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Next Generation Nuclear Plant Phenomena Identification and Ranking Tables (PIRTs)

Volume 3: Fission-Product Transport and Dose PIRTs

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Next Generation Nuclear Plant Phenomena Identification and Ranking Tables (PIRTs)

Volume 3: Fission-Product Transport and Dose PIRTs

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ABSTRACT

This Fission Product Transport (FPT) Phenomena Identification and Ranking Technique (PIRT) report briefly reviews the high-temperature gas-cooled reactor (HTGR) FPT mechanisms and then documents the step-by-step PIRT process for FPT. The panel examined three FPT modes of operation:

1. ***Normal operation*** which, for the purposes of the FPT PIRT, established the fission product circuit loading and distribution for the accident phase.
2. ***Anticipated transients*** which were of less importance to the panel because a break in the pressure circuit boundary is generally necessary for the release of fission products. The transients can change the fission product distribution within the circuit, however, because temperature changes, flow perturbations, and mechanical vibrations or shocks can result in fission product movement.
3. ***Postulated accidents*** drew the majority of the panel's time because a breach in the pressure boundary is necessary to release fission products to the confinement. The accidents of interest involved a vessel or pipe break, a safety valve opening with or without sticking, or leak of some kind.

Two generic scenarios were selected as postulated accidents:

1. the pressurized loss-of-forced circulation (P-LOFC) accident, and
2. the depressurized loss-of-forced circulation (D-LOFC) accidents.

FPT is not an accident driver; it is the result of an accident, and the PIRT was broken down into a two-part task. First, normal operation was seen as the initial starting point for the analysis. Fission products will be released by the fuel and distributed throughout the reactor circuit in some fashion. Second, a primary circuit breach can then lead to their release. It is the magnitude of the release into and out of the confinement that is of interest.

Depending on the design of a confinement or containment, the impact of a pressure boundary breach can be minimized if a modest, but not excessively large, fission product attenuation factor can be introduced into the release path. This exercise has identified a host of material properties, thermofluid states, and physics models that must be collected, defined, and understood to evaluate this attenuation factor.

The assembled PIRT table underwent two iterations with extensive reorganization between meetings. Generally, convergence was obtained on most issues, but different approaches to the specific physics and transport paths shade the answers accordingly.

The reader should be cautioned that merely selecting phenomena based on high importance and low knowledge may not capture the true uncertainty of the situation. This is because a transport path is composed of several serial linkages, each with its own uncertainty. The propagation of a chain of modest uncertainties can lead to a very large uncertainty at the end of a long path, resulting in a situation that is of little regulatory guidance.

FOREWORD

The Energy Policy Act of 2005 (EPAct), Public Law 109-58, mandates the U.S. Nuclear Regulatory Commission (NRC) and the U.S. Department of Energy (DOE) to develop jointly a licensing strategy for the Next Generation Nuclear plant (NGNP), a very high temperature gas-cooled reactor (VHTR) for generating electricity and co-generating hydrogen using the process heat from the reactor. The elements of the NGNP licensing strategy include a description of analytical tools that the NRC will need to develop to verify the NGNP design and its safety performance, and a description of other research and development (R&D) activities that the NRC will need to conduct to review an NGNP license application.

To address the analytical tools and data that will be needed, NRC conducted a Phenomena Identification and Ranking Table (PIRT) exercise in major topical areas of NGNP. The topical areas are: (1) accident analysis and thermal-fluids including neutronics, (2) fission product transport, (3) high temperature materials, (4) graphite, and (5) process heat and hydrogen production. Five panels of national and international experts were convened, one in each of the five areas, to identify and rank safety-relevant phenomena and assess the current knowledge base. The products of the panel deliberations are Phenomena Identification and Ranking Tables (PIRTs) in each of the five areas and the associated documentation (Volumes 2 through 6 of NUREG/CR-6944). The main report (Volume 1 of NUREG/CR-6944) summarizes the important findings in each of the five areas. Previously, a separate PIRT was conducted on TRISO-coated particle fuel for VHTR and high temperature gas-cooled reactor (HTGR) technology and documented in a NUREG report (NUREG/CR-6844, Vols. 1 to 3).

The most significant phenomena (those assigned an importance rank of "high" with the corresponding knowledge level of "low" or "medium") in the thermal-fluids area include primary system heat transport phenomena which impact fuel and component temperatures, reactor physics phenomena which impact peak fuel temperatures in many events, and postulated air ingress accidents that, however unlikely, could lead to major core and core support damage.

The most significant phenomena in the fission products transport area include source term during normal operation which provides initial and boundary conditions for accident source term calculations, transport phenomena during an unmitigated air or water ingress accident, and transport of fission products into the confinement building and the environment.

The most significant phenomena in the graphite area include irradiation effect on material properties, consistency of graphite quality and performance over the service life, and the graphite dust issue which has an impact on the source term.

The most significant phenomena in the high temperature materials area include those relating to high-temperature stability and a component's ability to withstand service conditions, long term thermal aging and environmental degradation, and issues associated with fabrication and heavy-section properties of the reactor pressure vessel.

The most significant phenomenon in the process heat area was identified as the external threat to the nuclear plant due to a release of ground-hugging gases from the hydrogen plant. Additional phenomena of significance are accidental hydrogen releases and impact on the primary system from a blowdown caused by heat exchanger failure.

The PIRT process for the NGNP completes a major step towards assessing NRC's research and development needs necessary to support its licensing activities, and the reports satisfy a major EPAct milestone. The results will be used by the agency to: (1) prioritize NRC's confirmatory research activities to address the safety-significant NGNP issues, (2) inform decisions regarding the development of independent and confirmatory analytical tools for safety analysis, (3) assist in defining test data needs for the validation and verification of analytical tools and codes, and (4) provide insights for the review of vendors' safety analysis and supporting data bases.

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ACRONYMS

D-LOFC	depressurized loss-of-forced circulation
FPT	fission-product transport
GA	General Atomics
GT-MHR	gas-turbine–modular helium reactor
HTGR	high-temperature gas-cooled reactor
IC	initial condition
IHX	intermediate heat exchanger
INL	Idaho National Laboratory
IRSN	L'Institut de Radioprotection et de Sûreté Nucléaire
LWR	light-water reactor
NGNP	next generation nuclear plant
NRC	Nuclear Regulatory Commission
O&M	operations and maintenance
P-LOFC	pressurized loss-of-forced circulation
PBMR	pebble-bed modular reactor
PIRT	phenomena identification and ranking tables
RCCS	reactor cavity cooling system
SNL	Sandia National Laboratory
SOK	state of knowledge
VHTR	very high temperature gas-cooled reactor

1. INTRODUCTION

This section of the next generation nuclear plant phenomena identification and ranking tables (NGNP PIRT) applies the Nuclear Regulatory Commission (NRC) PIRT process to the issue of fission-product transport (FPT) under routine and accident conditions in both the process heat and the electric-power-producing versions of the very high temperature gas-cooled reactor (VHTR) (either prismatic core or pebble-bed fuel). Currently, the direct-cycle VHTR is the main concept for power generation; the process heat version of the VHTR differs from earlier applications in that its purpose is to provide high-temperature process heat to some chemical process. As such, there is a linkage to the chemical process [through the intermediate heat exchanger (IHX)], the safety implications of which are relatively new. In addition, the chemical process itself can become a factor in fission-product transport evaluations. NGNP is based on aspects of VHTR, and for the purposes of the PIRT, they are considered equivalent.

The VHTR is expected to use one of the standard high-temperature gas-cooled reactor (HTGR) core configurations. HTGRs have been analyzed for fission-product transport many times; however, there still appear to be several incompletely resolved issues. In particular, use of a gas turbine in a direct cycle is relatively new with respect to safety and fission product-transport analysis.

Each version of the VHTR may use either a pebble-type fuel element or a fuel element of prismatic geometry. To date, the U.S. General Atomics and AREVA designs favor the prismatic fuel element, while the pebble-bed modular reactor (PBMR) of South Africa has adopted the pebble-type fuel element. The materials are somewhat different in these two fuel element types. While the PBMR uses fuel particles with UO_2 kernels, prismatic fuel-element designers prefer a UCO fuel form for future use, because this fuel offers improved burnup capability (due to less CO formation) and lessens the effect of "amoeba"-type fuel problems.

The main driver for the FPT PIRT exercise is the NGNP. This nuclear plant is based on a VHTR, as mentioned above, that is constructed of materials that are quite different from those used in a light water reactor (LWR), and the accident characteristics identified to date develop along different lines. Thus, there is reason to believe that the approaches used for LWR analysis may not be appropriate or successful when applied to VHTRs. A technology-neutral safety approach is needed and should be applied to the VHTR. Finally, the regulatory experience for this reactor type, especially in its high-temperature process heat configuration, is very limited [1–5, 50]. Material presented at the February 2007 PIRT meeting was used as guidance for the process.

Implicit in the panel's discussions was the role played by high-temperature materials, the large amounts of graphite, the high-pressure noncondensable coolant, and the dual role that the VHTR reactor could play.

One particular issue was noted, and this issue revolves around the fact that the FPT task depends on a high level of coordination with other groups. FPT is not an accident driver; it is the result of an accident, and in general, these accident scenarios will be identified and their evolution calculated by others. The role of this PIRT is seen as a two-part task. First, normal operation is seen as the initial starting point for the analysis. Fission products will be released by the fuel and distributed throughout the reactor circuit in some fashion. The major concern at this point is the dose and contamination associated with maintenance and operational issues. In the event of an accident, a transient occurs along with the possible redistribution of fission products within the reactor circuit; a primary circuit breach could then lead to their release. It is the magnitude of the release into and out of the confinement that then becomes the matter of interest.

This report segment first briefly reviews the HTGR fission-product transport mechanisms and then proceeds with the step-by-step PIRT process for fission-product transport. A previous fuel PIRT was conducted, and the starting point for this analysis is the outer surface of the fuel particle [49].

2. BRIEF HTGR FISSION PRODUCT TRANSPORT BACKGROUND

Even though the VHTR fuels are designed to preclude large scale fuel failure during accidents, dose significant fission product transport from the reactor cannot be discounted [1–8, 50], especially for the higher temperature VHTR. Even in the ideal case of no fuel failures during the accident, fission products are available for release because of three main factors:

1. The fuel is not perfect and some fraction ($\sim 10^{-5}$) of the particles is defective or damaged during fabrication. In addition, a small fraction of the fuel may fail during normal operation. These fuel populations partially release their fission products to the reactor system during normal operation and during the accident.
2. The reactor graphite components have uranium contamination due to natural causes or due to fuel particles that have been crushed during fuel element fabrication. This uranium fissions and releases some part of its fission products to the reactor circuit.
3. The high pressure coolant provides a means to transport fission products from the reactor circuit to the confinement building following primary system breaks.

Past VHTR (prior HTGR) work sets the desired maximum level of 10^{-4} as the fuel fraction release at the time of the accident, and the acceptable core release fraction at roughly 10^{-7}; thus, a fission-product attenuation factor (order of magnitude) of about 1000 is needed between the core and the site boundary [5, 9, 10]. Clearly, even with the best fuel and no additional fuel failures during the accident, fission-product transport will be an important issue.

Fission products released from the fuel can travel to and through the matrix material that holds the fuel particles, the graphite fuel blocks (prismatic), the graphite reflector and structural components, and into the coolant [11–17] (see Fig. 1). They can then travel onto and into metallic components and dust generated within the reactor circuit.

During normal operation, the fission products distribute themselves throughout the reactor circuit, depending on material diffusive and sorptive properties, chemical affinities, temperatures, material and coolant chemical impurities, flows, and mechanical vibrations (see Fig. 2).

Computing the distribution of fission products is a complex problem, and considerable effort has been expended in this area, both in the areas of single-effects data collection and integral testing [18–26]. The resulting distribution and its stability determines the starting point for the accident analysis. There may also be some interest in ^{14}C production and the transport of uranium and plutonium [27–29], although these are not expected to be important accident contributors. The transport area is much less developed in VHTRs than the analogous situation in LWRs; however, the LWR releases are much larger and can be more energetic. Some LWR analytical techniques may be applicable, especially for the transport in the containment [30–31], and some technical modeling problems are comparable (e.g., aerosol/dust retention in complex structures such as the IHX or gas turbine as compared to the secondary side of a steam generator for LWRs).

Three forms of radioactivity are usually categorized in the VHTR (note: past HTGR work will be assumed to be applicable to the VHTR and the qualifier HTGR will be dropped) reactor:

1. *Circulating activity* that is composed of gases/vapors (iodine, krypton, xenon), any aerosols that may be formed, and dust (mostly carbon with sorbed radionuclides).
2. *Surface activity* that is composed of radionuclides chemisorbed on steel and graphite, plated-out dust, and chemically combined with oxide films (impurities in the coolant establish the oxygen potential).
3. *Activity embedded* in solids such as fission products alloyed with metal components and retained on or within the graphite.

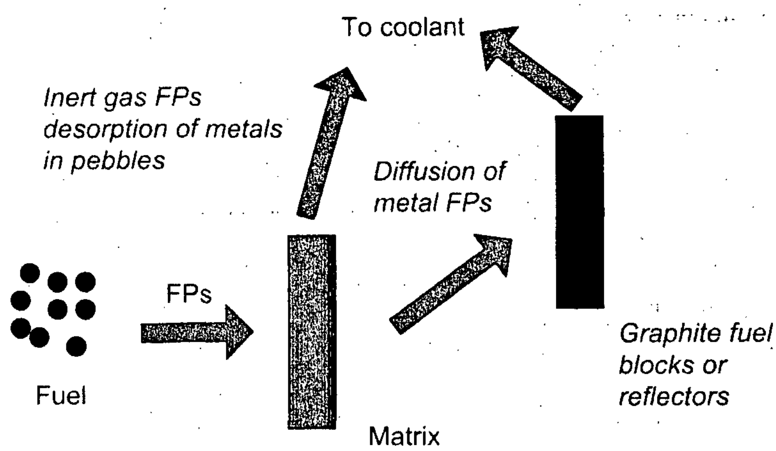

Fig. 1. Transport of fission products from fuel to reactor materials.

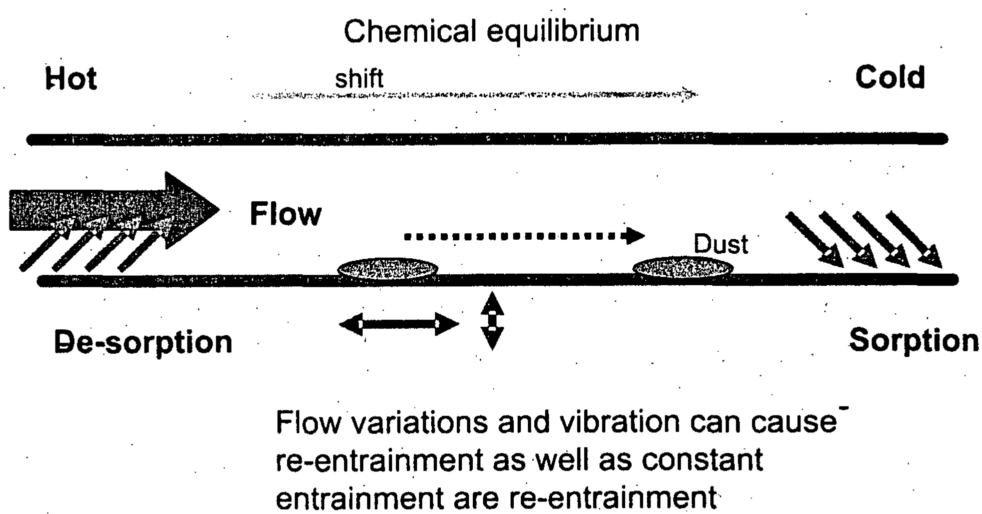

Fig. 2. Fission-product transport through the reactor circuit.

The first two items are of most concern as circulating activity is the most likely to be expelled during a pressure boundary break and surface activity may be spalled or lifted off by fluid or mechanical action [32–40]. Material embedded in solids is the least likely to be rapidly released but acts as a dose driver for maintenance because it is difficult to remove (decontaminate).

Historically, a handful of radionuclides have been the dominant drivers in VHTR dose and effluent calculations [41–42, 51]. Table 1 lists these elements and their primary impacts; this is for information only as the situation with the NGNP may or may not be the same.

Table 1. Historically dominant radionuclides in a VHTR

Nuclide	Half-life	Primary impact
^{131}I	8 days	Offsite dose, operations and maintenance (O&M) dose
^{137}Cs	30 years	Offsite dose, O&M dose
^{110m}Ag	250 days	O&M dose
^{90}Sr	28 years	Offsite dose
Kr and Xe	Hours to years	Gaseous effluent
^{3}H	12 years	Gaseous effluent

During normal operation, the five sources of circulating radionuclides originating from the core are [6–8]:

1. uranium contamination of graphite,
2. exposed fuel kernels (fuel particles broken during manufacture),
3. fuel with damaged SiC (metal release),
4. fuel that fails during normal operation (variety of reasons), and
5. activation of core structural materials (fixed but may spall off).

Over many years of operation, these five sources provide fission products and other radionuclides to the various transport mechanisms that spread radionuclides through the reactor circuit. About 10^{-4} of the core inventory of cesium and 10^{-6} of the iodine inventory are outside of the fuel particles and deposited either on the fuel, graphite, metal components, or dust [5, 9, 10].

In summary, a number of phenomena drive FPT on both the large and small scale; the fundamental driver is the release from the fuel and uranium contamination during normal operation and its deposition throughout the reactor circuit in a manner that allows some portion of it to be removed from the circuit as the result of a depressurization.

It should be noted at this point that the accident scenarios for the fission-product transport PIRT are actually generated by other PIRT groups as fission-product transport is a consequence of an event rather than an event driver [1–5] (only a massive redistribution of fission products would change the heat-generation profile of the core). The event of primary interest for the gas-turbine designs is a pressure boundary break that allows the high-pressure helium to expel fission products and provides a conduit from the reactor circuit to the confinement. This path has been the subject of the above introduction. For the historical steam cycle, HTGR steam generator failures which allow water into the core have been of major interest as they will open a primary-circuit pressure-relief valve and provide a transport path. The gas turbine or process heat designs are believed to be much less susceptible to this failure mode, and thus it is of much less concern.

For the NGNP, three other paths might be of interest. The first is diffusion from the primary side of an IHX to the secondary side. Currently, this appears to be more of a tritium diffusion issue for normal operation than an accident issue [42–44]. Another path is from the secondary side to the primary side and/or into the confinement. If the IHX were to suffer a major failure that exposed a high-pressure secondary side to the confinement, the confinement atmosphere and heat transfer properties might be drastically changed. This could affect the operation of the reactor cavity cooling system (RCCS) and the (possible) confinement filters. The simultaneous failure of both the primary side and the secondary side of the IHX would add the reactor coolant inventory as well as fission products to the confinement. A third IHX failure mode would be between the primary and secondary sides. In this case the working fluids could mix as well as transfer fission products. Chemical reactions as well as pressure boundary issues could then arise. These three IHX accidents are very application and design specific. While the basic HTGR design relies on passive safety to handle issues such as coolant flow transients, station blackouts, and seismic events, it is very design specific as to how these issues will affect the IHX circuit and feedback into the reactor system.

3. FISSION PRODUCT TRANSPORT PIRT PROCESS

The PIRT process was outlined in our introductory meeting by the NRC coordinator, Sudhamay Basu. It consists of nine steps, which are discussed below [45–47].

3.1 Step 1—Issues

The VHTR presents some new issues to FPT considerations. Generally, these new aspects are in addition to the more well-known issues relating to the past HTGR designs.

1. Higher-temperature fuel and primary coolant during normal operation leading to higher levels of circulating activity and a higher fraction of the core experiencing elevated temperature.
2. An IHX in place of a gas turbine or steam generator that may malfunction during normal operation, or fail during some accident.
3. The possibility of product contamination with radiation from the primary circuit either during normal operation or an accident.
4. Possibly higher occupational exposures.
5. Possibly new variations of accident scenarios involving the IHX or the process heat sink.

In addition, the VHTR has some well-known fission-product issues, some of which remain only partially resolved:

1. Fission-product contamination of the moderator graphite (for prismatic fuel element versions) and primary coolant during normal operation. This issue contributes to occupational dose and also presents an immediate source (coolant) for release during depressurization events.
2. Fission-product contamination of primary circuit surfaces incurred during normal operation, including the power conversion unit components. Such contamination may be of four types:
   a. chemisorption on metal surfaces,
   b. chemical combination with the oxide film of the metal surfaces,
   c. alloyed in the metal, and
   d. plated-out dust contaminated with fission products.
3. Transport of fission products into the containment building as a result of various types of accidents involving depressurization. There are a number of separate sub-issues related to fission-product transfer into the containment building:
   a. Liftoff of plated-out dust particles either by hydrodynamic forces or by vibrational forces resulting from the break or rapid gas flow.
   b. Desorption of chemically adsorbed fission products due to the generation of higher temperatures during the accident (for the particular component) or by change of oxygen potential in the case of water or air ingress.
   c. Transport of fission products during the natural convection phase of the depressurization event. This is basically a fluid dynamics issue but is affected by oxidation (air or steam ingress) of the graphite by modifying helium properties (gas mixture).
4. Transport of fission products from the containment or confinement building to the atmosphere. This is also primarily a building leakage problem but depends on the gaseous and suspended aerosol inventory of fission products in the building. In addition, chemical

reactions of fission products in the building may affect their transport. Other chemical reactions could also affect building pressure (e.g., cable fire) and transport. Dust combustion could lead to higher pressures and fission-product liberation.

5. Behavior of the fission-product inventory in the chemical cleanup or fuel handling system during an accident. An overheat event or loss of power may cause release from this system and transport by some pathway into the confinement building or environment.

During an unmitigated air or water ingress accident, four more radionuclide transport issues arise [8, 49, 52]:

1. Chemical reactions (and overall oxygen potential change in the reactor system) with fuel and graphite due to water and/or air.
2. Generation of particulates from matrix and graphite component oxidation and failure.
3. Change of the fission products' chemical state and the component surface properties which can affect the ability of components to retain fissions products.
4. Additional fuel failures due to high temperatures and chemical attack.

One issue of immediate transport concern is the amount of dust in the reactor circuit as dust is easily released during a primary boundary breach. Carbon-based dust is generally quite absorptive of fission products and, when combined with its high mobility, leads to an important path from the reactor core to the environment. Sources of dust in the reactor circuit include the following [6]:

1. Abrasion due to the relative movement of fuel pebbles (high) and prismatic blocks (low).
2. Metal corrosion products.
3. Carbon filaments that grow from the gas-phase reaction $2CO \rightarrow CO_2 + C$ due to coolant impurities and temperature gradients.
4. Soot from fast neutron damage (reflector graphite).
5. Construction and other debris.

The highest dust quantities are expected in the pebble-bed core (~10–50 kg for a test reactor and perhaps much more for a power reactor) and the lowest in the prismatic core (at least an order of magnitude less) [9, 10]. Dust is significant in at least three areas:

1. Circulating dust is readily available for depressurization release.
2. Plated-out dust can be re-entrained by shearing fluid forces due to flow velocity changes driven by the pressure boundary break or by the mechanical and acoustical forces generated by the shock of the break or generated by flow-driven vibrations.
3. Dust can have an erosive effect on turbine blades.
4. There has been some speculation on the possibility of dust ignition and explosions [9, 10].

Dust could be a major source of fission-product release for pebble-bed reactors; it is expected to be much less of an issue for the prismatic core reactors [6].

Dust size is a key parameter that may be highly dependent on the system design materials and manufacturing techniques used, so extrapolation of past knowledge to new reactors has to be done with caution. In particular, graphite-component manufacture may be different with different grain structure and different levels of impurities. In addition, the pebble design uses a mixture of binder and graphite for pebble-fabrication, so the pebble generated dust may be more sorptive of fission products.

3.2 Step 2—PIRT Objectives

The major objectives are to identify the safety-relevant phenomena and knowledge base and rank them in an approximately quantitative way. Since the NGNP exists as only a rough concept, it is not possible to take a concrete approach to this process; however, it must be surmised that the NGNP would share much in common with past HTGR designs, and these were used as a reference.

3.3 Step 3—Hardware and Scenarios

3.3.1 Hardware

At the present time, the NGNP is only in the concept stage, and historical analogues as well as PIRT presentations were used to model the hardware and possible scenarios. Tables 2 and 3 are a rough comparison between the direct-cycle prismatic block gas turbine HTGR (GT-MHR) investigated by the DOE and the Fissile Materials Deposition Program over the last decade and the conceptual NGNP. These tables are meant to be only a conceptual starting point and should not be taken as a point-by-point analysis.

Several confinement and containment options have been investigated in the past, with the vented confinement option generally selected as a baseline (with or without filters, depending on designer); see Ref. 54 for the results of a trade study (steam cycle) which assumes high-quality fuel and limited release of plated-out activity. The releases are time separated into a small early release and a larger later release. The early release is assumed to be very small and requires no holdup while the later release is assumed to be modest with little or no driving force. Reference 55 discusses the vented confinement with both ideal and less-than-ideal fuel for the steam-cycle version. It was presumed that this type of analysis would be the starting point for the NGNP design, to be modified later by analysis and test results.

Table 2. Rough comparison between the GT-MHR (DOE version as developed by GA) and the NGNP for normal operating conditions

Item	GT-MHR	NGNP
Coolant and primary-loop containment	Lower	Same or higher, depending on temperature; higher if pebbles are used (dust).
Maintenance dose	Depends on turbine issues; cesium and silver dose	Same if turbine; perhaps less if IHX system.
Contamination of secondary coolant	N/A	Issue will probably be tritium.
Confinement vs containment	Confinement	Probably confinement.
Primary coolant cleanup system	Fission gas collection; long-term issue is ^{85}Kr and some contaminated dust (?)	Fission gas collection; long-term issue is ^{85}Kr and perhaps contaminated dust; advanced designs may capture dust.
Fuel handling	Special equipment for handling blocks; reactor down during handling	Could be blocks (offline batch refueling) or pebbles (continuous online refueling).

Table 3. Rough comparison between the GT-MHR (DOE version as developed by GA) and the NGNP for design basis accident conditions

Item	GT-MHR	NGNP
Release to the atmosphere.	Designed to avoid public evacuation and sheltering requirements.	About equal unless the IHX or process heat side introduces unusual behavior; higher potential for fuel failure because of higher fuel and reactor outlet temperatures.
Release to the secondary coolant	N/A	Design specific; IHX breaks could transfer heat-transfer fluid either way and into confinement.
Releases from the cleanup system and/or fuel handling system	Designed to avoid public evacuation and sheltering requirements.	Not clearly established but likely similar except for dust and pebble handling faults; higher fuel failures could increase releases.

At the present time, an important issue is the type of fuel to be used by the reactor. Both prismatic and pebbles have been used in the past, and both have advantages and disadvantages. The following differences need to be understood however:

1. The pebble-fuel element consists of a 6-cm-diam sphere containing a central region of fuel particles and matrix material (graphite and binder) covered by a fuel-free region (a few mm thick) of matrix material only. The pebble has high mechanical integrity to withstand the drops and movement that are part of the function of the fuel form. The pebbles move continuously through the reactor during operation; as they exit the reactor, they are assessed for burnup and are then either returned to the reactor or sent to spent fuel. The reactor is continuously refueled and does not required downtime for refueling operations. The fuel burnup is modest (~10%) and the fuel-particle packing fraction is low (~10%).
2. The prismatic fuel element consists of many fuel compacts, which are right cylinders composed of fuel particles and matrix material roughly 12 mm in diameter by 50 mm long, inserted into deep holes drilled into graphite hexagonal prisms roughly 300 mm across the flats and 800 mm long and cemented into place. The compacts have relatively high packing fractions (~30–50%) and the fuel has a higher burnup(~15–25%).
3. The actual fuel kernel to be used is not defined at present but is likely to be either UO_2 or a two-phase mixture of UC/UC_2 and UO_2 known as UCO. The UO_2 material has much better characterization but suffers from burnup limitations and a problem known as the amoeba affect, which causes the kernel to migrate within the particle in the presence of temperature gradients; this migration ultimately damages the particle coatings. The prismatic core is believed to require the use of UCO because of this effect and the higher burnup; the pebble core will probably use UO_2.
4. The fission-product transport rate from the fuel particle to the coolant may be different for the pebble than for the prismatic block because of differences in temperature and transport path. For the purposes of this PIRT, it will be assumed that the time in operation prior to the accident is long enough that both systems have come to equilibrium with respect to the fission products deposited within the reactor circuit.
5. Air and water ingress accidents will require a separate evaluation of the pebbles and blocks because of the large differences in chemical reactions rates between graphite block and the pebble matrix material.

3.3.2 Accident scenarios

Possible accidents were presented at the February 2007 PIRT meeting which outlined the expected behavior of the concept. The following three areas were discussed by the panel:

1. *Normal operation,* which, for the purposes of the FPT PIRT, established the fission-product circuit loading and distribution for the accident phase. In addition, it will be input for evaluating the occupational dose.
2. *Anticipated transients,* which were of less importance to the panel because a break in the pressure circuit boundary is generally necessary for the release of fission products. The transients can change the fission-product distribution within the circuit, however, because temperature changes, flow perturbations, and mechanical vibrations or shocks can result in fission-product movement. They could also cause releases from pressure relief valves. The other issue associated with these transients is the possible redistribution of fission products that increases maintenance dose rates. Finally, minor leaks are a pathway for the release of fission products.
3. *Postulated accidents* drew the majority of the panel's attention because a breach in the pressure boundary is necessary to release fission products to the confinement. The accidents of interest involved a vessel or pipe break, a safety valve opening with or without sticking, or leak of some kind.

The following two generic scenarios were selected as the drivers for the accident [48]:

1. the pressurized loss-of-forced circulation (P-LOFC) accident; and
2. the depressurized loss-of-forced circulation (D-LOFC) accidents.

3.3.2.1 The P-LOFC accident

The reference case for P-LOFC is modeled on that for the GT-MHR and assumes a flow coast-down and scram with the passive reactor cavity cooling system (RCCS) operational for the duration of the event. The natural circulation of the pressurized helium coolant within the core tends to make core temperatures more uniform, lowering the peak temperatures, than would otherwise be the case for a depressurized core where the buoyancy forces would not establish significant recirculation flows. The chimney effect in P-LOFC events also tends to make the core (and vessel) temperatures higher near the top. Maximum vessel-head temperatures are typically limited by judiciously placed insulation, and the use of Alloy 800H for the core barrel allows for extra margin in that area. For the reference case, the peak fuel temperature of 1290°C occurs at 24 h, and the maximum vessel temperature is 509°C at 72 h (note: the reader should consider these and the following temperatures as representative values to estimate margins and not actual design values). In P-LOFCs, the peak fuel temperature is not a concern (well within the typical nominal limit for TRISO fuel ~1600°C); the major concern is more likely to be the maximum vessel temperature and the shift in peak heat load to near the top of the reactor cavity, resulting in the reactor axial distribution of maximum fuel temperature peaking toward the inlet (top of the core). Depending on the high-temperature capabilities of the vessel steel, some variations in vessel insulation strategies may be needed.

The parameter most likely to affect the P-LOFC outcome, assuming that the RCCS is functioning properly, is the emissivity controlling the radiation heat transfer between the vessel and RCCS (assumed to be 0.8 over the full range of normal-to-accident temperatures). For an assumed (unlikely) 25% decrease in both vessel and RCCS surface effective emissivities, the peak vessel temperature is 37°C higher. The difference in peak fuel temperature is small (7°C), which is typical of the decoupling between the peak fuel and vessel temperature in LOFC events [48].

These temperature changes can cause some fission product redistribution, but the convective flows (weaker than the forced flow) are not expected to drive major fission-product redistribution. The major concern with the P-LOFC is how it may change the distribution of fission products prior to a pressure boundary breach as the event itself does not release fission products. If the P-LOFC results in a pressure-relief-valve opening with or without sticking, a fission-product transport path will be generated. This path is design specific as a filter may be incorporated into the exhaust circuit.

3.3.2.2 The D-LOFC accident

The D-LOFC reference case assumes a rapid depressurization along with a flow coast-down and scram with the passive RCCS operational. It also assumes that the depressurized coolant is helium (no air ingress). This event is also known as a "conduction-heat-up" (or "-cool-down") accident, since the core effective conductivity is the dominant mechanism for the transfer of afterheat from the fuel to the reactor vessel. In the reference case, the maximum fuel temperature peaks at 1494°C 53 h into the transient and the maximum vessel temperature (555°C) occurs at 81 h. For this case, the peak fuel (and vessel) temperatures occur near the core center rather than near the top as in the P-LOFC case, since the convection effects for atmospheric pressure helium are minimal [48].

There are several parameter variations of interest for this accident, which is generally considered to be the defining accident for determining the reference-case-accident peak fuel temperature. These variations are effective core graphite conductivity (which is a function of irradiation history, temperature, orientation, and whether or not annealing is accounted for), afterheat power versus time after shutdown, and the power-peaking factor distribution in the core after shutdown. If maximum vessel temperatures are of concern, emissivity effects should again be considered.

For variations from the reference case event, the sensitivity of peak fuel temperature for the various assumed parameter changes is as follows:

1. 20% decrease in core conductivity (including annealing effects): a 124°C increase in fuel maximum temperature.
2. 15% increase in afterheat: a 120°C increase in fuel maximum temperature.
3. 20% increase in maximum radial peaking factor: a 30°C increase in fuel maximum temperature.

For the maximum vessel temperatures, again the emissivities figure in most prominently. An assumed 25% decrease in vessel and RCCS opposing surface emissivities results in an increase in maximum vessel temperature of 54°C , while the increase in fuel maximum temperature is only 14°C [48].

This event has a two-part impact on FPT. The first is the initial depressurization which releases fission products from the core by the physical shock of the event, any system vibrations, and the entrainment by the existing flow. This event can be the most important because some conceptual reactor building designs do not include a provision for filtering this rapid high-volume flow. Combustion of dust may add heat and more completely distribute the fission products in the confinement volume. The second part of interest is after the depressurization and the heat-up of the core and reactor system. The higher temperatures can cause the redistribution of fission products (and perhaps, some limited fuel failure depending on design and design margins); however, the driving force for the release of fission products is only the very weak thermal expansion of the gas. In addition, at this point in the accident, the building filters are expected to be operational in all designs.

The more extreme case of this accident is the significant and continued flow of air into the core, which is only possible with a major reactor building and reactor system fault that establishes a convective air path between the reactor vessel and the environment. In this case, high fuel temperatures are possible, high-fission product release is possible, and a convective path is available for the transport of material out of the building. Three mechanisms are available for the enhancement of fission product releases:

1. The locally increased temperatures due to graphite combustion can drive the movement of the volatile fission products such as cesium and if high enough and increase the amount of failed fuel and subsequent fuel releases.
2. The destruction of the graphite and matrix material releases the trapped fission products, which can then be carried along with the flow as particles, vapors, or aerosols.
3. The increased oxygen potential of the reactor environment may change the chemical forms of the fission products and surfaces they interact with.

Graphite oxidation with core consumption and possible collapse is a complex process which is highly dependent on the particular design, materials, and accident configuration. The key feature is the flow path and the amount of oxidizer available; the free flow of oxidizer must be stopped early in the accident to prevent serious fission-product releases from the core.

A more remote accident scenario is an intact sealed containment with the failure of the RCCS and the subsequent heat-driven decomposition of the nearby concrete, liberating H_2O and CO_2. These gases could react with the exposed core graphite (due to the pressure boundary failure), generating combustible gases that could pose a burning and thus overpressure hazard to the containment if air was part of the normal containment atmosphere [53].

As was noted above, historical designs and accident scenarios were used as the basis for this exercise; rather than focusing on the actual details of the scenario, the panel focused on the results of the scenarios that would significantly impact the release the fission products:

1. ***Large and small pressure boundary breaches.*** These breaks and leaks were assumed to have the potential to release not only the material entrained in the gas during normal operation but also material such as dust and fission products on metal surfaces. The main emphasis was on using normal operating conditions as the starting point and assuming that major fuel failure did not take place during the accident. However, if major fuel failure did take place during the accident, only the fission-product inventory available for release would change in the ranking; this would be supplied by the fuels material group as part of an accident scenario. Thus, this scenario is quite general as long as one has the steady-state fission-product inventory and distribution prior to the accident and is supplied information about additional fuel failures and their timing that may occur. A pressure-relief valve opening also falls into this category, but design-specific issues are more relevant because a specialized filter can be placed after the valve. Chemical attack, air or steam ingress, is also included in this scenario; however, the exact details are important for this situation because the core and fuel will be destroyed if the reactions are allows to run to completion.
2. ***Releases from the cleanup and hold-up systems.*** Breaks and leaks in these systems can release fission products to the confinement. These systems are only vaguely defined at the present time, but in addition to the historical inventory of inert gases and perhaps iodine, newer designs may include a facility for handling dust.

It should be noted that spent fuel storage is also a potential area for fission-product release and at the present time is treated like a hold-up system. As the design matures, this area should be broken out as an issue by itself, especially if it has unique subsystems for controlling contamination and releases.

3.3.3 Significant radionuclides

Based on historical information, the important radionuclides were categorized into two groups, public dose drivers and operational and maintenance drivers. Tables 4 and 5 list the significant radionuclides and the characteristics of interest for the two cases. These tables should be understood in the light of the incomplete design.

At the present time, the most significant radionuclide for the contamination of the secondary side is tritium. This should be considered to be quite tentative as very little is known about any secondary circuit; however, tritium is known to permeate metals at high temperatures.

Table 4. Public dose radionuclides

Nuclide	Characteristics
^{131}I	High inventory; high dose factor; high vapor pressure within HTGR circuit; effectively diffuses in graphite; adsorbs strongly on metals—weakly on graphite and oxide layers; can react with paint in confinement to form organic iodide.
^{137}Cs	High inventory; high dose factor; high mobility in graphite; likely to be in metallic form in reactor circuit, likely to be oxide in confinement; fairly high volatility at reactor circuit temperatures; can adsorb or condense on particles (dust and aerosols).
^{90}Sr	Inventory in graphite; high dose factor; low mobility in graphite; likely to be present in dust; probably SrO in confinement.
^{3}H	Effluent releases (and potential contamination of hydrogen produced by the NGNP).

Table 5. Operation and maintenance dose radionuclides

Nuclide	Characteristics
^{110m}Ag	Believed to plate-out on turbine and heat exchangers; activation product; high diffusion through fuel, matrix, and graphite; high energy gamma; may alloy with nickel based alloys; principal form is the metal which may transport as vapor, aerosol, or on dust.
^{137}Cs and ^{134}Cs	Believed to plate out on turbine and heat exchangers, but much less so than silver.
^{90}Sr	Could be important in a dust collection system.
^{131}I, ^{132}I, and ^{132}Te	Might be important for short-term maintenance issues in heat exchangers.
^{60}Co	Activation product of nickel, high-energy gamma, largely fixed, but may circulate in dust.

3.4 Step 4—Evaluation Criteria

Step 4 of the PIRT process involved the selection of figures of merit and determination of the component and phenomenological hierarchies. The following four figures of merit were selected:

1. Level 1 (Regulatory): Dose to control room and offsite location
2. Level 2 (System): Release to confinement/containment
3. Level 3 (Component): Release into primary system
4. Level 4 (Sub-component): Release from graphite in fuel form

These figures of merit were then used as the basis to determine the release from the fuel outward. Four areas of concern implied by the figures of merit are as follows:

1. The inventory of the fission products outside of the fuel (due to defects, contamination, and in-service failures) and fission products that are released due to accident-driven fuel failures (designers assume this to be very small for design base accidents).

2. Total curies released into the confinement, which is composed of the fission products of radiological (dose) interest. These are not clearly identified at present but are expected to be the ones that have been historically identified such as I, Te, Cs, and Sr.
3. Total curies beyond confinement, which is composed of the relevant fission products that penetrate all the boundaries and travel into the environment.
4. Time evolution of the cumulative release(s), which is the history of the release(s) into the confinement and beyond the confinement into the environment.

3.5 Step 5—Knowledge Base

The analysis of FPT must involve all three phenomenological levels; the system level to define the specific scenario, the component level to determine the overall fluid flow and temperatures, and, finally, the local level to determine relevant material properties, chemical interactions, and fission-product mass (and dust) fluxes. The system and component levels may be thought of as setting the fluid flow and thermodynamic environment, while the local level determines the fluxes into and out of the components and surfaces. The knowledge base is detailed in the next section as it is an intrinsic part of evaluating the transport path.

Implicit in the needs of the VHTR FPT are the models to be used for the determination of the fission-product distribution in the core and reactor circuit during normal operating conditions as this is the starting point for the accident. During the accident, similar models will be necessary with the addition of more aggressive dust entrainment models and the chemical reaction models. Models for the FPT might include the following [6, 8, 11–15, 23–44]:

1. Transport models, both simple effective diffusion and more mechanistic, first-principle models, which are needed to model the redistribution from the fuel through the matrix and into the graphite.
2. Sorption models, both Langmuir and empirical, to model the transfer of radionuclidies from the surface of the graphite block or pebble into the coolant.
3. Chemical species, surface state of materials, and coolant chemistry as the sorption on surfaces is very sensitive to the chemical state of both the surface and fission product.
4. Graphite oxidation models for air- or moisture-ingress accidents.
5. Dust abrasion models to determine the dust generation during normal operation.
6. Dust deposition and re-entrainment models that can model the dust distribution in the reactor circuit both prior to and during the accident. Vibration can result in continuous deposition and re-entrainment in circulating systems; also the shock, vibration, and acoustical noise of a high-pressure pipe break needs to be considered as a transport driver.

Appendix A contains some additional comments on transport modeling and issues that separate the VHTR from the more familiar LWR.

3.6 Steps 6 through 8—Identify Phenomena and Rank

Table 6 details the fission-product pathway from the fuel surface and serves as a foundation for the phenomena identification process. Note that most transport mechanisms are in place during both normal operation and accident conditions; only confinement transport is exclusively accident related.

Tables 7 through 10 are the individual phenomenological breakdown and ranking of the more general items identified in Table 6. Table 7 defines the ranking scale, Table 8 defines the knowledge scale, and Table 9 details the model and code knowledge level (ability to conduct useful and practical computations). All are approximate in nature but serve to provide insight into the general status of the evaluation.

Table 10 is the collective panel ranking of the table with the number of panelists ranking the particular item High, Medium, or Low. Individual ranking are contained in Appendix B, and the overall panel result is discussed in the next section.

After the individual phenomena have been identified and ranked, an assessment of the state of knowledge (SOK) was formulated. In particular, areas requiring additional experiments and models are identified. This includes an overall panel consensus assessment for the scenarios considered. As is the case for ranking the importance of phenomena, a High (H), Medium (M) and Low (L) scale is used to rank the SOK relative to the phenomena in the context shown in Table 9. Again, individual rationales for the assigned SOK rankings are provided in the PIRT entries.

The ranking table applies to all three situations—normal operations, anticipated transients, and postulated accidents—because all three conditions require detailed knowledge of the local parameters of the reactor circuit to compute the physical and chemical balances required. The major differences that could exist among the three conditions are the local flows which could be radically different from normal, the core temperature distribution, and the entrainment of dust, generation of aerosols, and sorption of fission products on graphite and metals. However, for the most part, the same information is needed for each case; there appears to be no computational shortcuts or approximations that allow one to drastically reduce the required data or effort. The only two exceptions are the effort required for the confinement and the failures associated with the IHX. Under normal conditions, the confinement and the secondary side are free of fission products. These two cases are noted in the table.

Table 6. Fission product transport pathways from the fuel particle surface

ID No.	Transport step	Accident/normal condition	Major phenomena	Affecting factors
1	Through the carbon matrix surrounding the particle	Both	1. Chemisorption on the carbon matrix 2. Diffusion through matrix	1. Fission-product chemical state 2. Radiation damage 3. Matrix density/quality 4. Chemical reactions (impurities and attack) 5. Temperature
2	Across the compact/block gap (prismatic) or the carbon matrix of the pebble fuel.	Both	1. Vaporization	1. Isotherms for matrix and graphite 2. Chemical form 3. Temperature
3	Through the graphite block (prismatic) or through the pebble outer, unfueled layer	Both	1. Diffusion through graphite or matrix outer layer 2. Chemisorption on graphite	1. Fission product chemical state 2. Radiation damage 3. Graphite properties 4. Temperature 5. Chemical reactions (impurities)
4	From the fuel form outer surface to the coolant	Both	1. Vaporization 2. Abrasion	1. Isotherms for graphite and matrix 2. Radiation damage 3. Chemical form 4. Temperature 5. Gas-phase concentrations 6. Mass transfer coefficients 7. Abrasion factors
5	Transport in the coolant, gas species, aerosol, or dust	Both	1. Chemisorption of FPs on dusts, and aerosols 2. Dust deposition and re-suspension 3. Aerosol physics	1. Isotherms for matrix, graphite, metals 2. Surface quality 3. Chemical form 4. Temperature 5. Gas-phase concentrations 6. Formation of aerosols 7. Aerosol concentrations and effects such as agglomeration and growth 8. Dust formation mechanisms and rate 9. Flow forces on dust and aerosols and vibration

Table 6 (continued)

ID No.	Transport step	Accident/normal condition	Major phenomena	Affecting factors
6	From coolant to reactor circuit components and power conversion equipment	Both	1. Fission product chemisorption, especially on metals 2. Dust plate-out	1. Isotherms for matrix, graphite, metals, especially for cesium and silver 2. Surface quality of power conversion equipment 3. Chemical form 4. Reactions with oxide film and alloying with base metal. 5. Temperature 6. Gas-phase concentrations 7. Formation of aerosols 8. Aerosol concentrations and effects such as agglomeration and growth 9. Dust formation mechanisms
7	Transport out of the reactor circuit during normal operation (tritium permeation, refueling)	Normal	1. Tritium permeation, leaks	1. Temperature 2. Permeation factor 3. Primary and secondary coolant concentrations 4. Size and number of leaks
8	Transport out of the reactor circuit due to pressure boundary breech, lift-off, venting, desorption, dust, aerosols	Accident (some variation of a depressurization)	1. Lift-off of dusts, aerosols, mechanical effects, spallation of surface layers 2. Desorption 3. Inertial impaction 4. Re-suspension	1. Dust re-entrainment 2. Surface layer cracking and spallation 3. Effects of mechanical vibration and acoustical noise 4. Chemical form 5. Temperature 6. Formation and growth of aerosols 7. Aerosols concentrations 8. Isotherms on metal surfaces 9. Dust combustion
9	Transport from the confinement to the environment	Accident	1. Aerosols, dusts, 2. Gaseous iodine 3. Chemical reaction of iodine with surface 4. Leakage from the confinement building	1. Dust re-entrainment 2. Aerosol concentrations 3. Chemical form 4. Temperature 5. Filter efficiencies 6. Radiation environment
10	Release from the clean-up system (and spent fuel storage)	Accident	1. Desorption from cleanup system components 2. Lift-off of dusts, aerosols,	1. Dust re-entrainment 2. Surface layer cracking and spallation 3. Effects of mechanical vibration and

Table 6 (continued)

ID No.	Transport step	Accident/normal condition	Major phenomena	Affecting factors
			mechanical effects, spallation of surface layers	acoustical noise 4. Chemical form 5. Temperature 6. Formation of aerosols 7. Aerosols concentrations 8. Properties of cleanup system components. 9. Cleanup system failure modes and location of cleanup systems
11	Transport issues associated with the IHX	Normal Accident	1. Tritium permeation 2. IHX leaks 3. IHX failures	1. Temperatures 2. Materials 3. Surface layers 4. Design-specific failure modes

Table 7. Phenomena importance ranking scale

Rank	Definition	Application outcomes
High (H)	Phenomenon has a controlling impact on the Figure of Merit	Experimental simulation and analytical modeling with a high degree of accuracy is critical
Medium (M)	Phenomenon has a moderate impact on the Figure of Merit	Experimental simulation and/or analytical modeling with a moderate degree of accuracy
Low (L)	Phenomenon has a minimal impact on the Figure of Merit	Modeling must be present to preserve functional dependencies

Table 8. State-of-knowledge (SOK) ranking scale

Rank	Definition
High (H)	Experimental simulation and analytical modeling with a high degree of accuracy is currently possible
Medium (M)	Experimental simulation and/or analytical modeling with a moderate degree of accuracy is currently possible
Low (L)	Experimental simulation and/or analytical modeling is currently marginal or not available

Table 9. Status of fission-product modeling ranking scale

Rank	Definition
Adequate	Existing codes and/or analytic models can be adapted to the problem with minimal effort
Minor mod	Deficiencies exist within existing codes and/or analytic models, or modest, measurable effort is required to adapt them to the problem
Major need	Useful codes and/or analytic models do not exist for this problem. Requires major development

Table 10. Overall PIRT ranking

This table generally applies to all cases—normal, anticipated transients, and accidents.
Specific cases are noted. This table contains a summary of the individual rankings and the April 18, 2007, consensus Rationales.
See Appendix B for details on individual ranking and their addition comments on the listed rationales ("Medium–High" was tallied as "Medium," and "Medium–Low" was tallied as "Low." Some minor interpolation was required when using the reorganized table). Overall, there was general agreement with only one extreme split (Highs and Lows)—entry #49.

Notes:

**denotes need for interface with other groups (materials, transient scenarios)*
IC—initial condition, the result of long-term normal operation
Trans.—transient and accident condition
TF—thermal fluids
FP—fission products

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
	Critical initial and/or boundary condition					
1	Decay heat and transient power level	5–High	Energy source driving problem (IC and Trans.)	5–*High	Boundary conditions expected from TF PIRT	Adequate
2	Material/structure properties	5–High	Density, viscosity, conductivity, etc., important parameters in calculations (IC and Trans.)	5–*Med (graphite): High (steel, concrete)	Graphite type not selected, expected from material PIRT	Minor mod (graphite) Adequate (steel, concrete)
3	Graphite impurity levels	4–Medium 1–High	Impurity reaction with FP, nuclear graphite expected to have low impurity levels	5–*High	Will be measured, expected from material PIRT	Adequate
4	Graphite geometry	5–High	Core structure (design information)	1–Medium 4–High	Well known for IC	Adequate for IC Major Need for air ingress

Table 10 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
5	Thermal-fluid properties	5–High	Temperature, pressure, velocity computations (IC and Trans.)	4–*Medium 1–*High	Well known for helium, uncertainty in composition of gas mixtures makes gas property calculation more difficult, expected from TF PIRT	Adequate
6	Gas composition	5–High	Oxygen potential and chemical activity	4–Medium 1–Low	Central issue for chemical reaction modeling, FP speciation, scenario dependent	Adequate (depressurization) Major need (air ingress)
7	Gas flow path prior, during and post accident	5–High	Information needed to model accident (IC and Trans.)	5–*Same as TF group	Need to coordinate with other groups; expected from TF PIRT	Same as TF group
8	Temperature (structure and gas) and pressure distribution	5–High	Information needed to model accident (IC and Trans.)	5–High	Need to coordinate with other groups; expected from TF PIRT	Same as TF group
9	FP plate-out and dust distribution under normal operation	5–High	Starting conditions	1–Low 4–Medium	Theory and models lack specifics	Major need

Table 10 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
			Graphite and core materials			
10	Matrix permeability, tortuosity	1–Medium 4–High	Needed for first principle transport modeling (IC and Trans.)	4–*Low 1–*Medium	FP holdup as barrier, release as dust; expected from material PIRT.	Major need
11	FP transport through matrix	5–High	Effective release rate coefficient (empirical constant) as an alternative to first principles (IC and Trans.)	5–Low	FP holdup as barrier, release as dust; expected from material PIRT	Major need
12	Fuel block permeability, tortuosity	1–Medium 4–High	Needed for first principle transport modeling (IC and Trans.)	5–*Medium	Depends on specific graphite; expected from material PIRT	Major need
13	FP transport through fuel block	5–High	Effective release rate coefficient (empirical constant) as an alternative to first principles (IC and Trans.)	1–*Low 4– Medium	Depends on specific graphite; expected from material PIRT	Major need
14	Thermal (Soret) diffusion	5–Low	Thermal gradients are not large outside of fuel	5–Low	Little data	Not req'd
15	Basal plane diffusion	5–Low	Porosity is preferred transport pathway through graphite	5–Medium	Past work and literature available	Not req'd

Table 10 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
16	Reflector (in contact w/flow) permeability, tortuosity	5–Low	Needed for first principle transport modeling (IC and Trans.)	5–*Medium	Depends on specific graphite; expected from material PIRT	Minor mod
17	FP transport through reflector (in contact w/flow)	5–Low	Effective release rate coefficient (empirical constant) as an alternative to first principles (IC and Trans.)	1–*Low 4–*Medium	Depends on specific graphite; expected from material PIRT	Minor mod
18	Sorbtivity graphite	5–High	Can determine holdup and release of FP (IC and Trans.)	5–Medium	Historical data, need specific information on graphite and radiation effects	Minor mod
19	Fluence effect on transport in graphite	5–High	Influences transport, chemical reactivity	5–Medium	Historical data, need specific information on graphite and radiation effects	Major need
20	C-14, Cl-36, Co-60 generation and inventory	4–Low 1–Medium	Radioisotope generated from impurities, might become operational issue (IC)	5–Medium	Historical data, Peach Bottom HTGR	Minor mod, sensitive to graphite handling
21	Air attack on graphite	5–High	Graphite erosion/oxidation, Fe/Cs catalysis liberating FPs (Trans.)	1–Low 4–Medium	Historical data	Major need for severe accidents
22	Steam attack on graphite	5–High	If credible source of water present; design dependent (Trans.)	1–Low 4–Medium	Historical data	Major need for severe accidents

Table 10 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
Fission product transport in reactor coolant system and confinement						
23	FP speciation in carbonatious material	5–Hgh	Chemical form in graphite affects transport (IC and Trans.)	5–Low	Uncertain and/or incomplete	Major need
24	FP speciation during mass transfer	5–High	Chemical change can alter volatility	1–Low 4–Medium	Historical data; need specific information. Good for metals, oxides. Uncertain for carbides and carbonyls.	Major need
25	"Knock-along"	5–Low	Alpha recoil transport of deposited particles on surfaces slow compared to fluid flow transport	5–Medium	Studied in actinide-bearing particles	Adequate
26	Dust generation	5–High	Vector for FP transport; possibility of high mobility	5–Medium	Limited experience; lack specific system information	Major need, import from other groups
27	(De)Absorption on dust	5–High	Provides copious surface area for FP absorption	2–Low 3–Medium	Limited experience, lack specific details	Major need
28	H-3 generation and circulating coolant inventory	4–Medium 1–High	Radioisotope, an issue with operational release. H-3 production from He-3 in coolant, ternary fission, and Li-6 in graphite	5–Medium	Historical data; Peach Bottom HTGR	Minor mod

Table 10 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
29	Ag-110*m* generation, transport	5–High (O&M) 5–Low (release)	Radioisotope, significant O&M dose on cool, metallic components	5–Low	Limited data, unknown transport mechanism	Major need
30	Other activation products (e.g., Cs-134, Mn-55, Fe-56)	5–Low	Radioisotopes, potential O&M dose	5–Medium	Experience, limited information	Minor mod
31	Nucleation	5–Medium	Unclear due to extremely low FP vapor concentration anticipated	5–Medium	Historical data	Major need
32	Aerosol growth	1–Medium 4–High	Low concentration growth can lead to high-shape factors and unusual size distribution	5–Low	Regime has not been studied previously	Major need
33	Surface roughness	5–Medium	Affects aerosol deposition 1–5 micron particles (IC and Trans.)	5–Medium	Initial information from manufacturer; evolution of surface roughness during operation not well known	Minor mod
34	Coolant chemical interaction with surfaces	5–High	Changes oxygen and carbon potential which can affect nature and quantity of sorbed species (IC and Trans.)	5–Medium	Surface properties are critical; need alloy data	Major need
35	FP diffusivity, sorbtivity in nongraphite surfaces	5–High	Determines FP location during operation; acts as a trap during transient (IC and Trans.)	5–Low	Little information on materials of interest	Major need

Table 10 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
36	Aerosol/dust deposition	5–High	Gravitational, inertial, thermophoresis, electrostatic, diffusional, turbophoresis (Trans.)	5–Medium	Reasonably well-developed theory of aerosol deposition by most mechanisms except inertial impact in complex geometries; applicability to NGNP unclear	Minor mod
37	Aerosol/dust bounce, breakup during deposition	4–Medium 1–High	Can modify deposition profile and suspended aerosol distribution	4–Low 1–Medium	Theory, data, and models lacking	Major need
38	Resuspension	5–High	Flow/vibration induced, saltation; mechanical forces can release FPs from pipe surface layers/films (Trans.)	4–Low 1–Medium	Lack of data and models for anticipated conditions	Major need
39	Confinement aerosol physics	5–High	Analogous to LWR aerosol behavior/physics, delta-T, chemistry; important holdup mechanism (Trans.)	5–Medium	Reasonably well-developed theory of aerosol behavior; applicability to NGNP unclear	Minor mod
40	Dust deposition on vessel and RCCS hardware	5–Low	Not important for FP transport but may affect radiative heat transfer in reactor cavity	5–Low	Very limited data	Major need

Table 10 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
41	Corrosion products	5–Low	Spalled surface films; low corrosion environment (IC and Trans.)	5–High	Past experience	Adequate
42	Erosion products, noncarbon	5–Low	Low concentration of coarse materials (IC and Trans.)	5–Low	Lack of design information; configuration and materials specific	Adequate
43	Wash-off	5–High	If credible source of water present; design dependent (Trans.)	5–Medium	Some experimental data available	Minor mod
44	Failure modes of auxiliary systems (e.g., gas cleanup, holdup, refueling)	5–Medium	Potential release due to failure (Trans.)	5–Medium	Design specific; have experience from other designs	Minor mod
45	Radiolysis effects in confinement	5–High	FP (e.g., I, Ru, Te) chemistry, paint chemistry (dependent on confinement radiation level) (Trans.)	5–Medium	LWR experience and data	Minor mod
46	Filtration	5–High	Traditional passive charcoal/HEPA (Trans.)	5–High	Historical experience	Adequate
47	Production/combustion of flammable gas	5–Medium	CO, H_2 production issues, IHX secondary-primary leak, potential resuspension and chemical transformation of FPs (Trans.)	1–Medium 4–High	Historical experience	Adequate

Table 10 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
48	Combustion of dust in confinement	5–High	Source of heat and distribution of FPs with in confinement	1–Low 4–Medium	ITER data	Major need
49	NGNP-unique leakage path beyond confinement	5–High	IHX to secondary site contamination; could be risk dominant (Trans.)	1–Low 4–High	Contingent on specific design knowledge	Minor mod
50	Confinement leakage path, release rate through penetrations	5–High	Cable/pipe penetrations, cracks, holes, HVAC (Trans.)	5–Medium	Building leakage experience, design specific	Adequate
51	Cable pyrolysis, fire	5–High	Soot generation and changes to iodine chemistry	5–Medium	LWR experience	Major need
52	Pressure-relief-valve filter	5–Low	Opening of the relief valve generates a transport path that may be filtered; depends on design	5–High	Air cleaning technology	Adequate
53	Recriticality (slow)	5–High	Additional thermal load to fuel. Increases source but not expected to affect transport path.	5–Medium	Heat load easily computed with existing tools; effect on fission products not completely known	Minor mod
54	Fuel-damaging RIA	5–High	An intense pulse could damage fuel. Increases source but not expected to affect transport path	5–Medium	Some data exists, but outside of expected accident envelope	Minor mod

Table 10 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
55	Argon activation in reactor cavity	5–High (normal operation)	Air in cavity activated by neutron leakage and can escape to environment	5–High	Easily computed with existing tools	Adequate
56	Redistribution of fission products due to control rod movement	5–Low	Articulated control rod joints can collect and redistribute fission products	5–Low	Specifics on CRD housing and articulated SiC composite housing TBD	Minor mod

The crucial information that is required to begin an accident analysis is the initial condition (IC), the situation prior to the accident. It is this situation that will set the basic source term for a depressurization release. Unlike the LWR case, massive fuel failure is not anticipated during the course of the accident (unless unlimited air ingress occurs); any incremental fuel failure is anticipated to occur after the depressurization is complete; thus, the late accident release driver is then reduced because the major driving term, helium pressure, is gone due to the leak or break. The driving terms later in the accident are the weak flows driven by temperature and atmospheric variations. In addition, some designs may filter the later releases, but not all designs may filter the main source of dust and fission-product aerosols during the initial (large volume and short duration) depressurization.

If an air or moisture ingress accident occurs with an unimpeded flow path and is allowed to run to completion, high levels of fuel failure due to high temperatures are possible. In this case, large fission-product releases can occur later in the accident and the convective flows will carry the fission products outside the core.

3.7 Step 9—Document PIRT—Summary

The panel discussions allowed the assembly of the desired ranking table; however, it must be noted that the FPT issue is a consequence of an accident scenario and not the accident driver. Depending on the design of a confinement or containment, the impact of a pressure boundary breach can be minimized if a modest, but not excessively large, fission-product attenuation factor can be introduced into the release path. This exercise has identified a host of material properties, thermofluid states, and physics models that must be collected, defined, and understood to evaluate this attenuation factor.

Table 11 is a condensed version of Table 10, containing only those items with at least one ranking of high importance and one ranking of low knowledge. An expanded rationale column has been added to more completely explain the issues and why they were ranked in this manner. Because of the small allowable releases during a depressurization from this reactor type (due to a vented confinement), dust and aerosol issues are important even though the amounts of fission products involved may be modest (compared to an LWR accident). Also, the mechanical impact of the failure needs to be assessed because it can re-entrain dust as well as generate particles by spalling off internal surface layers. The mechanical shock issue has seen less emphasis in the gas reactor transport literature, and NUREG-0800 specifically calls for the evaluation of "pipe whip" issues.

The reader should be cautioned that merely selecting phenomena based on high importance and low knowledge may not capture the true uncertainty of the situation. This is because a transport path is composed of several serial linkages, each with its own uncertainty. The propagation of a chain of modest uncertainties can lead to a very large uncertainty at the end of a long path, resulting in a situation that is of little regulatory value.

Table 11. Selected PIRT items from Tables 10 that have at least one high importance and low knowledge ranking

Notes:

**denotes need for interface with other groups (materials, transient scenarios)*
IC—initial condition, the result of long term normal operation
Trans.—transient and accident condition
TF—thermal fluids
FP—fission products

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Level of knowledge (High, Medium, Low)	Rationale
6	Gas composition	5–High	4–Medium 1–Low	Oxygen potential and chemical activity are central issues for chemical reaction modeling and FP speciation. Volatility of FPs can depend on chemical form and oxidizing conditions will cause matrix and graphite damage leading to the release of contained FPs. Holdup of FPs on metal surfaces can depend on surface oxidation state. This is scenario dependent. Can influence the IC due to gas impurities. Most needed for the air ingress accident.
9	FP Plate-out and dust distribution under normal operation	5–High	1–Low 4–Medium	The plate-out and dust distribution form the IC for an accident. Theory and models lack specifics; must be coupled with flow and mechanical models as high deposition areas subjected to large changes in flow, temperature, and mechanical shock/vibration are candidates for re-entrainment during an accident.
10	Matrix permeability, tortuosity	1–Medium 4–High	4–*Low 1–*Medium	Needed for first principle transport modeling (IC and Trans) and functions as FP holdup barrier for less volatile FPs (both in fuel form and as dust). Some form of fairly comprehensive model over the conditions of interest is needed. Note that this affects FP dust (pebble bed) modeling as well. See item 11 below.

Table 11 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Level of knowledge (High, Medium, Low)	Rationale
11	FP transport through matrix	5–High	5–Low	Once through the particle, the matrix is the first barrier (note that pebbles are largely matrix); it also collects FPs as dust. Effective release rate coefficient (empirical constant) as an alternative to first principles (IC and Trans) may be more tractable. Matrix holdup can be important for the less volatile FPs. Dust in the PBMR may be largely composed of matrix, so this issue will affect dust FP modeling as well.
13	FP transport through fuel block	5–High	1–*Low 4–*Medium	Graphite can offer substantial attenuation to the transport of FPs and hold up the less volatile ones. Effective release rate coefficient (empirical constant) as an alternative to first principles (IC and Trans) may be more tractable but could be highly dependent on the type of graphite. Important for prismatic core because of the series path. Absorption in graphite blocks is desirable to that in dust because of less mobility.
21	Air attack on graphite	5–High	1–Low 4–Medium	Graphite erosion/oxidation can release the contained FPs and change the chemical form of the FPs as well as weaken the core and damage the fuel. Issues such as Fe/Cs catalysis can change pore structure, leading to greater FP release. Some historical data is available, but the very small acceptable release fraction may require more detail. Major need for severe accidents.
22	Steam attack on graphite	5–High	1–Low 4–Medium	If credible source of water are present, contained FPs can be released with problems similar to above; this is design dependent and much less of a problem for a helium-only system. Major need for severe accidents.
23	FP speciation in carbonatious material	5–High	5–Low	The chemical form of the FPs in graphite and matrix material affects transport and hold up under both IC and accidents. Uncertain and/or incomplete information in this area. The higher temperatures in the VHTR may influence this. Major need as chemical forms strongly influence transport.

Table 11 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Level of knowledge (High, Medium, Low)	Rationale
24	FP speciation during mass transfer	5–High	1–Low 4–Medium	Chemical change can alter FP volatility. There is some historical data, but specific data may be needed for the VHTR. There appears to be good information for metals and oxides. Uncertain for carbides and carbonyls. Need to determine the importance of the issue.
27	(De)Absorption on dust	5–High	2–Low 3–Medium	Dust provides copious surface area for FP absorption, and the high mobility of dust allows the transport of FPs throughout the reactor system. Can be a mechanism that works in parallel with FP volatility for the distribution of FPs. Limited experience; lack specific details. Some data from AVR.
29	Ag-110*m* generation, transport	5–High (O&M) 5–Low (release)	5–Low	Both Ag (and Cs) can drive a significant O&M dose on power conversion and heat exchanger equipment. Limited data; unknown transport mechanism. May alloy with metal components and make decontamination difficult. Possible large impact on maintenance shielding.
32	Aerosol growth	1–Medium 4–High	5–Low	Low aerosol concentration and dry environment can result in the growth of particles with high shapes factors and unusual size distribution. Regime has not been studied previously, and results need to be determined to assess impact. Vented confinement makes even modest aerosol concentrations important.
35	FP diffusivity, sorbtivity in nongraphite surfaces	5–High	5–Low	These factors determine FP location during normal operation and act as traps during transient conditions. Can impact O&M as well as accident doses. Past work has examined some metals, but little information may be available for the materials and temperatures of interest. Could be sensitive to the surface oxidation state. Major need for modeling the reactor circuit.
37	Aerosol/dust bounce, breakup during deposition	4–Medium 1–High	4–Low 1–Medium	Aerosol behavior can modify deposition profile and the suspended aerosol distribution—theory, data, and models lacking. Because of the small acceptable releases due to the vented confinement option, aerosols and dusts take on an exaggerated transport importance. Mechanical issues such as vibration and mechanical shocks need to be taken into consideration as well.

Table 11 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Level of knowledge (High, Medium, Low)	Rationale
38	Resuspension	5–High	4–Low 1–Medium	Since the actual FP content of the gas is expected to be low, the FPs that can be released from the surfaces of components becomes important. Past analysis has often focused on flow-induced lift-off of oxide layers and dust, but mechanical- shock- and vibration-induced lift-off can be major drivers as well. NUREG-0800 requires that pipe whip issues be examined. Mechanical shocks/forces/vibrations can release FPs from pipe surface layers/films during accidents. Lack of data and models for anticipated conditions, especially mechanically induced ones.
48	Combustion of dust in confinement	5–High	1–Low 4–Medium	Source of heat and distribution of FPs within confinement if conditions allow the oxidation of the dust. Results may depend on composition—graphite or matrix—and the amount of air in the confinement. Some ITER data. Need to assess. Biggest impact on vented confinement. A more remote issue is damage to the vents that prevent later closure.
49	NGNP-unique leakage path beyond confinement	5–High	1–Low 4–High	IHX to secondary site contamination could be risk dominant in some accidents. This is only vaguely defined and highly contingent on specific design knowledge. Wide variation in panel response is due to the lack of design details. Once design information is available, ranking should be much easier as it is suspected that knowledge about historical failure modes will apply to the design. There is a wealth of experience with LWR containment leakages issues and general heat exchanger operation.

The initial fission product contamination of the reactor circuit is of great importance because the most powerful driving term, helium pressure, will provide the driving force for transport of the source term out of the primary circuit during the earliest stages of the accident. If an air ingress accident occurs with an unimpeded flow path, large fission product releases can occur later in the accident.

In addition to the consensus and compiled entries in Table 10, the individual ranking tables (Appendix B) may be of particular interest to the reader.

The PIRT table underwent two iterations with extensive reorganization between meetings; the results shown in the Appendix are the panelists' changes and additions to the final PIRT table, which was assembled after extensive discussions. The panelists' thoughts (after several days of additional individual review, noted in red italics) are contrasted with the group consensus of the last meeting.

Generally, convergence is seen on most issues, but different approaches to the specific physics and transport paths shade the answers accordingly. One item of particular interest is the final approach to the ranking process. Two methods are apparent; the identification of the phenomena in either a general or path-dependent way. The general identification method allows one to collect all the items of interest without specifically outlining a transport path within the ranking table, although Table 6 was used as a general guide. This method avoids forcing a specific transport path model on the analyses but may not clearly identify the relative importance of particular phenomena along a specific path.

The path-dependent approach allows the reader to see the importance of the particular phenomena along a path (at the expense of some redundancy in the PIRT entries), but requires the identification of the transport subpaths. These paths were based on historical work because of the lack of a specific NGNP design, but should be relevant unless some truly unique design is proposed. The reader is encouraged to explore each approach to help develop insight that can be applied to a VHTR once a particular design has been developed along with its approach to FP transport needs. Even with these two approaches to the PIRT table layout, the results are very similar.

One item of interest that may not have been clearly identified in the starting PIRT table but was listed in the path-dependent reorganized table is the release of fission products due to normal helium leakage from the reactor system (implied in table item #7 but not individually listed). This table also contains many other (redundant) entries that are related to the original PIRT table entries; this was necessary because of the path structure.

A second issue of importance is the approach to modeling graphite properties. Technically, this issue is beyond the scope of the PIRT as the panel was to focus only on phenomena, but it does impact how one approaches the collection of data for the models. Briefly, one approach is basic physics in nature, and the other is more empirical in nature. The basic physics approach would have the advantage that measured graphite and fission product properties can be related to transport over a wide range of situations, but the physics may be very challenging. The empirical approach offers less theoretical complexity but may be limited by the cost of experiments and the range of accidents that can be covered. In any event, this issue will have to be resolved by a review of the state of the art in graphite and transport theory and will be influenced by the specific safety approaches taken by the designers.

Other table entry comments included variations in nomenclature and the physics of particular phenomena, but these clarifications and comments did not appear to change the ranking in any substantial way.

Finally, one item that was rated as important and may not have been explored in the past was the effect of mechanical shock and vibration on the transport and re-entrainment of dust and spalled-off oxide flakes. A failure of a large pipe would generate large mechanical forces (vibration, shocks, and pipe whip), and the resulting flow can generate a large amount of acoustic energy, both of which can launch dust and small particles into the existing gas flow as well as cause additional failures. Much of the literature is concerned with changes in temperature and flow velocity during an accident, but these impulsive and vibratory mechanical effects should also be considered, especially if the reactor internal surfaces are formally required to retain fission products during an accident to meet safety requirements.

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APPENDIX A

COMMENTS ON TRANSPORT MODELING

A.1 Brief Discussion of Transport Modeling Through Porous Media

Once fission product vapors have migrated from a fuel particle, or are created from fissioning of "tramp uranium," transport of these vapors through the porous medium of matrix graphite and other graphite structures becomes a key process leading to release of radionuclides to the more open regions of the reactor coolant system and eventually to the confinement in accident situations. Porous materials that the vapors must transit may be cracked, and such cracks provide parallel and often more efficient routes for transport than the inherent, interconnected porosity of the graphite material. Transport through cracks and the pore structure can be driven by concentration differences, temperature differences, and pressure differences. The resistance to transport is created by the collision of the vapor molecules with each other and with surfaces lining the transport pathway. When molecule-molecule collisions dominate, the diffusion process is classical gas-phase diffusion. When molecular collisions with surfaces dominate, the transport is Knudsen diffusion. Most situations of interest for safety analyses lie within the transition between the molecular diffusion and Knudsen diffusion extremes. For these situations, small changes in the permeability, slip, and tortuosity features of the transport pathway can have significant impacts on the total vapor flux through a porous material.

In the past, it was common to treat vapor transport through a porous material in terms of either an effective diffusivity or an effective permeability measured under particular conditions of temperature, pressure, and gas composition. Such empirical practices work satisfactorily when the range of conditions is narrow and well known. Unfortunately, for accident conditions, a much wider range of conditions, depending on the particular features of the accident initiation and progression, can be anticipated. It is not feasible to develop empirical effective diffusivities for all the conditions and all of the radionuclides of interest. Thus, it may be necessary to take a more fundamental approach to the transport processes if detailed path-dependent calculations are required to analyze a particular event. Fortunately, there have been rather significant advances in the understanding of porous medium transport processes since the last gas-cooled reactors were built. This more advanced understanding of multicomponent mass transport in porous media makes it possible to approach radionuclide transport under accident conditions from a more fundamental point of view.

Essential characterization of the porous medium for the analysis of radionuclide transport includes the following:

1. Porosity, especially interconnected porosity
2. Tortuosity—essentially the actual path length through a porous body relative to the geometrical distance across the body
3. Poiseulle permeability parameter
4. Knudsen permeability parameter

The initial porosity of a specific graphite will be well known. Indeed, this porosity may well be specified in the course of acquisition of the graphite. Permeability parameters for nuclear graphites have been measured with acceptable accuracy since the late 1950s. Tortuosity is not routinely measured for graphites, though it is routinely measured for catalyst support materials.

Porosity and permeability properties of the graphite can be expected to change during power plant operation and under accident conditions. Certainly, irradiation is expected to cause some initial densification of graphite followed by expansion as atomic and unit cell displacements accumulate in the material. Locations along transport paths where displacements have occurred are high-energy sites, and radionuclide vapors may well absorb preferentially onto these sites. Under conditions where the graphite is exposed to an oxidant and temperatures are sufficiently low that chemical kinetics controls the rate of graphite reaction with the oxidant (typically ~<1200°C), locations of irradiation-induced displacements along transport pathways will be preferred sites for reaction and gasification of the graphite. This removal of material will open the transport pathways. Such changes in the graphite and the ease with which vapors can transport through porous graphite will need to be predicted mechanistically by accident analysis computer codes. Such predictions cannot be made when effective diffusivities and effective permeabilities are used to calculate the vapor transport of radionuclides. Again, a more fundamental approach to vapor mass transport through a porous medium is needed.

A.2 Speciation

Speciation of radionuclides and the diversity of speciation will affect the volatility and the transport of radionuclides. It can be anticipated that the speciation will be determined especially for the gas phase by thermochemical calculations. Thermochemical databases available for the prediction are reasonably well developed for elements and oxides. The database is less well developed but still useful for vapor-phase carbides. Predictions of vapor pressures for solid carbides are always complicated by the tendency for these phases to be nonstoichiometric, which demands modeling of the nonstoichiometry. The intrusion of water raises the possibility of the formation of vapor-phase hydrides and hydroxides. Most of the available thermodynamic data on vapor-phase hydroxides and hydrides for elements of interest have been estimated by analogy to other systems. A class of possible vapor-phase compounds for which there are few data are vapor-phase carbonyls. Stable carbonyls of elements like ruthenium, palladium, and rhodium are fairly well known, but these carbonyls are unlikely to contribute significantly to vaporization or transport of these elements since the polycarbonyls are not especially stable. Of more interest are mono- and di-carbonyls that can accentuate vaporization of otherwise fairly nonvolatile radionuclides. Such species have received some theoretical consideration, but the necessary high CO pressure experiments to demonstrate the contributions of these elements to either release or transport have not been usually done.

A.3 Aerosols

Certainly in the containment and to some extent in the reactor coolant system, radionuclide transport will be predominantly by aerosol transport. Modeling of conventional aerosol has been well developed and validated by the NRC, and routine calculations can be done. By and large these computational tools have been optimized for rather "wet" or highly humid environments. The dry environment typical of many classes of gas reactors will pose a challenge. In such dry environments, water condensation within the interstices of particle agglomerates will not be possible. There will, then, not be a strong surface-tension driving force to convert linear-chain agglomerates into more spherical aerosol particles assumed for the analyses with existing computer codes. Shape factors will have to be introduced into the calculations, and these shape factors will not necessarily be small. Kops and coworkers have reported shape factors as high as 35 for dry aerosols formed from the condensation of high-temperature vapors. Furthermore, the shape factors will vary with particle size—something codes such as MAEROS, used widely for nuclear application, cannot handle.

A more bothersome issue is that of electrostatic charging of aerosols in the dry environment. Aerosol particles can be charged in the dry environment because of gas-phase ions formed in the intense radiation field. Negatively charged ions typically have higher mobilities than do positively charged ions. Consequently aerosol particles are bombarded more often by negatively charged ions and can assume a negative charge. The magnitude of the charge depends on the particle size. Coulombic forces among aerosol particles due to like charges on particles are not addressed in currently available models of aerosol behavior. The electrostatic forces among charged particles are much stronger than the forces that ordinarily drive the agglomeration of aerosol particles to sizes such that they readily deposit by gravitational settling or inertial impaction on structures. What deposition of particles does occur will develop either a surface charge or a mirror image charge that could also produce forces capable of interfering with the deposition of additional particles. Again, current models do not account for such effects that are important only where the radiation field is large.

APPENDIX B

INDIVIDUAL PANELISTS' RANKING TABLES

Each panelist individually reviewed the last PIRT table and included rankings and comments if they differed from the group consensus. Both the original text and the change are shown so that the reader can understand the rationale for the change.

Table B-1. Individual FPT PIRT Ranking Table
Final Version April 18, 2007
Panelist: Dana A. Powers

Changes in *ITALICS* are differences from the final group discussions on April 18, 2007

This table generally applies to all cases, normal, anticipated transients, and accidents. Specific cases are noted.

Notes:

** denotes need for interface with other groups (materials, transient scenarios)*
IC—initial condition, the result of long term normal operation
Trans.—transient and accident condition
TF—thermal fluids
FP—fission products

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
			Critical initial and/or boundary condition			
1	Decay heat and transient power level	High	Energy source driving problem (IC and Trans.)	*High	Boundary conditions expected from TF PIRT	Adequate
2	Material/structure properties	High	Density, viscosity, conductivity, etc., important parameters in calculations (IC and Trans.)	*Med (graphite) High (steel, concrete)	Graphite type not selected; expected from material PIRT	Minor mod (graphite) Adequate (steel, concrete)
3	Graphite impurity levels	Medium	Impurity reaction with FP, nuclear graphite expected to have low impurity levels	*High	Will be measured; expected from material PIRT	Adequate *because impurity levels are expected to be quite low*
4	Graphite geometry	High	Core structure (design information)	High	Well known for IC	Adequate for IC Major need for air ingress

Table B-1 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
5	Thermal-fluid properties	High	Temperature, pressure, velocity computations (IC and Trans.)	*Medium	Well known for He, uncertainty in composition of gas mixtures makes gas property calculation more difficult, expected from TF PIRT	Adequate
6	Gas composition	High	Oxygen potential and chemical activity; *also carbon potential and hydrogen potential*	Medium	Central issue for chemical reaction modeling, FP speciation, scenario dependent	Adequate (depressurization) Major meed (air ingress *or water ingress*)
7	Gas flow path prior, during and post accident	High	Information needed to model accident (IC and Trans). *The flow path will be affected during air ingression and water ingression accidents as a result of graphite oxidation along the flow path.*	*Same as TF group	Need to coordinate w/ other groups; rxpected from TF PIRT. *Only the initial conditions of the pathways will come from thermal fluids. Transformation of the pathways as a result of long-term chemical erosion during an air or water ingress accident will have to be calculated. Thermal stress and cracking to form new pathways needs to be considered perhaps by the materials group.*	Same as TF group *Calculation of the opening of pathways as a result of chemical reactions can be challenging especially if temperatures are such that graphite oxidation is affected by catalysis.*
8	Temperature (structure and gas) and Pressure distribution	High	Information needed to model accident (IC and Trans)	*High	Need to coordinate w/ other groups; expected from TF PIRT	Same as TF group

Table B-1 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
9	FP Plate-out and dust distribution under normal operation	High	Starting conditions	Medium	Theory and models lack specifics	Major need
			Graphite and core materials			
10	Matrix permeability, tortuosity	High	Needed for first principle transport modeling (IC and Trans). *Modeling fission product transport on a more fundamental basis is required since it will not be possible to test for all accident conditions and all pathways that may arise.*	*Low	FP holdup as barrier, release as dust; expected from material PIRT	Major need. *Such information has been provided for other nuclear graphites. Mass transport through porous media has developed substantially since early gas reactors were designed, so modeling on a more fundamental basis is entirely feasible.*
11	FP transport through matrix	High	Effective release rate coefficient (empirical constant) as an alternative to first principles (IC and Trans)	Low	FP holdup as barrier, release as dust; expected from material PIRT	Major need
12	Fuel block permeability, tortuosity	High	Needed for first principle transport modeling (IC and Trans). *Modeling fission product transport on a more fundamental basis is required since it will not be possible to test for all accident conditions and all pathways that may arise.*	*Medium	Depends on specific graphite; expected from material PIRT	Major need. *Such information has been provided for other nuclear graphites. Mass transport through porous media has developed substantially since early gas reactors were designed, so modeling on a more*

Table B-1 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
						fundamental basis is entirely feasible
13	FP transport through fuel block	High	Effective release rate coefficient (empirical constant) as an alternative to first principles (IC and Trans)	*Medium	Depends on specific graphite; expected from material PIRT	Major need
14	Thermal (Soret) diffusion	Low	Thermal gradients are not large outside of fuel	Low	Little data	Not req'd
15	Basal plane diffusion	Low	Porosity is preferred transport pathway through graphite	Medium	Past work and literature available	Not req'd
16	Reflector (in contact w/flow) permeability, tortuosity	Low	Needed for first principle transport modeling (IC and Trans)	*Medium	Depends on specific graphite; expected from material PIRT	Minor mod
17	FP transport through reflector (in contact w/flow)	Low	Effective release rate coefficient (empirical constant) as an alternative to first principles (IC and Trans)	*Medium	Depends on specific graphite; expected from material PIRT	Minor mod
18	Sorbtivity graphite	High	Can determine holdup and release of FP (IC and Trans.)	Medium	Historical data; need specific information on graphite and radiation effects	Minor mod; *development of adsorption/desorption modifications to a porous medium mass transport model may require more than minor effort.*
19	Fluence effect on transport in graphite	High	Influences transport, chemical reactivity	Medium	Historical data; need specific information on graphite and radiation effects	Major need

Table B-1 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
20	C-14, Cl-36, Co-60 generation and inventory	Low	Radioisotope generated from impurities, might become operational issue (IC)	Medium	Historical data; Peach Bottom HTGR	Minor mod, sensitive to graphite handling
21	Air attack on graphite	High	Graphite erosion/oxidation, Fe/Cs catalysis liberating FPs (Trans.)	Medium	Historical data	Major need for severe accidents
22	Steam attack on graphite	High	If credible source of water present; design dependent (Trans.)	Medium	Historical data	Major need for severe accidents
Fission product transport in reactor coolant system and confinement						
23	FP Speciation in carbonaceous material	High	Chemical form in graphite affects transport (IC and Trans.)	Low	Uncertain and/or incomplete	Major need
24	FP Speciation during mass transfer	High	Chemical *form* change can alter volatility	Medium	Historical data, need specific information. Good for metals, oxides. Uncertain for carbides and carbonyls	Major need
25	"Knock-along"	Low	Alpha recoil transport of deposited particles on surfaces slow compared to fluid flow transport; *may be much more important in the evaluation of the effectiveness of filters*	Medium	Studied in actinide-bearing particles	Adequate
26	Dust generation	High	Vector for FP transport, possibility of high mobility	Medium	Limited experience; lack specific system information	Major need; import from other groups
27	(De)Absorption on dust	High	Provides copious surface area for FP absorption	Medium	Limited experience; lack specific details	Major need; *dust suspension and expulsion from the*

Table B-1 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
						reactor coolant system during a depressurization event may provide the equivalent of gap release to the containment in accidents
28	H-3 generation and circulating coolant inventory	Medium	Radioisotope, an issue with operational release. H-3 production from He-3 in coolant, ternary fission, and Li-6 in graphite	Medium	Historical data, Peach Bottom HTGR	Minor mod
29	Ag-110*m* generation, transport	High (O&M) Low (release)	Radioisotope, significant O&M dose on cool, metallic components	Low	Limited data, unknown transport mechanism	Major need
30	Other activation products (e.g., Cs-134, Mn-55, Fe-56)	Low	Radioisotopes, potential O&M dose	Medium	Experience, limited information	Minor mod
31	Nucleation	Medium	Unclear due to extremely low FP vapor concentration anticipated	Medium	Historical data	Major need
32	Aerosol growth	High	Low concentration growth can lead to high shape factors and unusual size distribution	Low	Regime has not been studied previously	Major need
33	Surface roughness	Medium	Affects aerosol deposition 1 to5 micron particles (IC and Trans.)	Medium	Initial information from manufacturer; evolution of surface roughness during operation not well known	Minor mod

Table B-1 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
34	Coolant chemical interaction w/ surfaces	High	Changes oxygen and carbon potential which can affect nature and quantity of sorbed species (IC and Trans.)	Medium	Surface properties are critical; need alloy data *on the formation of oxide and carbide surface films*	Major need
35	FP diffusivity, sorbtivity in nongraphite surfaces	High	Determines FP location during operation; acts as a trap during transient (IC and Trans.)	Low	Little information on materials of interest	Major need
36	Aerosol/dust deposition	High	Gravitational, inertial, thermophoresis, electrostatic, diffusional, turbophoresis (Trans.)	Medium	Reasonably well-developed theory of aerosol deposition by most mechanisms except inertial impact in complex geometries; applicability to NGNP unclear; *modeling the effects of electrostatic charging of particles is not developed. Size-dependent particle shape factors need to be modeled in solutions to the aerosol dynamic equation*	Minor mod
37	Aerosol/dust bounce, breakup during deposition	Medium	Can modify deposition profile and suspended aerosol distribution	Low	Theory, data, and models lacking	Major need *for particles larger than about 1 μm.*

Table B-1 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
38	Resuspension	High	Flow/vibration induced, saltation; mechanical forces can release FPs from pipe surface layers/films (Trans.)	Low	Lack of data and models for anticipated conditions	Major need *to model the resuspension and to predict the shocks and vibrations to equipment during an accident*
39	Confinement aerosol physics	High	Analogous to LWR aerosol behavior/physics, delta-T, chemistry; important holdup mechanism (Trans.)	Medium	Reasonably well-developed theory of aerosol behavior; applicability to NGNP unclear	Minor mod
40	Dust deposition on vessel and RCCS hardware	Low	Not important for FP transport but may affect radiative heat transfer in reactor cavity	Low	Very limited data	Major need
41	Corrosion products	Low	Spalled surface films; low corrosion environment (IC and Trans.)	High	Past experience	Adequate
42	Erosion products, noncarbon	Low	Low concentration of coarse materials (IC and Trans.)	Low	Lack of design information; configuration and materials specific	Adequate
43	Wash-off	High	If credible source of water present; design dependent (Trans.)	Medium	Some experimental data available	Minor mod
44	Failure modes of auxiliary systems (e.g., gas cleanup, holdup, refueling)	Medium	Potential release due to failure (Trans.)	Medium	Design specific; have experience from other designs	Minor mod

Table B-1 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
45	Radiolysis effects in confinement	High	FP (e.g., I, Ru, Te) chemistry, paint chemistry (dependent on confinement radiation level) (Trans.)	Medium	LWR experience and data	Minor mod
46	Filtration	High	Traditional passive charcoal/HEPA (Trans.)	High	Historical experience	Adequate; *knock along effect may limit effectiveness of filters for actinides if they are released from the fuel*
47	Production/combustion of flammable gas	Medium	CO, H_2 production issues, IHX secondary-primary leak, potential resuspension and chemical transformation of FPs. (Trans.).	High	Historical experience	Adequate
48	Combustion of dust in confinement	High	Source of heat and distribution of FPs w/in confinement	Medium; *Low*	ITER data	Major need
49	NGNP-unique leakage path beyond confinement	High	IHX to secondary site contamination, could be risk-dominant (Trans.)	High	Contingent on specific design knowledge	Minor mod
50	Confinement leakage path, release rate through penetrations	High	Cable/pipe penetrations, cracks, holes, HVAC (Trans.)	Medium	Building leakage experience, design specific	Adequate
51	Cable pyrolysis, fire	High	Soot generation and changes to iodine chemistry	Medium	LWR experience	Major need
52	Pressure-relief-valve filter	Low	Opening of the relief valve generates a transport path that may be filtered; depends on design	High	Air cleaning technology	Adequate

Table B-1 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
53	Recriticality (slow)	High	Additional thermal load to fuel. Increases source but not expected to affect transport path	Medium	Heat load easily computed with existing tools; effect on fission products not completely known	Minor mod
54	Fuel-damaging RIA	High	An intense pulse could damage fuel. Increases source but not expected to affect transport path	Medium	Some data exists, but outside of expected accident envelope	Minor mod
55	Argon activation in reactor cavity	High (normal operation)	Air in cavity activated by neutron leakage and can escape to environment	High	Easily computed with existing tools	Adequate
56	Redistribution of fission products due to control rod movement	Low	Articulated control rod joints can collect and redistribute fission products	Low	Specifics on CRD housing and articulated SiC composite housing TBD	Minor mod

Table B-2. Individual FPT PIRT Ranking Table
Final Version April 18, 2007
Panelist: David Petti

Changes in *ITALICS* are differences from the final group discussions on April 18, 2007

This table generally applies to all cases, normal, anticipated transients, and accidents. Specific cases are noted.

Notes:

** denotes need for interface with other groups (materials, transient scenarios)*
IC—initial condition, the result of long term normal operation
Trans.—transient and accident condition
TF—thermal fluids
FP—fission products

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
Critical initial and/or boundary condition						
1	Decay heat and transient power level	High	Energy source driving problem (IC and Trans.)	*High	Boundary conditions expected from TF PIRT	Adequate
2	Material/structure properties	High	Density, viscosity, conductivity, etc., important parameters in calculations (IC and Trans.)	*Med (graphite) High (steel, concrete)	Graphite type not selected; expected from material PIRT	Minor mod (graphite) Adequate (steel, concrete)
3	Graphite impurity levels	Medium	Impurity reaction with FP; nuclear graphite expected to have low impurity levels	*High	Will be measured; expected from material PIRT	Adequate
4	Graphite geometry	High	Core structure (design information)	High	Well known for IC	Adequate for IC Major need for air ingress

Table B-2 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
5	Thermal-fluid properties	High	Temperature, pressure, velocity computations (IC and Trans.)	*High*	Well known for He; uncertainty in composition of gas mixtures makes gas property calculation more difficult; expected from TF PIRT	Adequate
6	Gas composition	High	Oxygen potential and chemical activity	Medium	Central issue for chemical reaction modeling, FP speciation, scenario dependent	Adequate (depressurization) Major need (air ingress)
7	Gas flow path prior, during and post accident	High	Information needed to model accident (IC and Trans)	*Same as TF group	Need to coordinate w/other groups; expected from TF PIRT	Same as TF group
8	Temperature (structure and gas) and pressure distribution	High	Information needed to model accident (IC and Trans)	High	Need to coordinate w/ other groups, Expected from TF PIRT	Same as TF group
9	FP plate-out and dust distribution under normal operation	High	Starting conditions	Medium	Theory and models lack specifics; *modest understanding in Fort St. Vrain and AVR*	Major need
Graphite and core materials						
10	Matrix permeability, tortuosity	High	Needed for first principle transport modeling (IC and Trans)	*Low	FP holdup as barrier; release as dust; expected from material PIRT	Major need
11	FP transport through matrix	High	Effective release rate coefficient (empirical	Low	FP holdup as barrier, release as dust; *new*	Major need

Table B-2 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
			constant) as an alternative to first principles (IC and Trans)		*matrix material requires characterization* ~~Expected from material PIRT~~	
12	Fuel block permeability, tortuosity	High	Needed for first principle transport modeling (IC and Trans)	*Medium	Depends on specific graphite; expected from material PIRT	Major need
13	FP transport through fuel block	High	Effective release rate coefficient (empirical constant) as an alternative to first principles (IC and Trans)	*Low*	Depends on specific graphite; expected from material PIRT	Major need
14	Thermal (Soret) diffusion	Low	Thermal gradients are not large outside of fuel	Low	Little data	Not req'd
15	Basal plane diffusion	Low	Porosity is preferred transport pathway through graphite	Medium	Past work and literature available	Not req'd
16	Reflector (in contact w/flow) permeability, tortuosity	Low	Needed for first principle transport modeling (IC and Trans)	*Medium	Depends on specific graphite; expected from material PIRT	Minor mod
17	FP transport through reflector (in contact w/flow)	Low	Effective release rate coefficient (empirical constant) as an alternative to first principles (IC and Trans)	*Low*	Depends on specific graphite; expected from material PIRT	Minor mod
18	Sorbtivity graphite	High	Can determine holdup and release of FP (IC and Trans.)	Medium	Historical data, need specific information on graphite and radiation effects	Minor mod
19	Fluence effect on transport in graphite	High	Influences transport, chemical reactivity	Medium	Historical data, need specific information on graphite and radiation effects	Major need

Table B-2 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
20	C-14, Cl-36, Co-60 generation and inventory	Low	Radioisotope generated from impurities; might become operational issue (IC)	Medium	Historical data; Peach Bottom HTGR	Minor mod, sensitive to graphite handling
21	Air attack on graphite	High	Graphite erosion/oxidation; Fe/Cs catalysis liberating FPs (Trans)	Medium	Historical data	Major need for severe accidents
22	Steam attack on graphite	High	If credible source of water present; design dependent (Trans)	Medium	Historical data	Major need for severe accidents
			Fission product transport in reactor coolant system and confinement			
23	FP speciation in carbonatious material	High	Chemical form in graphite affects transport (IC and Trans.)	Low	Uncertain and/or incomplete	Major need
24	FP speciation during mass transfer	High	Chemical change can alter volatility	*Low*	Historical data, need specific information. Good for metals, oxides. Uncertain for carbides and carbonyls; *low concentrations expected may result in kinetic issues that make speciation more complex*	Major need
25	"Knock-along"	Low	Alpha recoil transport of deposited particles on surfaces slow compared to fluid flow transport. *Major FPs are not alpha emitters*	Medium	Studied in actinide-bearing particles	Adequate

Table B-2 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
26	Dust generation	High	Vector for FP transport, possibility of high mobility	Medium	Limited experience; lack specific system information	Major need, import from other groups
27	(De)Absorption on dust	High	Provides copious surface area for FP absorption	Medium	Limited experience; lack specific details	Major need
28	H-3 generation and circulating coolant inventory	Medium	Radioisotope, an issue with operational release. H-3 production from He-3 in coolant, ternary fission, and Li-6 in graphite	Medium	Historical data; Peach Bottom HTGR	Minor mod
29	Ag-110*m* generation, transport	High (O&M) Low (release)	Radioisotope, significant O&M dose on cool, metallic components	Low	Limited data; unknown transport mechanism	Major need
30	Other activation products (e.g., Cs-134, Mn-55, Fe-56)	Low	Radioisotopes, potential O&M dose	Medium	Experience; limited information	Minor mod
31	Nucleation	Medium	Unclear due to extremely low FP vapor concentration anticipated	Medium	Historical data	Major need
32	Aerosol growth	High	Low concentration growth can lead to high shape factors and unusual size distribution	Low	Regime has not been studied previously	Major need
33	Surface roughness	Medium	Affects aerosol deposition 1 to 5 micron particles (IC and Trans.)	Medium	Initial information from manufacturer; evolution of surface roughness during operation not well known	Minor mod
34	Coolant chemical interaction w/surfaces	High	Changes *local* oxygen and carbon potential which can affect nature and quantity of sorbed species (IC and Trans.)	Medium	Surface properties are critical, need alloy data	Major need

Table B-2 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
35	FP diffusivity, sorbtivity in nongraphite surfaces	High	Determines FP location during operation; acts as a trap during transient (IC and Trans.)	Low	Little information on materials of interest	Major need
36	Aerosol/dust deposition	High	Gravitational, inertial, thermophoresis, electrostatic, diffusional, turbophoresis (Trans.)	Medium	Reasonably well-developed theory of aerosol deposition by most mechanisms except inertial impact in complex geometries; applicability to NGNP unclear	Minor mod
37	Aerosol/dust bounce, breakup during deposition	Medium	Can modify deposition profile and suspended aerosol distribution	Low	Theory, data, and models lacking	Major need
38	Resuspension	High	Flow/vibration induced, saltation; mechanical forces can release FPs from pipe surface layers/films (Trans.)	Low	Lack of data and models for anticipated conditions	Major need
39	Confinement aerosol physics	High	Analogous to LWR aerosol behavior/physics, delta-T, chemistry; important holdup mechanism (Trans.)	Medium	Reasonably well-developed theory of aerosol behavior; applicability to NGNP unclear	Minor mod
40	Dust deposition on vessel and RCCS hardware	Low	Not important for FP transport but may affect radiative heat transfer in reactor cavity	Low	Very limited data	Major need
41	Corrosion products	Low	Spalled surface films; low corrosion environment (IC and Trans.)	High	Past experience	Adequate

Table B-2 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
42	Erosion products, noncarbon	Low	Low concentration of coarse materials (IC and Trans.)	Low	Lack of design information; configuration and materials specific	Adequate
43	Wash-off	High	If credible source of water present; design dependent (Trans.)	Medium	Some experimental data available	Minor mod
44	Failure modes of auxiliary systems (e.g., gas cleanup, holdup, refueling)	Medium	Potential release due to failure (Trans.)	Medium	Design specific; have experience from other designs	Minor mod
45	Radiolysis effects in confinement	High	FP (e.g., I, Ru, Te) chemistry, paint chemistry (dependent on confinement radiation level) (Trans.)	Medium	LWR experience and data	Minor mod
46	Filtration	High	Traditional passive charcoal/HEPA (Trans.)	High	Historical experience	Adequate
47	Production/combustion of flammable gas	Medium	CO, H_2 production issues, IHX secondary-primary leak, potential resuspension and chemical transformation of FPs (Trans.)	High	Historical experience	Adequate
48	Combustion of dust in confinement	High	Source of heat and distribution of FPs w/in confinement	Medium	ITER data	Major need
49	NGNP-unique leakage path beyond confinement	High	IHX to secondary site contamination; could be risk dominant (Trans.)	High	Contingent on specific design knowledge	Minor mod
50	Confinement leakage path, release rate through penetrations	High	Cable/pipe penetrations, cracks, holes, HVAC (Trans.)	Medium	Building leakage experience, design specific	Adequate

Table B-2 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
51	Cable pyrolysis, fire	High	Soot generation and changes to iodine chemistry	Medium	LWR experience	Major need
52	Pressure relief valve filter	Low	Opening of the relief valve generates a transport path that may be filtered; depends on design	High	Air cleaning technology	Adequate
53	Recriticality (slow)	High	Additional thermal load to fuel. Increases source but not expected to affect transport path	Medium	Heat load easily computed with existing tools; effect on fission products not completely known	Minor mod
54	Fuel-damaging RIA	High	An intense pulse could damage fuel. Increases source but not expected to affect transport path	Medium	Some data exists, but outside of expected accident envelope	Minor mod
55	Argon activation in reactor cavity	High (normal operation)	Air in cavity activated by neutron leakage and can escape to environment	High	Easily computed with existing tools	Adequate
56	Redistribution of fission products due to control rod movement	Low	Articulated control rod joints can collect and redistribute fission products	Low	Specifics on CRD housing and articulated SiC composite housing TBD	Minor mod

Table B-3. Individual FPT PIRT Ranking Table
Final Version April 18, 2007
Panelist: Robert Morris

Changes in *ITALICS* are differences from the final group discussions on April 18, 2007

This table generally applies to all cases, normal, anticipated transients, and accidents. Specific cases are noted.

Notes:

** denotes need for interface with other groups (materials, transient scenarios)*
IC—initial condition, the result of long term normal operation
Trans.—transient and accident condition
TF—thermal fluids
FP—fission product

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
Critical initial and/or boundary condition						
1	Decay heat and transient power level	High	Energy source driving problem (IC and Trans.)	*High	Boundary conditions expected from TF PIRT	Adequate
2	Material/structure properties	High	Density, viscosity, conductivity, etc., important parameters in calculations (IC and Trans.)	*Med (graphite) High (steel, concrete)	Graphite type not selected, expected from material PIRT	Minor mod (graphite) Adequate (steel, concrete)
3	Graphite impurity levels	Medium	Impurity reaction with FP; nuclear graphite expected to have low impurity levels	*High	Will be measured; expected from material PIRT	Adequate
4	Graphite geometry	High	Core structure (design information)	High	Well known for IC	Adequate for IC Major need for air ingress

Table B-3 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
5	Thermal-fluid properties	High	Temperature, pressure, velocity computations (IC and Trans.)	*Medium	Well known for He, uncertainty in composition of gas mixtures makes gas property calculation more difficult, expected from TF PIRT	Adequate
6	Gas composition	High	Oxygen potential and chemical activity	Medium	Central issue for chemical reaction modeling, FP speciation, scenario dependent	Adequate (depressurization) Major need (air ingress)
7	Gas flow path prior, during, and post accident	High	Information needed to model accident (IC and Trans)	*Same as TF group	Need to coordinate w/ other groups; expected from TF PIRT	Same as TF group
8	Temperature (structure and gas) and pressure distribution	High	Information needed to model accident (IC and Trans)	High	Need to coordinate w/ other groups; expected from TF PIRT	Same as TF group
9	FP plate-out and dust distribution under normal operation	High	Starting conditions	Medium	Theory and models lack specifics	Major need
			Graphite and core materials			
10	Matrix permeability, tortuosity	High	Needed for first principle transport modeling (IC and Trans)	*Low	FP holdup as barrier; release as dust; expected from material PIRT	Major need
11	FP transport through matrix	High	Effective release rate coefficient (empirical constant) as an alternative to first principles (IC and Trans)	Low	FP holdup as barrier; release as dust; expected from material PIRT	Major need

Table B-3 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
12	Fuel block permeability, tortuosity	High	Needed for first principle transport modeling (IC and Trans)	*Medium	Depends on specific graphite; expected from material PIRT	Major need
13	FP transport through fuel block	High	Effective release rate coefficient (empirical constant) as an alternative to first principles (IC and Trans)	*Medium	Depends on specific graphite; expected from material PIRT	Major need
14	Thermal (Soret) diffusion	Low	Thermal gradients are not large outside of fuel	Low	Little data	Not req'd
15	Basal plane diffusion	Low	Porosity is preferred transport pathway through graphite	Medium	Past work and literature available	Not req'd
16	Reflector (in contact w/flow) permeability, tortuosity	Low	Needed for first principle transport modeling (IC and Trans)	*Medium	Depends on specific graphite; expected from material PIRT	Minor mod
17	FP transport through reflector (in contact w/flow)	Low	Effective release rate coefficient (empirical constant) as an alternative to first principles (IC and Trans)	*Medium	Depends on specific graphite; expected from material PIRT	Minor mod
18	Sorbtivity graphite	High	Can determine holdup and release of FP (IC and Trans.)	Medium	Historical data; need specific information on graphite and radiation effects	Minor mod
19	Fluence effect on transport in graphite	High	Influences transport, chemical reactivity	Medium	Historical data; need specific information on graphite and radiation effects	Major need
20	C-14, Cl-36, Co-60 generation and inventory	Low	Radioisotope generated from impurities; might become operational issue (IC)	Medium	Historical data; Peach Bottom HTGR	Minor mod, sensitive to graphite handling

Table B-3 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
21	Air attack on graphite	High	Graphite erosion/oxidation; Fe/Cs catalysis liberating FPs (Trans)	Medium	Historical data	Major need for severe accidents
22	Steam attack on graphite	High	If credible source of water present; design dependent (Trans)	Medium	Historical data	Major need for severe accidents
			Fission product transport in reactor coolant system and confinement			
23	FP speciation in carbonatious material	High	Chemical form in graphite affects transport (IC and Trans.)	Low	Uncertain and/or incomplete	Major need
24	FP speciation during mass transfer	High	Chemical change can alter volatility	Medium	Historical data; need specific information; good for metals, oxides; uncertain for carbides and carbonyls	Major need
25	"Knock-along"	Low	Alpha recoil transport of deposited particles on surfaces slow compared to fluid flow transport	Medium	Studied in actinide-bearing particles	Adequate
26	Dust generation	High	Vector for FP transport, possibility of high mobility.	Medium	Limited experience; lack specific system information	Major need, import from other groups
27	(De)Absorption on dust	High	Provides copious surface area for FP absorption	Medium	Limited experience; lack specific details	Major need
28	H-3 generation and circulating coolant inventory	Medium	Radioisotope, an issue with operational release. H-3 production from He-3 in coolant, ternary fission, and Li-6 in graphite	Medium	Historical data, Peach Bottom HTGR	Minor mod
29	Ag-110*m* generation, transport	High (O&M) Low (release)	Radioisotope, significant O&M dose on cool, metallic components	Low	Limited data, unknown transport mechanism	Major need

Table B-3 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
30	Other activation products (e.g., Cs-134, Mn-55, Fe-56)	Low	Radioisotopes, potential O&M dose	Medium	Experience, limited information	Minor mod
31	Nucleation	Medium	Unclear due to extremely low FP vapor concentration anticipated	Medium	Historical data	Major need
32	Aerosol growth	High	Low concentration growth can lead to high shape factors and unusual size distribution	Low	Regime has not been studied previously	Major need
33	Surface roughness	Medium	Affects aerosol deposition 1 to 5 micron particles (IC and Trans.)	Medium	Initial information from manufacturer; evolution of surface roughness during operation not well known	Minor mod
34	Coolant chemical interaction w/surfaces	High	Changes oxygen and carbon potential, which can affect nature and quantity of sorbed species (IC and Trans.)	Medium	Surface properties are critical; need alloy data	Major need
35	FP diffusivity, sorbtivity in nongraphite surfaces	High	Determines FP location during operation; acts as a trap during transient (IC and Trans.)	Low	Little information on materials of interest	Major need
36	Aerosol/dust deposition	High	Gravitational, inertial, thermophoresis, electrostatic, diffusional, turbophoresis (Trans.)	Medium	Reasonably well-developed theory of aerosol deposition by most mechanisms except inertial impact in complex geometries; applicability to NGNP unclear	Minor mod

Table B-3 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
37	Aerosol/dust bounce, breakup during deposition	Medium	Can modify deposition profile and suspended aerosol distribution	Low	Theory, data, and models lacking	Major need
38	Resuspension	High	Flow/vibration induced, saltation; mechanical forces can release FPs from pipe surface layers/films (Trans.)	Low	Lack of data and models for anticipated conditions	Major need
39	Confinement aerosol physics	High	Analogous to LWR aerosol behavior/physics, delta-T, chemistry; important holdup mechanism (Trans.)	Medium	Reasonably well-developed theory of aerosol behavior; applicability to NGNP unclear	Minor mod
40	Dust deposition on vessel and RCCS hardware	Low	Not important for FP transport but may affect radiative heat transfer in reactor cavity	Low	Very limited data	Major need
41	Corrosion products	Low	Spalled surface films; low corrosion environment (IC and Trans.)	High	Past experience	Adequate
42	Erosion products, noncarbon	Low	Low concentration of coarse materials (IC and Trans.)	Low	Lack of design information; configuration and materials specific	Adequate
43	Wash-off	High	If credible source of water present; design dependent (Trans.)	Medium	Some experimental data available	Minor mod
44	Failure modes of auxiliary systems (e.g., gas cleanup, holdup, refueling)	Medium	Potential release due to failure (Trans.)	Medium	Design specific; have experience from other designs	Minor mod

Table B-3 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
45	Radiolysis effects in confinement	High	FP (e.g., I, Ru, Te) chemistry, paint chemistry (dependent on confinement radiation level) (Trans.)	Medium	LWR experience and data	Minor mod
46	Filtration	High	Traditional passive charcoal/HEPA (Trans.)	High	Historical experience	Adequate
47	Production/combustion of flammable gas	Medium	CO, H_2 production issues, IHX secondary-primary leak, potential resuspension and chemical transformation of FPs. (Trans.)	High	Historical experience	Adequate
48	Combustion of dust in confinement	High	Source of heat and distribution of FPs w/in confinement	Medium	ITER data	Major need
49	NGNP-unique leakage path beyond confinement	High	IHX to secondary site contamination, could be risk-dominant (Trans.)	High	Contingent on specific design knowledge	Minor mod
50	Confinement leakage path, release rate through penetrations	High	Cable/pipe penetrations, cracks, holes, HVAC (Trans.)	Medium	Building leakage experience, design specific	Adequate
51	Cable pyrolysis, fire	High	Soot generation and changes to iodine chemistry	Medium	LWR experience	Major need
52	Pressure-relief-valve filter	Low	Opening of the relief valve generates a transport path that may be filtered; depends on design	High	Air cleaning technology	Adequate

Table B-3 (continued)

ID No.	Issue (phenomena, *process, geometry* condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
53	Recriticality (slow)	High	Additional thermal load to fuel; increases source but not expected to affect transport path	Medium	Heat load easily computed with existing tools; effect on fission products not completely known	Minor mod
54	Fuel-damaging RIA	High	An intense pulse could damage fuel; increases source but not expected to affect transport path	Medium	Some data exists, but outside of expected accident envelope	Minor mod
55	Argon activation in reactor cavity	High (normal operation)	Air in cavity activated by neutron leakage and can escape to environment	High	Easily computed with existing tools	Adequate
56	Redistribution of fission products due to control rod movement	Low	Articulated control rod joints can collect and redistribute fission products	Low	Specifics on CRD housing and articulated SiC composite housing TBD	Minor mod

Table B-4. Individual FPT PIRT Ranking Table
Final Version April 18, 2007
Panelist: Martin Kissane

Changes in *ITALICS* are differences from the final group discussions on April 18, 2007

This table generally applies to all cases, normal, anticipated transients, and accidents. Specific cases are noted.

Notes:

** denotes need for interface with other groups (materials, transient scenarios)*
IC—initial condition, the result of long term normal operation
Trans.—transient and accident condition
TF—thermal fluids
FP—fission product

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
			Critical initial and/or boundary condition			
1	Decay heat and transient power level	High	Energy source driving problem (IC and Trans.)	*High	Boundary conditions expected from TF PIRT	Adequate
2	Material/structure properties	High	Density, viscosity, conductivity, etc., important parameters in calculations (IC and Trans.)	*Med (graphite) High (steel, concrete)	Graphite type not selected, expected from material PIRT	Minor mod (graphite) Adequate (steel, concrete)
3	Graphite impurity levels	*High*	Impurity reaction with FP; nuclear graphite expected to have low impurity levels	*High	Will be measured, expected from material PIRT	Adequate
4	Graphite geometry	High	Core structure (design information)	High	Well known for IC	Adequate for IC. Major need for air ingress

Table B-4 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
5	Thermal-fluid properties	High	Temperature, pressure, velocity computations (IC and Trans.)	*Medium	Well known for helium; uncertainty in composition of gas mixtures makes gas property calculation more difficult, expected from TF PIRT	Adequate
6	Gas composition	High	Oxygen potential and chemical activity	Medium	Central issue for chemical reaction modeling, FP speciation, scenario dependent	Adequate (depressurization) Major need (air ingress)
7	Gas flow path prior, during, and post accident	High	Information needed to model accident (IC and Trans)	*Same as TF group	Need to coordinate w/ other groups; expected from TF PIRT	Same as TF group
8	Temperature (structure and gas) and pressure distribution	High	Information needed to model accident (IC and Trans)	High	Need to coordinate w/ other groups; expected from TF PIRT	Same as TF group
9	FP Plate-out and dust distribution under normal operation	High	Starting conditions	Medium	Theory and models lack specifics	Major need
	Graphite and core materials					
10	Matrix permeability, tortuosity	High	Needed for first principle transport modeling (IC and Trans)	*Low	FP holdup as barrier, release as dust; expected from material PIRT	Major need
11	FP transport through matrix	High	Effective release rate coefficient (empirical constant) as an alternative to first principles (IC and Trans)	Low	FP holdup as barrier, release as dust; expected from material PIRT	Major need

Table B-4 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
12	Fuel block permeability, tortuosity	High	Needed for first principle transport modeling (IC and Trans)	*Medium	Depends on specific graphite; expected from material PIRT	Major need
13	FP transport through fuel block	High	Effective release rate coefficient (empirical constant) as an alternative to first principles (IC and Trans)	*Medium	Depends on specific graphite; expected from material PIRT	Major need
14	Thermal (Soret) diffusion	Low	Thermal gradients are not large outside of fuel	Low	Little data	Not req'd
15	Basal plane diffusion	Low	Porosity is preferred transport pathway through graphite	Medium	Past work and literature available	Not req'd
16	Reflector (in contact w/flow) permeability, tortuosity	Low	Needed for first principle transport modeling (IC and Trans)	*Medium	Depends on specific graphite; expected from material PIRT	Minor mod
17	FP transport through reflector (in contact w/flow)	Low	Effective release rate coefficient (empirical constant) as an alternative to first principles (IC and Trans)	*Medium	Depends on specific graphite; expected from material PIRT	Minor mod
18	Sorbtivity graphite	High	Can determine holdup and release of FP (IC and Trans.)	Medium	Historical data; need specific information on graphite and radiation effects	Minor Mod
19	Fluence effect on transport in graphite	High	Influences transport, chemical reactivity	Medium	Historical data; need specific information on graphite and radiation effects	Major need
20	C-14, Cl-36, Co-60 generation and inventory	Low	Radioisotope generated from impurities, might become operational issue (IC)	Medium	Historical data; Peach Bottom HTGR	Minor mod, sensitive to graphite handling

Table B-4 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
21	Air attack on graphite	High	Graphite erosion/oxidation; Fe/Cs catalysis liberating FPs (Trans)	Medium	Historical data	Major need for severe accidents
22	Steam attack on graphite	High	If credible source of water present; design dependent (Trans)	Medium	Historical data	Major need for severe accidents
			Fission product transport in reactor coolant system and confinement			
23	FP speciation in carbonaceous material	High	Chemical form in graphite affects transport (IC and Trans.)	Low	Uncertain and/or incomplete; *specific impurity effects need to be determined*	Major need
24	FP speciation during mass transfer	High	Chemical change can alter volatility	Medium	Historical data, need specific information. Good for metals, oxides. Uncertain for carbides and carbonyls	Major need
25	"Knock-along"	Low	Alpha recoil transport of deposited particles on surfaces; slow compared to fluid flow transport	Medium	Studied in actinide-bearing particles	Adequate
26	Dust generation	High	Vector for FP transport; possibility of high mobility	Medium	Limited experience; lack specific system information	Major need; import from other groups
27	(De)Absorption on dust	High	Provides copious surface area for FP absorption	*Low*	Limited experience; lack specific details	Major need
28	H-3 generation and circulating coolant inventory	Medium	Radioisotope, an issue with operational release. H-3 production from He-3 in coolant, ternary fission, and Li-6 in graphite	Medium	Historical data; Peach Bottom HTGR	Minor mod
29	Ag-110*m* generation, transport	High (O&M) Low (release)	Radioisotope; significant O&M dose on cool; metallic components	Low	Limited data; unknown transport mechanism	Major need

Table B-4 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
30	Other activation products (e.g., Cs-134, Mn-55, Fe-56)	Low	Radioisotopes; potential O&M dose	Medium	Experience; limited information	Minor mod
31	Nucleation	Medium	Unclear due to extremely low FP vapor concentration anticipated	Medium	Historical data	Major need
32	Aerosol growth	*Medium*	Low concentration growth can lead to high shape factors and unusual size distribution; *basic dust characteristics (known) will have a major influence*	Low	Regime has not been studied previously	Major need
33	Surface roughness	Medium	Affects aerosol deposition 1-5 micron particles (IC and Trans.)	Medium	Initial information from manufacturer; evolution of surface roughness during operation not well known	Minor mod
34	Coolant chemical interaction w/ surfaces	High	Changes oxygen and carbon potential which can affect nature and quantity of sorbed species (IC and Trans.)	Medium	Surface properties are critical, need alloy data	Major need
35	FP diffusivity; sorbtivity in nongraphite surfaces	High	Determines FP location during operation; acts as a trap during transient (IC and Trans.)	Low	Little information on materials of interest	Major need
36	Aerosol/dust deposition	High	Gravitational, inertial, thermophoresis, electrostatic, diffusional, turbophoresis (Trans.)	Medium	Reasonably well-developed theory of aerosol deposition by most mechanisms except inertial impact in complex geometries; applicability to NGNP unclear	Minor mod; *major need with respect to components such as turbine and IHX*

Table B-4 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
37	Aerosol/dust bounce, breakup during deposition	Medium	Can modify deposition profile and suspended aerosol distribution	Low	Theory, data, and models lacking	Major need
38	Resuspension	High	Flow/vibration induced, saltation; mechanical forces can release FPs from pipe surface layers/films (Trans.)	Low	Lack of data and models for anticipated conditions	Major need
39	Confinement aerosol physics	High	Analogous to LWR aerosol behavior/physics, delta-T, chemistry; important holdup mechanism (Trans.)	Medium	Reasonably well-developed theory of aerosol behavior; applicability to NGNP unclear	Minor mod
40	Dust deposition on vessel and RCCS hardware	Low	Not important for FP transport; but may affect radiative heat transfer in reactor cavity	Low	Very limited data	Major need
41	Corrosion products	Low	Spalled surface films; low corrosion environment (IC and Trans.)	High	Past experience	Adequate
42	Erosion products, noncarbon	Low	Low concentration of coarse materials (IC and Trans.)	Low	Lack of design information; configuration and materials specific	Adequate
43	Wash-off	High	If credible source of water present; design dependent (Trans.)	Medium	Some experimental data available	Minor mod
44	Failure modes of auxiliary systems (e.g., gas cleanup, holdup, refueling)	Medium	Potential release due to failure (Trans.)	Medium	Design specific; have experience from other designs	Minor mod

Table B-4 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
45	Radiolysis effects in confinement	High	FP (e.g., I, Ru, Te) chemistry, paint chemistry (dependent on confinement radiation level) (Trans.)	Medium	LWR experience and data	Minor mod
46	Filtration	High	Traditional passive charcoal/HEPA (Trans.)	High	Historical experience	Adequate
47	Production/combusti on of flammable gas	Medium	CO, H_2 production issues, IHX secondary-primary leak, potential resuspension and chemical transformation of FPs (Trans.)	High	Historical experience	Adequate
48	Combustion of dust in confinement	High	Source of heat and distribution of FPs w/in confinement	Medium	ITER data	Major need
49	NGNP-unique leakage path beyond confinement	High	IHX to secondary site contamination; could be risk dominant (Trans.)	High	Contingent on specific design knowledge	Minor mod
50	Confinement leakage path; release rate through penetrations	High	Cable/pipe penetrations, cracks, holes, HVAC (Trans.)	Medium	Building leakage experience, design specific	Adequate
51	Cable pyrolysis, fire	High	Soot generation and changes to iodine chemistry	Medium	LWR experience	Major need
52	Pressure relief-valve-filter	Low	Opening of the relief valve generates a transport path that may be filtered; depends on design.	High	Air cleaning technology	Adequate
53	Recriticality (slow)	High	Additional thermal load to fuel; increases source but not expected to affect transport path	Medium	Heat load easily computed with existing tools; effect on fission products not completely known	Minor mod

Table B-4 (continued)

ID No.	Issue (phenomena, process, geometry condition)	Importance for NGNP (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
54	Fuel-damaging RIA	High	An intense pulse could damage fuel; increases source but not expected to affect transport path	Medium	Some data exists but outside of expected accident envelope	Minor mod
55	Argon activation in reactor cavity	High (normal operation)	Air in cavity activated by neutron leakage and can escape to environment	High	Easily computed with existing tools	Adequate
56	Redistribution of fission products due to control rod movement	Low	Articulated control rod joints can collect and redistribute fission products	Low	Specifics on CRD housing and articulated SiC composite housing TBD	Minor mod

Table B-5. Individual PIRT Ranking Table
Panelist: Robert Wichner
April 23, 2007

OUTLINE

Part A: General issues affecting FP transport

Issues:
- Input from other PIRT areas
- Production of activation products
- Material properties

ID No.	Phenomena	Importance (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
1	~~Decay heat & transient power level~~ *Not direct input to FP transport; subsumed in item-8*	~~High~~	~~Energy source driving problem (IC and Trans.)~~	~~*High~~	~~Boundary conditions expected from TF PIRT~~	~~Adequate~~
2	~~Material/structure properties~~ *Too general. Specific properties cited in Parts B, D and G.*	~~High~~	~~Density, viscosity, conductivity, etc., important parameters in calculations (IC and Trans.)~~	~~*Med (graphite) High (steel, concrete)~~	~~Graphite type not selected, expected from material PIRT~~	~~Minor Mod (graphite) Adequate (steel, concrete)~~
4	~~Graphite geometry~~ *Too general, and basic*	~~High~~	~~Core structure (design information)~~	~~High~~	~~Well known for IC~~	~~Adequate for IC Major Need for air ingress~~
5	~~Thermal-fluid properties,~~ *Transferred to item 6, Part D, and item 125, Part H.1*	~~High~~	~~Temperature, pressure, velocity computations (IC and Trans.)~~	~~*Medium~~	~~Well known for He. Uncertainty in composition of gas mixtures makes gas property calculation more difficult, expected from TF PIRT~~	~~Adequate~~
8	Temperature (structure and gas) and pressure distribution	High	Information needed to model accident (IC and Trans)	High	Need to coordinate w/ other groups; expected from TF PIRT	Same as TF group
20	C-14, Cl-36, Co-60	~~Low~~ *Medium*	Radioisotope generated from impurities, might become operational issue. *C-14 may become a public issue*	Medium	Historical data; Peach Bottom HTGR	Minor mod, sensitive to graphite handling

Part A (continued)

ID No.	Phenomena	Importance (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
29	Ag-110*m* generation, transport, *and inventory distribution*	High (O&M) Low (release)	Radioisotope; significant O&M dose on cool; metallic components	Low	Limited data, unknown transport mechanism	Major need
30	Other activation products (e.g. Cs-134, Mn-55, Fe-56)	Low	Radioisotopes; potential O&M dose	Medium	Experience, limited information	Minor mod
33	Surface roughness	Medium	Affects aerosol deposition 1 to 5 micron particles (IC and Trans.)	Medium	Initial information from manufacturer; evolution of surface roughness during operation not well known	Minor mod
53	Recriticality (slow)	High	Additional thermal load to fuel. Increases source but not expected to affect transport path.	Medium	Heat load easily computed with existing tools; effect on fission products not completely known	Minor mod
54	Fuel-damaging RIA	High	An intense pulse could damage fuel. Increases source but not expected to affect transport path.	Medium	Some data exists, but outside of expected accident envelope	Minor mod
100	*Cs-134, Cs-136 production*	*Medium*	*Affects maintenance dose*	*High*	*Production method known*	*Minor Mod*
101	*H-3, production from all sources, inventory distribution*	*High*	*Can diffuse across IHX boundary.*	*Medium*	*Data on earlier materials available*	*Minor mod*

Part B: Transport holdup in carbon matrix and graphite

[Terminology: PBMR carbon is termed "matrix" in both the fuelled and unfueled zones.
Prismatic fuel "matrix" refers to the compact; graphite to the block.]

Issues:
- FP transport rates
- FP Inventory in matrix/graphite
- FP Behavior during accidents

ID No.	Phenomena	Importance (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
3	Graphite impurity levels	Medium	Impurity reaction with FP, nuclear graphite expected to have low impurity levels	*High	Will be measured; expected from material PIRT	Adequate
10	Matrix permeability, ~~tortuosity~~ *Tortuosity is a derived quantity, not directly usable*	~~High~~ *Medium*	~~Needed for first principle transport modeling (IC and Trans)~~ *Needed to determine permeation flow due to CP across matrix; some FPs may be so transported*	~~Low~~ *Medium*	FP holdup as barrier; release as dust; expected from material PIRT	Major need
11	FP transport through matrix	High	~~Effective release rate coefficient (empirical constant) as an alternative to first principles (IC and Trans)~~ *Required to assess FP holdup and transport in matrix*	Low	FP holdup as barrier, ~~release as dust, Expected from material PIRT.~~ *One or two constant empirical model needs to be developed. Radiation effect may be significant.*	Major need

Part B (continued)

ID No.	Phenomena	Importance (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
12	Fuel block permeability, ~~tortuosity~~ *Tortuosity is a derived quantity, not directly usable*	~~High~~ *Medium*	~~Needed for first principle transport modeling (IC and Trans)~~ *Needed for determining permeation flow due to a ΔP across graphite web; some FPs may be so transported*	*Medium	Depends on specific graphite; expected from material PIRT	~~Major need~~ *Minor mod; permeation for a given ΔP is predictable from a well-known correlation.*
13	FP transport through fuel block	High	~~Effective release rate coefficient (empirical constant) as an alternative to first principles (IC and Trans)~~ *Required to assess FP holdup and transport in graphite; significant transport factor*	*Medium	Depends on specific graphite; ~~Expected from material PIRT~~ *affected by radiation level and fluence; depends on FP species in graphite; requires test data, some of which is available*	Major need
14	Thermal (Soret) diffusion	Low	Thermal gradients are not large outside of fuel	Low	Little data	Not req'd
15	Basal plane diffusion	Low	Porosity is preferred transport pathway through graphite	Medium	Past work and literature available	Not req'd
16	Reflector (in contact w/flow) permeability; ~~tortuosity~~ *tortuosity is not directly usable*	Low	~~Needed for first principle transport modeling (IC and Trans).~~ *Required to determine permeation flow due to an applied ΔP*	*Medium	Depends on specific graphite; expected from material PIRT	Minor mod
17	FP transport through reflector (in contact w/flow)	Low	Effective release rate coefficient (empirical constant) as an alternative to first principles (IC and Trans)	*Medium	Depends on specific graphite; expected from material PIRT	Minor mod

Part B (continued)

ID No.	Phenomena	Importance (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
18	Sorbtivity of graphite (*i.e., chemisorption of FPs in matrix and graphite*)	High	Can ~~determine~~ *affect* holdup and release of FP (IC and Trans.)	Medium	Historical data; need specific information on graphite and radiation effects	Minor mod
19	Fluence effect on transport in graphite	High	Influences transport; chemical reactivity	Medium	Historical data; need specific information on graphite and radiation effects	Major need
23	FP speciation in ~~carbonaceous *material*~~ *in matrix and graphite*	High	Chemical form in graphite affects transport	Low	Uncertain and/or incomplete	Major need
26	Dust generation in matrix and graphite by abrasion and other mechanisms	High	Destination for FP via sorption	Medium	Some data for pebble fuels; less for prismatic	Minor mod
102	*Internal surface area of matrix and graphite*	*Medium*	*Parameter affects interpretation of transport rate*	*Medium*	*Will be specified and/or measured*	*Minor mod*
103	*Inventory of FPs in matrix and graphite*	*High*	*Initial condition for accident assessment.*	*Medium*	*May be estimated from production, transport and sorption data*	*Minor mod*
104	*Impurity levels in matrix and graphite*	*Low*	*Affects sorption and oxidation rates*	*Medium*	*To be given by tech specs*	*Adequate*
105	*Chemical and physical interaction of FPs with graphite*	*Medium*	*Aids understanding of transport*	*Low*	*Known for some FPs; not known for many*	*Minor mod*

Part C: Emission from fuel element surface

Issues:
- Volatility of FP species on graphite/matrix surface
- Mass transfer rate

ID No.	Phenomena	Importance (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
24	FP speciation during mass transfer	High	Chemical change can alter volatility	Medium	Historical data; need specific information; good for metals, oxides; uncertain for carbides and carbonyls	Major need
25	"Knock-along"	Low	Alpha recoil transport of deposited particles on surfaces; slow compared to fluid flow transport	Medium	Studied in actinide-bearing particles	Adequate
106	*Volatility of FPs on graphite and matrix surfaces*	*High*	*Key factor in mass transport*	*Low*	*FP species usually not well-known*	*Minor mod*
107	*FP removal with dust*	*Medium*	*Unevaluated transport step*	*Low*	*No known data*	*Minor mod*
108	*Mass transfer rate from matrix and graphite to coolant*	*High*	*Defines graphite to coolant transfer rate*	*Medium*	*May be estimated, if FP species are known*	*Minor mod*

Part D: FP transport in the coolant, normal operation

Issues:
- FP speciation in coolant
- Oxygen potential
- FP association with dust
- Nucleation of low volatile FPs

ID No.	Phenomena	Importance (High, Medium, Low)	Rationale	Level of knowledge (High, Med, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
6	Gas composition during normal operation	High	Oxygen potential and chemical activity. *There is also a need to know the He-3 level for assessing H-3 production in the coolant.*	Medium Low	Central issue for chemical reaction modeling; FP speciation; ~~scenario dependent,~~ not known for normal operation	Adequate (depressurization) Major need (air ingress)
27	(De)~~Absorption~~ on dust *Adsorption*	High	Provides copious surface area for FP ~~absorption~~ *adsorption*	~~Medium~~ *Low*	Limited experience; lack specific details; *little or no data*	Major need
28	H-3 generation *in the coolant* and circulating coolant inventory	~~Medium~~ *High*	*Critical issue for process heat versions*; radioisotope, an issue with operational release; H-3 production from He-3 in coolant; *(also* ternary fission, and Li-6 in graphite*)*	Medium	Historical data; Peach Bottom HTGR; *may be determined from neutron flux and He-3 level*	Minor mod
31	Nucleation	Medium	~~Unclear due to extremely low FP vapor concentration anticipated.~~ *An important factor in deposition and liftoff*	Medium	~~Historical data~~ *Unclear due to extremely low FP vapor concentration*	Major need
32	Aerosol growth	High	Low concentration growth can lead to high shape factors and unusual size distribution	Low	Regime has not been studied previously	Major need
55	Argon activation in reactor cavity	High (normal operation)	Air in cavity activated by neutron leakage and can escape to environment	High	Easily computed with existing tools	Adequate

Part D (continued)

ID No.	Phenomena	Importance (High, Medium, Low)	Rationale	Level of knowledge (High, Med, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
110	*FP speciation in the coolant*	*High*	*Affects deposition and sorption*	*Medium*	*Can be approximated if conditions are specified*	*Minor mod*
111	*Ag-110m and Cs-137 transport in the coolant*	*High*	*Important special cases of item 110*	*Low*	*Depends on coolant environment*	*Major need*
120	*FP inventory in the coolant cleanup system*	*Medium*	*Should be evaluated for possible involvement in accident releases*	*Low*	*Not yet analyzed*	*Minor mod*

Part E: Deposition sorption on primary system surfaces—normal operation

Issues:
- Aerosol and dust deposition
- Chemisorption on metallic surfaces
- Chemical reaction with surfaces

ID No.	Phenomena	Importance (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
9	~~FP plate-out and~~ dust distribution under normal operation. *FP plate-out is an ambiguous term that can apply to either chemical adsorption or dust deposition; it should be avoided*	High	Initial condition for accident	~~Medium~~ *Low*	Theory and models lack specifics; *enormous error bands in dust deposition data; disagreements in predictive models*	Major need
34	Coolant chemical interaction w/ surfaces	High	~~Changes oxygen and carbon potential which can affect nature and quantity of sorbed species (IC and Trans.)~~ *Affects deposition and liftoff predictions; affects decontamination methods*	Medium	Surface properties are critical; need alloy data; *interactions depend on coolant oxygen potential, and coolant impurities*	Major Need
35	FP ~~diffusivity,~~ sorbtivity in nongraphite surfaces; *chemical sorptivity should be emphasized*	High	~~Determines~~ *Affects* FP location during operation; acts as a trap during transient (IC and Trans.)	Low	Little information on materials of interest; *affects of radiation on sorptivity are significant and insufficiently known*	Major Need
36	Aerosol/dust deposition *(Closely related to item 9)*	High	~~Gravitational,~~ inertial, thermophoresis, electrostatic, diffusional, turbophoresis (Trans.)	Medium	~~Reasonably well-developed theory of aerosol deposition by most mechanisms except inertial impact~~	Minor mod

Part E (continued)

ID No.	Phenomena	Importance (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
			No gravitational settling in the primary system; turbophoresis is a new one on me		~~in complex geometries;~~ *Enormous error bands for primary loop conditions; "reasonably well-developed" may refer to confinement* Applicability to NGNP unclear	
37	~~Aerosol/dust bounce, breakup during deposition~~ *Details subsumed in deposition correlation.*	~~Medium~~	~~Can modify deposition profile and suspended aerosol distribution~~	~~Low~~	~~Theory, data, and models lacking~~	~~Major Need~~
40	Dust deposition on vessel and RCCS hardware	Low	Not important for FP transport but may affect radiative heat transfer in reactor cavity	Low	Very limited data	Major need
41	Corrosion products	Low	Spalled surface films; low corrosion environment (IC and Trans.)	High	Past experience	Adequate
42	Erosion products, noncarbon	Low	Low concentration of coarse materials (IC and Trans.)	Low	Lack of design information; configuration and materials specific	Adequate
113	*Sorption and dust deposition on turbine surfaces*	*High*	*Important special case; affects turbine life and maintenance procedures; special case of deposition and sorption*	*Low*	*Extreme conditions; beyond usual correlations*	*Major need*

Part F: Releases from the primary system—normal operation

Issues:
- Release modes (leakage, refueling)
- Diffusion into the IHX

ID No.	Phenomena	Importance (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
115	*Diffusion of H-3 through the IHX*	*High*	*Important for process heat concepts*	*Medium*	*Some data on other metals; need to improve error band*	*Minor mod*
116	*Product contamination, other than H-3*	*High*	*Important for process heat concepts*	*Medium*	*Unexplored area; effect of small leaks in the IHX*	*Minor mod*
117	*Contamination of the He coolant by the secondary fluid*	*High*	*Possible effect on the reactor; investment question*	*Medium*	*Unexplored area; effect of small leaks in the IHX*	*Minor mod*
118	*He (containing FPs) leakage into the secondary system*	*Medium*	*Does not appear to be a serious issue*	*Medium*	*Unexplored area*	*Minor mod*
119	*He (containing FPs) leakage into the confinement*	*Medium*	*Leakage modes under normal operation should be identified*	*Medium*	*Unexplored area (?)*	*Minor mod*

Part G: Factors affecting releases from the primary system—accident conditions

G.1 General issues and power version
G.2 Process heat version

Issues:
- Releases due to D-LOFC
- Releases due to P-LOFC with venting

Part G.1—General issues and power conversion

ID No.	Phenomena	Importance (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
7	Gas flow path prior, during and post accident (also applies to Part F)	High	Information needed to model accident (IC and Trans)	*Same as TF group	Need to coordinate w/ other groups; expected from TF PIRT	Same as TF group
21	Air attack on graphite *and its affect on FP release*	High	Graphite erosion/ oxidation; Fe/Cs catalysis liberating FPs (Trans)	~~Medium~~ *Low*	~~Historical data~~ *There are no data on the effect of air oxidation on retention of FPs in graphite*	Major need for severe accidents
22	Steam attack on graphite *and its affect on FP release*	High	Graphite erosion and oxidation; Fe/Cs catalysis liberating FPs (trans)	~~Medium~~ *Low*	~~Historical data~~ *There are no data on the effect of air oxidation on retention of FPs in graphite*	Major need for severe accidents
43	Washoff	High	If credible source of water is present; design dependent	Medium	Some experimental data available	Minor mod
44	Failure modes of auxiliary systems (e.g., gas cleanup, holdup, refueling) *and FP release from the gas cleanup system*	Medium High	Potential release due to failure; possible direct path to the atmosphere from gas cleanup system failure (Trans.)	Medium	Design specific; have experience from other designs but no experience for gas cleanup system failure	Minor mod

Part G (continued)

ID No.	Phenomena	Importance (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
52	Pressure relief valve filter	Low	Opening of the relief valve generates a transport path that may be filtered; depends on design	High	Air cleaning technology	Adequate
47	Production/combustion of flammable gas	Medium High	CO, H_2 production issues; IHX secondary-primary leak; potential resuspension and chemical transformation of FPs. (Trans.) during air ingress event	High Medium	Historical experience; inadequate data on CO, H_2, CO_2 production during air ingress	Adequate
56	Redistribution of fission products due to control rod movement	Low	Articulated control rod joints can collect and redistribute fission products	Low	Specifics on CRD housing and articulated SiC composite housing TBD	Minor mod
112	*Chemical desorption from metal surfaces under accident conditions, due to depressurization and/or heatup*	*High*	*Important release source*	*Low*	*Require high temperature data and data under accident environments*	*Major need*
114	*Chemical desorption of FPs under accident conditions from graphite and matrix (PBMR), due to venting and heatup*	*High*	*Desorption from graphite or matrix (PBMR) may be significant input to source term*	*Low*	*Affects of imposition of accident conditions on graphite unknown*	*Minor mod.*
109	*Gas composition during accidents*	*High*	*Intrusion of O_2 and N_2 during D-LOFC and CO and CO_2 generation affects speciation, gas properties, and production of flammable gases*	*Low*	*Requires input from accident flow analysis*	*Major need*

Part G (continued)

ID No.	Phenomena	Importance (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
121	*Dust and aerosol liftoff from metal surfaces due to depressurization flows and vibration*	*High*	*Important source of release*	*Low*	*1. Affect of vibration unknown* *2. Liftoff correlations for depressurization flows uncertain* *3. Affect of relief valve venting should be examined*	*Major need*
122	*Affect of air ingress on desorption from metal surfaces*	*High*	*Important for air ingress case*	*Low*	*Few data*	*Minor mod*
125	*Affect of air ingress on coolant properties*	*High*	*Large change possible in viscosity and thermal diffusivity; affects Re and Pr moduli and therefore heat and mass transfer coefficient.*	*Medium*	*Theory on affect of CO, CO_2, O_2, N_2 on viscosity and thermal diffusivity of He is not well established*	*Major mod*
126	*Spallation from metal surfaces during accidents*	*Medium*	*Possible source of dust on which FPs may adsorb*	*Low*	*No data for accident conditions and relevant materials*	*Minor mod*

Part G.2—Process heat version

ID No.	Phenomena	Importance (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
127	*IHX failure modes under D-LOFC or excessive accident temperatures*	*High*	*[Requires input from the Process Heat or High Temperature Materials Panel]*	*[Low]*	*Not yet studied*	
128	*Affects of secondary fluid on the release of FPs from metal and graphite surfaces*	*High*	*Affects FP release*	*Low*	*Not yet studied*	*Major mod*
129	*FP contamination of the secondary system due to IHX failure*	*High*	*Important consideration for process heat concepts*	*Low*	*Not yet studied*	*Major mod*
130	*Affect of IHX failure on the reactor system, chemical effects*	*High*	*Investment risk consideration*	*Low*	*Not yet studied*	*Major mod*

Part H: Releases from the confinement

Issues:
- Physical/chemical affects of accidents on confinement
- Leakage rate
- Possible filtration or cleanup system

ID No.	Phenomena	Importance (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
39	Confinement aerosol ~~physics~~ *dynamics (i.e., agglomeration and deposition)*	High	Analogous to LWR aerosol behavior/physics, delta-T, chemistry; important holdup mechanism	Medium	Reasonable well-developed theory of aerosol behavior; applicability to NGNP unclear	Minor mod
45	Radiolysis effects in confinement	High	FP (e.g., I, Ru, Te) chemistry, paint chemistry (dependent on confinement radiation level) (Trans.)	Medium	LWR experience and data	Minor mod
46	Filtration	High	Traditional passive charcoal/HEPA (Trans.)	High	Historical experience	Adequate
48	Combustion of *graphite* dust in confinement	High	Source of heat and distribution of FPs w/in confinement	Medium	ITER data	Major need
49	NGNP-unique leakage path beyond confinement	High	IHX to secondary site contamination; could be risk dominant (Trans.)	~~High~~ *Low*	Contingent on specific design knowledge	Minor mod
50	Confinement leakage path, release rate through penetrations	High	Cable/pipe penetrations, cracks, holes, HVAC (Trans.)	Medium	Building leakage experience, design specific	Adequate
51	Cable pyrolysis, fire	High	Soot generation and changes to iodine chemistry	Medium	LWR experience	Major need
132	*FP speciation in the confinement*	*High*	*Affects deposition rate*	*Medium*	*Uncertain kinetics at low temperature*	*Minor mod*
133	*Chemical interaction of FPs with confinement surfaces*	*High*	*Affects FP attenuation by confinement*	*Medium*	*Uncertain kinetics at low temperature*	*Minor mod*

Part H (continued)

ID No.	Phenomena	Importance (High, Medium, Low)	Rationale	Level of knowledge (High, Medium, Low)	Rationale	Status of FP modeling (adequate, minor mod, major need)
134	*Flammable gas entry into the confinement and possible combustion*	*High*	*Important consideration*	*Medium*	*Defined by accident sequence*	*Major need*

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10. SUPPLEMENTARY NOTES
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11. ABSTRACT *(200 words or less)*

This Fission Product Transport (FPT) Phenomena Identification and Ranking Technique (PIRT) report briefly reviews the high-temperature gas-cooled reactor (HTGR) FPT mechanisms and then documents the step-by-step PIRT process for FPT. The panel examined three FPT modes of operation: normal operation, anticipated transients, and postulated accidents. Two generic scenarios were selected as postulated accidents: the pressurized loss-of-forced circulation (P-LOFC) accident, and the depressurized loss-of-forced circulation (D-LOFC) accidents.

First, normal operation was seen as the initial starting point for the analysis. Fission products will be released by the fuel and distributed throughout the reactor circuit in some fashion. Second, a primary circuit breach can then lead to their release. It is the magnitude of the release into and out of the confinement that is of interest. Depending on the design of a confinement or containment, the impact of a pressure boundary breach can be minimized if a modest, but not excessively large, fission product attenuation factor can be introduced into the release path. This exercise has identified a host of material properties, thermofluid states, and physics models that must be collected, defined, and understood to evaluate this attenuation factor.

The reader should be cautioned that merely selecting phenomena based on high importance and low knowledge may not capture the true uncertainty of the situation. This is because a transport path is composed of several serial linkages, each with its own uncertainty. The propagation of a chain of modest uncertainties can lead to a very large uncertainty at the end of a long path, resulting in a situation that is of little regulatory guidance.

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