus Assessment: All panel members had identical assessment of importance and knowledge level.

Majority Assessment [3]	High Importance	Knowledge Level
		Low or mid-range 1-6
	7	8

[3] Majority Assessment: Two members of the three-member panel

Divergent Assessment [4]	Importance [5]	Knowledge Level [4]
All fuel temperatures	13	

[4] Divergent Assessment: A range of High to Low importance assessed by individual panel members.
[5] Knowledge level deemed secondary to the divergent importance rankings amongst the panel members.

The panel determined that 25 of the 77 Air Intrusion Accident factors, characteristics and phenomena are of "High" importance. The twenty-five factors are:

Kernel	Temperature vs. time transient conditions Maximum fuel temperature Thermodynamic state of fission products
Buffer layer	None
Inner PyC layer	Oxidation Cracking Gas phase diffusion Chemical attack by air: kinetics Chemical attack by air: changes in chemical form of fission products Chemical attack by air: temperature distributions
SiC layer	Gas-phase diffusion Fission product release through failures, e.g., cracking Chemical attack by air: changes in chemical form of fission products Chemical attack by air: temperature distributions Chemical attack by air: kinetics
Outer PyC layer	Gas phase diffusion Layer oxidation Chemical attack by air: kinetics Chemical attack by air: temperature distributions Chemical attack by air: changes in chemical form of fission products

Fuel element	Gas phase diffusion Transport of metallic fission products through fuel element – chemical form Chemical attack by air: kinetics Chemical attack by air: changes in chemical form of fission products Chemical attack by air: changes in graphite properties Chemical attack by air: temperature distributions

There is a consensus among the panel members that the level of knowledge is Mid-range (4-6) for chemical attack by air – changes in form of fission products, outer PyC layer-gas-phase diffusion, SiC layer chemical attack by air – kinetics, and inner PyC layer – gas phase diffusion. There was a consensus that the level of knowledge was Low for inner PyC layer oxidation.

There are no factors, characteristics, or phenomona for which all three panel members agreed that the importance is High and the knowledge level is Low or Mid-range.

There are six factors, characteristics and phenomena ranked of High importance by a majority of the panel (two members) and the knowledge level assessed as either Low or Mid-Range. The factors are:

Kernel	Buffer carbon-kernel interaction
Buffer layer	Layer oxidation
Inner PyC layer	None
SiC layer	Layer oxidation
Outer PyC layer	Cracking
Fuel element	Condensed phase diffusion Chemical attack by air – catalysis

There are thirteen factors, characteristics, or phenomena for which the range of panel importance assessments varies from High to Low. These thirteen items should be the focus of particular attention by the international peer review group, with the objective of developing a clear majority assessment of importance. The thirteen items are:

Kernel	Chemical attack by air: kinetics Chemical attack by air: changes in chemical form of fission products
Buffer layer	Gas phase diffusion Condensed phase diffusion Maximum fuel gaseous fission product uptake Layer oxidation Thermal gradient Chemical attack by air: changes in chemical form of fission products
Inner PyC layer	Pressure loading (fission products) Pressure loading (carbon monoxide) Stress state (compression/tension)
SiC layer	Fission product corrosion
Outer PyC layer	None
Fuel element	Chemical attack by air: holdup reversals

5.8 Lessons Learned

The PIRT process is still evolving with each new application. Given this evolution, it is worthwhile to record any lessons learned for the benefit of subsequent PIRT efforts. There were three such lessons learned from the TRISO-coated particle fuel PIRT effort. They are described in the following sections.

5.8.1 Development of PIRT Objectives

The importance of developing a clear objective statement for each PIRT effort is presented in Section 1.2. The following description of this step in the PIRT process is provided. *"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 if 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."*

The specific objectives of the TRISO-coated particle fuel PIRT evolved during the course of the first panel meeting. The number of PIRTs originally envisioned was four: (1) Design, (2) Manufacturing, (3) Operations, and (4) Accident, with the latter being a single accident. The final TRISO-coated particle fuel PIRT objectives focused on (1) Manufacturing, (2) Operations, (3) Depressurized Heatup Accident, (4) Reactivity Accident, (5) Depressurization Accident with Water Ingress, and (6) Depressurization Accident with Air Ingress. A PIRT effort was started for the Design phase (Appendix H) of the TRISO-coated particle fuel life cycle but it was not continued to completion.

The importance of developing a precise and definitive objective statement for each PIRT effort is emphasized. Having such a statement does not preclude changes in the objectives, as was the case with the TRISO-coated particle fuel PIRT. However, such a statement should minimize such occurrences. Generally, the objective statements are to be developed by the institution sponsoring the PIRT effort. If the PIRT effort involves several institutions, e.g., the NRC and industry, every effort should be made to reach agreement on the objectives before the initial PIRT meeting.

5.8.2 PIRT Panel Size

PIRT panels have been created utilizing between three and twenty-five expert panel members. The TRISO-coated particle fuel PIRT panel had three expert members.

Significant challenges were encountered with this small number of PIRT panel members. For the most part, these challenges arise when the panel members do not develop a consensus regarding the importance and knowledge level of a particular PIRT phenomenon.

For example, if two panel members believe a phenomenon is of High importance and the remaining panel member concludes that the importance is Medium or Low, the two-to-one vote cannot be considered to be conclusive.

More importantly, if each of the panel members evaluates importance differently, i.e., one ranks the importance High, one Medium, and one Low, little can be concluded other than that phenomenon should be the focus of additional consideration by a wider group of experts. The use of the PIRT as a tool for informing the evaluation of experimental data, experimental facilities, analytical methods and resource allocation is compromised.

Similar statements can be made with the panel members do not reach consensus or near consensus on the level of knowledge.

Based upon the experience with panels having as many as 25 members and panels with intermediate numbers of panel members, the optimal panel size appears to be approximately five to seven members. With PIRT panel membership of this intermediate size, it is still possible to have extensive in-meeting discussion, make assignments for out-of-meeting contributions, and reach consensus. Should a consensus not be reached, it is more likely that a clear majority (near-consensus) will evolve. With this near majority, it is feasible to apply the PIRT as a tool for informing the evaluation of experimental data, experimental facilities, analytical methods and resource allocation is compromised.

Having made this point, it is recognized that care should be taken that minority opinions are not dismissed without careful consideration of the rationales provided for importance and knowledge level.

5.8.3 Documentation of Rationales

The recording of written rationales for importance and knowledge level has become an important part of a quality PIRT effort. When questions arise regarding the basis for the importance and knowledge levels assigned, the PIRT user can consider the written rationales appearing in the PIRT report. Thus, the written rationales can and do enhance the PIRT applicability and utility.

In previous PIRT efforts, written rationales have been developed in several ways. For example, rationales have been developed and recorded during the course of PIRT meetings. The advantage of this approach is that the rationales are discussed, adopted, and recorded immediately. This approach limits the out-of-meeting time requirements of the PIRT panel members. However, the rationales tend to be brief. Other than the brief rationale statement, supporting evidence is rarely cited or documented.

For the TRISO-coated particle fuel PIRT effort, ranking and rationale development proceeded largely outside the meeting and at the panel member’s home base. Thus, the rationales were developed largely on an individual basis. Importance rankings, knowledge levels, and the rationales were then discussed in PIRT panel meetings. The effort required to prepare the requested written rationales was large and frequently repetitive. However, the written rationales cited supporting evidence, included figures and tables on occasion, and were often detailed. Thus, one of the prime contributions of the TRISO-coated particle fuel PIRT panel, given the limitations of a three-member panel (see Section 5.8.2) is the very detailed panel member inputs provided for each of the six PIRTs summarized in Chapter 4. This information should prove useful to the international peer review group. These detailed PIRT inputs are provided in Appendices A-F of this report.