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PIRT Report for NuScale Stability

Phenomena Identification and Ranking Table Report for NuScale Stability. Work done under Research Assistance Request NRO-2016-004.

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PIRT Report for NuScale Stability

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Executive Summary

By memorandum dated June 21, 2016 (Ref. 1), the Office of New Reactors (NRO) requested that the Office of Nuclear Regulatory Research (RES) develop a phenomena identification and ranking table (PIRT) report for NuScale stability in order to support the safety evaluation of the proposed stability methodology.

This report describes the PIRT developed by an expert panel that pertains to NuScale stability. The panel built upon previous work described by Reference 5, and this report is an addendum to that earlier report.

The panel convened in several meetings to reach consensus on the identification of phenomena, the importance ranking for those phenomena, and ranking of the associated knowledge level for each phenomenon. At the conclusion of these meetings, the panel compiled the PIRT. In total, the panel considered 185 phenomena occurring in various components through the primary and secondary systems of the NuScale power module. The importance and knowledge level rankings for all of the phenomena are summarized in Table 2 of this report.

After reviewing the final consensus rankings, the panel identified 24 highly important phenomena. These 24 phenomena are summarized in Table 3 of this report. Most of these 24 phenomena were considered to have a high knowledge level, but three were found to have only a medium knowledge level ranking. These phenomena are:

- Convection heat transfer to the steam generator tubes occurring in the steam generator annulus of the primary side was considered to be of high importance, but the knowledge level was ranked as medium.
- Vertical/radial natural circulation occurring in steam generator annulus of the primary side was considered to be of high importance, but the knowledge level was ranked as medium.
- Two phase heat transfer occurring on the secondary side of the steam generator tubes was considered to be of high importance, but medium knowledge level.

In reviewing the capabilities of TRACE relative to these phenomena, the panel concluded that these phenomena fall under "Category B," which means that TRACE is expected to be applicable and should be capable of simulating the associated processes and phenomena with only limited code development or additional assessment. However, the determination of TRACE applicability to analyze NuScale stability is the subject of future work, and these items will be addressed more fully in that subsequent work.

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1 Introduction

By memorandum dated June 21, 2016 (Ref. 1), the Office of New Reactors (NRO) requested that the Office of Nuclear Regulatory Research (RES) develop a phenomena identification and ranking table (PIRT) report for NuScale stability in order to support the safety evaluation of the proposed stability methodology. The NuScale stability methodology is described by topical report (TR), TR-0516-49417-P, "Evaluation Methodology for Stability Analysis of the NuScale Power Module," July 2016 (Ref. 2). The RES staff accepted the assistance request via the NuScale Reactor Systems Research Plan (Ref. 3).

The RES staff intends to use the TRACE and PARCS computer codes for confirmatory analysis of the NuScale design in support of the review of the stability TR. The TRACE and PARCS models will be used for simulation of the power module stability. In order to support the applicability determination of TRACE/PARCS for NuScale stability, and in accordance with the standard evaluation model development and approval process (EMDAP), as described by Regulatory Guide 1.203 (RG 1.203, Ref. 4), it is necessary to first develop a PIRT.

The RES staff has previously developed PIRTs for small break loss of coolant accidents (SBLOCAs) and anticipated operational occurrences (AOOs) for integral PWRs (iPWRs), including the NuScale design. The current work builds on this previous experience. The SBLOCA/AOO PIRT is documented as part of a broader TRACE/PARCS applicability determination documented in Ref. 5. This report is an addendum to the Ref. 5 report that expands the PIRT discussions to cover stability for the NuScale power module.

Section 2 provides a brief description of the NuScale plant. Section 3 provides the scenario identification. Section 4 discusses the figure of merit. Section 5 discusses the subdivision of the plant into systems, subsystems, and components. Section 6 describes the PIRT panel membership and overall PIRT methodology. Section 7 provides the phenomena ranking and associated discussion. Section 8 identifies any issues relative to phenomena that are identified with high importance but low knowledge level. Section 9 provides summary and conclusions.

2 Plant Description

Section 1.2.1 of Ref. 5 and Section 3.0 of Ref. 2 describe the NuScale plant. For completeness, a summary of plant description from Ref. 5 is provided in this section. The NuScale concept is a modular, small, passive PWR with a rated thermal power of 160 MW(t). A schematic diagram of the reactor concept is shown in Figure 1 and Figure 2. The reactor is a self-contained assembly consisting of the reactor core, a riser, a pressurizer, and a set of helical steam generators (SGs) all housed within a single pressure vessel. The primary coolant flow during steady-state operation is via natural circulation, thereby eliminating the need for any reactor coolant pumps. During normal operation, the core serves as a source of heat and the steam generators act as elevated heat sinks. The temperature and consequent density difference between these two thermal centers drives the flow. The core is connected to a riser that acts as a "hot leg" transporting hot (and lighter) water to the upper plenum. The water in the upper plenum turns downwards and is cooled as it passes on the outside of the helical steam generator tubes. The cooler (and heavier) water returns to the core via the downcomer region.

The entire reactor pressure vessel is housed in a compact steel containment that is immersed in a water pool that acts as the ultimate heat sink in the event of an accident or transient. The emergency core cooling system of the NuScale reactor consists of two Reactor Vent Valves (RVVs), two Reactor Recirculation Valves (RRVs), and the Containment Heat Removal System (CHRS). The RVVs are located at the top of the reactor vessel and act as depressurization valves connecting the pressurizer region of the reactor pressure vessel to the containment vessel. The RRVs are located at the elevation of the top of core and connect the downcomer region with the containment vessel. The CHRS system consists of the containment vessel and the containment cooling pool. The design also includes a Decay Heat Removal System (DHRS) that works passively to remove residual decay heat from the core.

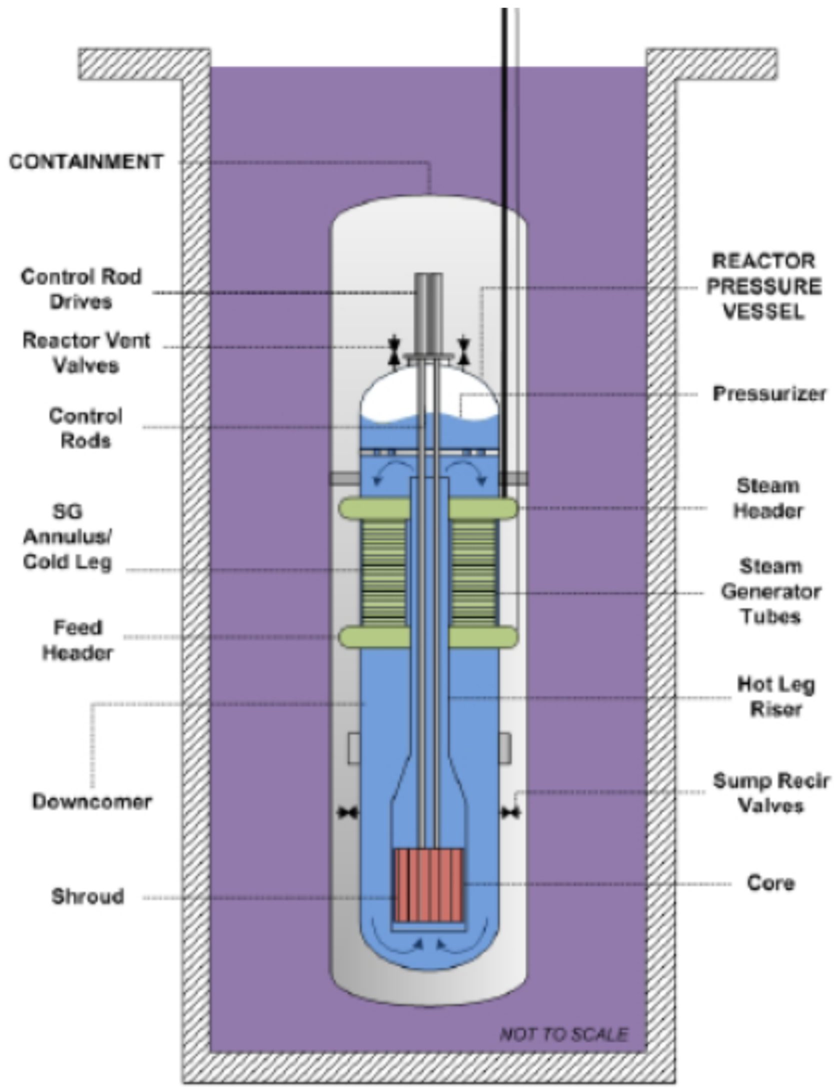

Figure 1: Schematic Representation of the NuScale Reactor Design (from Ref. 5)

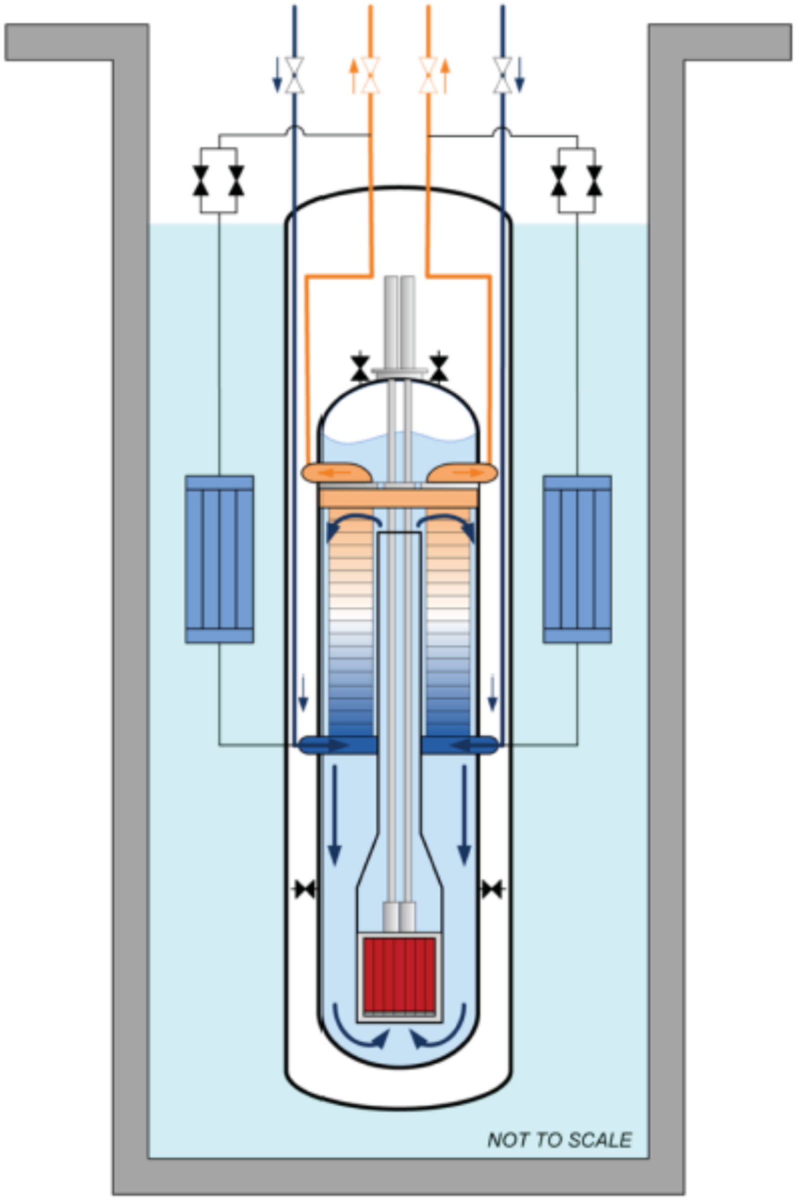

Figure 2: NuScale Reactor Systems Showing Steam Generator and Reactor Flow (From Ref. 2).

3 Scenario Identification

In the current work, a PIRT is developed for stability. Stability evaluation is generally not characterized as an analysis of a transient per se. Rather, the stability evaluation determines if the reactor would be subject to a run-away excursion based on its response to a perturbation. In the scenario identification context, the RES staff identified three scenarios of interest. The first is normal, 100 percent power operation. This scenario refers to the stability of the reactor at normal operating, steady-state conditions. Secondly, the staff identified startup and shutdown maneuvers. Lastly, the staff considered stability during AOOs.

The scenarios of steady-state normal operation and startup and shutdown are fairly straightforward. It should be noted that the staff considered startup operations assuming that the power module is pressurized using non-nuclear heat. This is an important assumption because a postulated AOO initiated during the pressurization phase of the start-up sequence will progress without any reactivity feedback. What is meant by the AOO scenario is slightly more complex. AOO refers to anticipated conditions of operation that can be reasonably expected to occur during the life of the facility. While these events are typically analyzed as part of a final safety analysis report (FSAR) or design certification document (DCD), those AOOs that produce the most limiting adverse conditions from the perspective of specified acceptable fuel design limits (SAFDLs) are likely not the AOOs of interest in the current work.

Many postulated AOOs produce conditions that result in the automatic trip of the reactor. These events are not of interest from the standpoint of stability. Rather, events that could occur that produce changes in the system thermal-hydraulic state without resulting in automatic reactor trip are of the most interest. Therefore, when evaluating the ranking of certain phenomena that may occur during postulated AOOs, the staff is generally considering an event that is not sufficiently severe as to result in the automatic trip of the reactor. An example would be consideration of a partially stuck open relief valve compared to an inadvertent opening of a relief valve. The milder transient from a partially stuck open valve could affect thermal-hydraulic conditions in the reactor system without resulting in an automatic trip based on pressure.

In summary, the staff considered the ranking of phenomena for three conditions: (1) normal, 100 percent power, steady-state operation, (2) startup and shutdown, and (3) during AOOs.

4 Figure of Merit

The staff notes that the proposed stability solution for the NuScale reactor is an exclusion region (ER) type (Ref. 2). ER type long term stability (LTS) solutions rely on avoiding instability. ER based LTS solutions are commonly accompanied by a set of analyses that demonstrate that the reactor remains stable under normal operating conditions, including the effects of AOOs. An analysis of this type demonstrates that the decay ratio (DR) is within an acceptable limit (e.g., less than 0.8). The RES staff adopted DR as the figure of merit in the current work.

Time domain codes such as TRACE have been used to calculate parameters such as DR for stability applications (Ref. 6). In these calculations, a perturbation is applied and the transient response is calculated. An examination of the transient response, for a stable system, will show the decay of oscillations with subsequent oscillation peaks being smaller in magnitude compared to earlier peaks. The DR is a measure of the damping and can be thought of as the ratio of the amplitude of subsequent peaks in the oscillatory response to the initial perturbation.

It should be noted that the DR is a property of the reactor system regardless of whether the system has been perturbed.

5 Systems, Subsystems and Components

In performing the ranking of phenomena, not all phenomena that occur do so with equal importance uniformly through the reactor system. Therefore, it is generally necessary to consider the importance of phenomena based on the system, subsystem, or component where they occur within the overall reactor system. To this end, the RES staff relied on previous PIRT experience for SBLOCA and AOO and subdivided the NuScale reactor system into smaller systems and components.

Table 1 summarizes the division of the NuScale reactor system into the subsystems and components. The divisions listed in Table 1 track closely with the convention adopted in Ref. 5. The divisions are largely self-explanatory, but the staff notes some nuances here.

Table 1: Systems and Components

System	Component
Core	Barrel/Baffle, control rods and guide tubes, fuel rods, kinetics, and subchannel
Instrumentation and Controls	Primary and secondary side control systems, primary pressurizer control system, reactor protection, and secondary side control systems
Primary System	Baffle plate, downcomer, downcomer to lower plenum region, hot leg riser, lower plenum, pressurizer, steam generator annulus, and upper plenum
Secondary System	Steam generator tubes

In the reactor core, a listed component is “Kinetics.” The staff divided out the phenomena having to do with neutron kinetics and considered these phenomena all separately under the category of “Kinetics” as it relates to the core. Under instrumentations and controls, there are separate listings for primary, secondary, and primary and secondary side control systems. These differentiations are made in cases where the staff clearly knows how a process or phenomenon applies to either just the primary or just the secondary. However, a catch-all category of primary and secondary side control systems is also added. This category would catch phenomena applying equally to controllers for either side, but also, would capture any situations where, perhaps, a primary side signal is used to provide secondary side control functions, or vice-versa. The last nuance of note is for the primary side, a differentiation is drawn between the downcomer, lower plenum, and the transition region between the downcomer and lower plenum. The transition region is called the "downcomer-to-lower plenum region."

6 PIRT Membership and Methodology

In developing this PIRT, the staff relied on the process as described by Step 4 of RG 1.203 (Ref. 4). The PIRT panel is comprised of Dr. Stephen Bajorek, Dr. Matthew Bernard, Dr. Andrew Bielen, Dr. Peter Lien, and Dr. Peter Yarsky from RES. The PIRT panel was facilitated by Kathy Gibson from RES.

As its starting point, the panel referred to the previous PIRTs developed for SBLOCAs and AOOs documented in Ref. 5. The phenomena identification and ranking began by compiling the phenomena identified in Ref. 5. From this starting point, the PIRT panel convened and held a meeting to update the list of phenomena. The purpose of meeting to update the list of phenomena was to ensure that the existing list was not lacking phenomena that are specifically related to the stability characteristics of the NuScale (and therefore, might not have been considered previously). This resulted in the addition of several phenomena and clarification of other phenomena. After the initial meeting of the panel, a tentative phenomena listing was used by each member to perform an individual ranking. Individuals ranked the importance of phenomena using a scale of one through nine. A numerical value of one indicates that the phenomenon is inactive, impossible, or highly unlikely to occur. Values of two or three indicate that the phenomenon is of low importance, but three indicating slightly more important than two. Values four, five, and six indicate medium importance while values seven, eight, and nine are for high importance. The panel used these numerical values to more finely differentiate between the broader importance rankings of low, medium, and high and to facilitate subsequent discussions.

In subsequent meetings, the panel discussed individual importance rankings to reach a consensus on the importance ranking for each phenomenon. Following the determination of the consensus importance rankings, the PIRT panel convened a final time to reach consensus on the characterization of the knowledge level for each phenomenon.

In the consensus ranking, the phenomena are ranked as being:

(1) Low (L) importance – having only a small influence on the figure of merit,
(2) Medium (M) importance – having a moderate influence on the figure of merit,
(3) High (H) importance – having a significant or dominant influence on the figure of merit, or
(4) Not Applicable (N/A) – that the phenomenon is not possible or highly unlikely.

The knowledge level was ranked according to a similar scale, namely:

(1) Low (L) – the phenomenon is not well understood. Modeling the phenomenon is currently either not possible or is possible only with large uncertainty,

(2) Medium (M) – the phenomenon is understood, however, can only be modeled with moderate uncertainty, or
(3) High (H) – the phenomenon is well understood and can be accurately modeled.

7 Phenomena Ranking and Discussion

This section provides the rationale for the PIRT panel's consensus rankings for the importance to stability and knowledge level of each phenomenon considered by the panel. These rationales are organized in this section first by system, then component, and finally phenomenon or process. Table 2 provides a summary of the importance and knowledge level rankings.

7.1 Core

7.1.1 Barrel/Baffle

7.1.1.1 Bypass Flow

The panel reached a consensus that bypass flow occurring in the barrel/baffle is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the bypass flow represents a small fraction of the total flow rate, making active flow of fluid through the core much more important than phenomena occurring in this region. The panel also considered the state of the knowledge with respect to bypass flow and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.1.1.2 Density Wave Propagation

The panel reached a consensus that density wave propagation occurring in the barrel/baffle is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the bypass flow represents a small fraction of the total flow rate, making active flow of fluid through the core much more important than phenomena occurring in this region. The panel also considered the state of the knowledge with respect to density wave propagation and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.1.1.3 Entrance Effects/Developing Length

The panel reached a consensus that entrance effects/developing length occurring in the barrel/baffle is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the bypass flow represents a small fraction of the total flow rate, making active flow of fluid through the core much more important than phenomena occurring in this region. The panel also considered the state of the knowledge with respect to entrance effects/developing length and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.1.1.4 Pressure Wave Propagation

The panel reached a consensus that pressure wave propagation occurring in the barrel/baffle is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the bypass flow represents a small fraction of the total flow rate, making active flow of fluid through the core much more important than phenomena occurring in this region. The panel also considered the state of the knowledge with respect to pressure wave propagation and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.1.1.5 Stored Energy

The panel reached a consensus that stored energy occurring in the barrel/baffle is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the bypass flow represents a small fraction of the total flow rate, making active flow of fluid through the core much more important than phenomena occurring in this region. The panel also considered the state of the knowledge with respect to stored energy and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.1.1.6 Water Thermal Expansion

The panel reached a consensus that water thermal expansion occurring in the barrel/baffle is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that density changes with temperature changes can significantly affect the natural circulation behavior within the primary system, however the volume fraction of fluid in the barrel/baffle is small compared to the volume in the active core. The panel also considered the state of the knowledge with respect to control rod and guide tube effects on flow and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.1.2 Control Rods and Guides Tubes

7.1.2.1 Effects on Flow

The panel reached a consensus that effect of control rods and guides tubes on flow is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the bypass flow through the control rod guide tubes represents a small fraction of the total flow rate, making active flow of fluid through the core much more important than phenomena occurring in the guide tubes. The panel also considered the state of the knowledge with respect to control rod and guide tube effects on flow and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.1.2.2 Effects on Heat Transfer

The panel reached a consensus that effect of control rods and guides tubes on heat transfer is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the bypass flow through the control rod guide tubes represents a small fraction of the total flow rate, making active flow of fluid through the core much more important than phenomena occurring in the guide tubes. The panel also considered the state of the knowledge with respect to control rod and guide tube effects on heat transfer and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.1.3 Fuel Rods

7.1.3.1 Assembly Burnup Distribution

The panel reached a consensus that the assembly-level burnup distribution occurring in the core is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the most important quantity from the core with respect to stability is average core exit coolant density. Phenomena affecting the power distribution, such as assembly-wise burnup distribution, are expected to be in essence averaged out and rendered unimportant. The panel also considered the state of the knowledge with respect to assembly burnup distribution. Based on extensive analysis experience and validation against light water reactor (LWR) benchmarks, the panel agreed on ranking the knowledge level as high.

7.1.3.2 Boron Precipitation

The panel reached a consensus that boron precipitation occurring on the fuel rods of the core is not applicable to NuScale stability during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered the operating conditions expected during the range of stability-type events. Boron precipitation only would be expected to occur in long-term, high-void fraction situations, which are not expected to occur for NuScale. The panel also considered the state of the knowledge with respect to boron precipitation and based on the well-defined chemistry involved agreed on ranking the knowledge level as high.

7.1.3.3 Cladding Conductivity

The panel reached a consensus that the cladding conductivity of the fuel rods of the core is of medium importance during normal operation and during AOOs, and of low importance during startup and shutdown. In determining this importance ranking, the panel considered that cladding conductivity is a small resistance to heat transfer from the fuel to the coolant, and that its effect should be taken into account when determining cladding conditions in operating and transient situations. At lower power conditions, heat resistance is less important, warranting a ranking of low in startup and shutdown conditions. The panel also considered the state of the knowledge with respect to cladding conductivity and, based on the extensive existing database, agreed on ranking the knowledge level as high.

7.1.3.4 Cladding Oxidation

The panel reached a consensus that cladding oxidation occurring on the fuel rods of the core is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that while cladding oxidation contributes a small amount to the heat resistance from fuel to coolant, its contribution is overshadowed by the fuel-clad gap and cladding contributions. The panel also considered the state of the knowledge with respect to cladding oxidation and, based on the extensive existing database and the fundamental understanding of oxidation phenomena, agreed on ranking the knowledge level as high.

7.1.3.5 Cladding Strain

The panel reached a consensus that cladding strain occurring in the fuel rods of the core is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that applicable cladding strain specified acceptable fuel design limits would be met during conditions of normal operation, startup and shutdown, and during AOOs. Therefore, the panel considered that cladding strain resulting in appreciable changes in the heat resistance of the fuel would be unlikely to occur in any transient or postulated instability prior to reactor trip. The panel also considered the state of the knowledge with respect to cladding strain and, based on the extensive existing database, agreed on ranking the knowledge level as high.

7.1.3.6 Core Pin-by-Pin Burnup Distribution

The panel reached a consensus that the pin-wise burnup distribution occurring in the fuel rods of the core is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that for the purposes of stability evaluation, the details of core radial power distribution are essentially averaged out due cross-flow in the core and flow mixing in the riser and upper plenum. The panel also considered the state of the knowledge with respect to core pin-by-pin burnup distribution and, based on comparisons with LWR plant data and high-order benchmarks, agreed on ranking the knowledge level as high.

7.1.3.7 Fission Power

The panel reached a consensus that the fission power produced by the core is of high importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that, since the NuScale design is entirely reliant on natural circulation, the flow characteristics and response to perturbations are dictated by the corresponding fission power behavior. Therefore, it is imperative that this quantity be well-characterized by analysis methodologies. The panel also considered the state of the knowledge with respect to fission power and, based on extensive instrumentation and existing plant benchmarks, agreed on ranking the knowledge level as high.

7.1.3.8 Fuel Conductivity and Density

The panel reached a consensus that the thermal conductivity and density of the fuel in the core is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered the importance of these quantities to calculating the fuel temperature, which in turn influences the Doppler reactivity and the dynamic power response of the reactor core. The panel also considered the state of the knowledge with respect to fuel conductivity and density, and, based on current fuel measurements and fabrication quality assurance programs, agreed on ranking the knowledge level as high.

7.1.3.9 Fuel Heat Capacity

The panel reached a consensus that the heat capacity of the fuel in the core is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered the influence of heat capacity on fuel temperature and therefore Doppler reactivity. This in turn affects the overall power response of the reactor core. The panel also considered the state of the knowledge with respect to fuel heat capacity and, based on the extensive existing database, agreed on ranking the knowledge level as high.

7.1.3.10 Gap Conductance

The panel reached a consensus that conductance across the fuel-cladding gap is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that gap conductance is the limiting heat transfer resistance from fuel pellet to coolant, and could influence the timing and duration of stability events. Because of this, it is considered to be an important phenomenon; however, since the time constant of the fuel (~1-2 seconds) is roughly an order of magnitude less than the expected coolant loop transit time (~20 seconds), its importance may be somewhat limited for NuScale stability. The panel also considered the state of the knowledge with respect to gap conductance and, based on the convolution of the uncertainties associated with each component of gap conductance models, agreed on ranking the knowledge level as medium.

7.1.3.11 Initial Gap Pressure

The panel reached a consensus that the initial gap pressure of the fuel rods of the core is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered the importance of gap pressure to the calculation of gap conductance. Since gap gas pressure is but one of several contributors to gap conductance, and gap conductance was ranked medium, it follows that gap pressure has less importance than conductance. The panel also considered the state of the knowledge with respect to initial gap pressure and, based on validation of fission gas release models and operating rod pressure data, agreed on ranking the knowledge level as high.

7.1.3.12 Pellet Radial Power Distribution

The panel reached a consensus that the intra-pellet radial power distribution is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered the relative importance of the detailed power distribution and related quantities (such as pellet radial burnup). As described in other sections, for stability purposes information down to the pin level is averaged out in computing the core exit average coolant density, and therefore is not important for stability evaluations. The panel also considered the state of the knowledge with respect to pellet radial power distribution and, based on extensive numerical and experimental evaluation, agreed on ranking the knowledge level as high.

7.1.3.13 Stored Energy

The panel reached a consensus that the stored energy of the reactor fuel is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that stored energy within the fuel can be expected to have a modulating effect on the instantaneous heat release from the fuel during an oscillation. In other words, instead of all energy being directly deposited into the coolant from the fuel during a transient, some will instead go towards heating the fuel during power increases; likewise, during power decreases, some of that stored energy will then be released into the coolant. Stored energy may thus serve to help stabilize the system response to perturbations. The panel also considered the state of the knowledge with respect to stored energy and based on the well-characterized nature of fuel thermal conductivity, density, and fission power agreed on ranking the knowledge level as high.

7.1.3.14 Total Peaking Factor

The panel reached a consensus that the total peaking factor (i.e., the maximum local power generation) of the reactor core is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered the relative importance of local power phenomena on stability. It is the integral power deposited by the core into the system, rather than the details of the intra-core power distribution, which dictate stability behavior. Therefore, the effects of the total peaking factor are lost in this integration. The staff notes that consideration of potential, alternative figures of merit would require reconsideration of the ranking of this phenomenon. In particular, if the panel had considered departure from nucleate boiling ratio as a figure of merit, this importance ranking would be higher. The panel also considered the state of the knowledge with respect to the total peaking factor and, based on the well-characterized resolution of pin-by-pin power distribution, agreed on ranking the knowledge level as high.

7.1.4 Kinetics

7.1.4.1 Assembly Interaction

The panel reached a consensus that assembly neutronic interaction (e.g., through Assembly Discontinuity Factors (ADFs)) as applied to core kinetics is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered the relative importance of the three-dimensional power shape. As the integral power deposited to the coolant by the core outweighs the details of the power shape for stability purposes, it is not expected that neutronic interaction has a strong effect on the stability behavior. The panel also considered the state of the knowledge with respect to assembly interaction and, based on extensive validation experience, agreed on ranking the knowledge level as high.

7.1.4.2 Axial/Radial Reflector Representation

The panel reached a consensus that the neutronic representation of the axial and radial reflector regions as applied to core kinetics is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered the relative importance of the three-dimensional power shape. As the integral power deposited to the coolant by the core outweighs the details of the power shape for stability purposes, it is not expected that reflector representation (which will have an influence on the three dimensional power shape) has a strong effect on the stability behavior. The panel also considered the state of the knowledge with respect to axial and radial reflector representation and based on uncertainties surrounding the stainless steel radial reflector agreed on ranking the knowledge level as medium.

7.1.4.3 Decay Heat

The panel reached a consensus that decay heat as applied to core kinetics is of medium importance during normal operation and during AOOs, and high importance during startup and shutdown (particularly shutdown). In determining this importance ranking, the panel considered the contribution to core power of decay heat under the different scenarios under consideration. During normal operation and AOO situations, decay heat is a minor but significant source of energy for the primary system. During startup and especially shutdown scenarios, decay heat may be the *only* source of heat dictating the natural circulation flow dynamics of the system. The panel also considered the state of the knowledge with respect to decay heat and, based on the extensive existing data and analysis base, agreed on ranking the knowledge level as high.

7.1.4.4 Delayed Neutrons

The panel reached a consensus that delayed neutrons as applied to core kinetics are of high importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered the direct impact delayed neutrons have on the timing and magnitude of the system power response to potentially de-stabilizing perturbations. The panel also considered the state of the knowledge with respect to delayed neutrons and, based on the well-characterized nature of the delayed neutron source in uranium dioxide fuel, agreed on ranking the knowledge level as high.

7.1.4.5 Fuel Temperature Feedback

The panel reached a consensus that fuel temperature feedback as applied to core kinetics is of high importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered the relative importance of reactivity response to changes in fuel temperature. Based on the behavior of similar cores to NuScale, Doppler feedback is expected to be the most important contributor to the overall response of the core to perturbations causing changes in the core state. The panel also considered the state of the knowledge with respect to fuel temperature feedback and, based on extensive applicable operating measurements and analysis in existing LWRs, agreed on ranking the knowledge level as high.

7.1.4.6 Moderator Density Feedback

The panel reached a consensus that moderator density feedback as applied to core kinetics is of high importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered the relative importance of the core reactivity response to changes in core-average moderator density. Based on the behavior of similar cores to NuScale, moderator density feedback is expected to be the second-most important contributor to the overall response of the core to perturbations causing changes in the core state. The panel also considered the state of the knowledge with respect to moderator density feedback and, based on extensive applicable operating measurements and analysis in existing LWRs, agreed on ranking the knowledge level as high.

7.1.4.7 Moderator Temperature Feedback

The panel reached a consensus that moderator temperature feedback as applied to core kinetics is of medium importance during normal operation, and of high importance during startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered the relative importance of the core reactivity response to changes in core-average moderator temperature. Based on the behavior of similar cores to NuScale, moderator temperature feedback is expected to be the third-most important contributor to the overall response of the core to perturbations causing changes in the core state. Moderator density feedback is likely to be larger due to its direct relationship to the number density of coolant atoms within the core; however, moderator temperature feedback is an important secondary consideration. The panel also considered the state of the knowledge with respect to moderator temperature feedback and, based on extensive applicable operating measurements and analysis in existing LWRs, agreed on ranking the knowledge level as high.

7.1.4.8 Pellet Burnup Distribution

The panel reached a consensus that intra-pellet burnup distribution as applied to core kinetics is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered the relative importance of local phenomena (such as intra-pellet burnup) to the overall system dynamics, and concluded that these effects are likely to be averaged out when considering stability of the whole system. The panel also considered the state of the knowledge with respect to pellet burnup distribution and based on extensive numerical and experimental evaluation agreed on ranking the knowledge level as high.

7.1.4.9 Pellet/Structure/Coolant Direct Energy Deposition

The panel reached a consensus that direct energy deposition in the pellet, structures and coolant as applied to core kinetics is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered the expected quantity of energy directly deposited into coolant and structures, and concluded that the amount will be small. The panel also considered the state of the knowledge with respect to direct energy deposition and, based on extensive existing analysis, agreed on ranking the knowledge level as high.

7.1.4.10 Pin-by-Pin Power Distribution

The panel reached a consensus that pin-by-pin power distribution as applied to core kinetics is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered the relative importance of detailed, local phenomena (such as pin-by-pin power distribution) to the overall system dynamics. The panel concluded that from a stability standpoint, detailed power distribution information is not important. The panel also considered the state of the knowledge with respect to pin-by-pin power distribution and, based on extensive numerical and experimental evaluation, agreed on ranking the knowledge level as high.

7.1.4.11 Shutdown Bank Speed

The panel reached a consensus that shutdown bank speed as applied to core kinetics is of low importance during normal operation and during startup and shutdown, and of medium importance during AOOs. In determining this importance ranking, the panel considered the differences in importance of reactor trip speed in relation to the scenarios under consideration. In normal operation, a reactor trip will not occur. In startup/shutdown and AOOs, a perturbation which leads to instability would be terminated via a reactor trip. While the natural period of the NuScale power module is expected to be large compared with the required insertion time, the panel decided trip time is moderately important in assuring stability events are terminated prior to fuel exceeding SAFDLs. The panel also considered the state of the knowledge with respect to shutdown bank speed and, based on existing measurements at operating plants and expected measurements within the NuScale module during startup testing, agreed on ranking the knowledge level as high.

7.1.4.12 Shutdown Bank Worth

The panel reached a consensus that shutdown bank worth as applied to core kinetics is of low importance during normal operation, and of medium importance during startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered the differences in importance of reactor trip worth in relation to the scenarios under consideration. In normal operation, reactor trips will not occur, so worth is not important. Under startup/shutdown and AOO conditions, provided the trip worth is sufficient to shut down the reactor, the specifics of trip worth are of moderate importance in ensuring shutdown prior to fuel exceeding SAFDLs. The panel also considered the state of the knowledge with respect to shutdown bank worth and, based on extensive benchmarking to the existing neutronics database, agreed on ranking the knowledge level as high.

7.1.4.13 Soluble Boron Reactivity Feedback

The panel reached a consensus that soluble boron reactivity feedback as applied to core kinetics is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered the importance of soluble boron to the overall feedback behavior of the reactor core. Soluble boron concentration does have an impact on the value of the other reactivity coefficients (particularly moderator temperature/density). There could be a scenario where an instability is initiated due to irregularities during a planned boron dilution as part of normal plant operation. The panel also considered the state of the knowledge with respect to soluble boron reactivity feedback and, based on extensive applicable operating measurements and analysis in existing LWRs, agreed on ranking the knowledge level as high.

7.1.4.14 Steady-State Assembly-by-Assembly Radial Peaking

The panel reached a consensus that the initial, steady-state assembly-by-assembly radial peaking as applied to core kinetics is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered the importance of steady-state radial power distribution on the flow dynamics of the core. The radial power peaking will affect the degree of subcooled boiling in the core, which could affect the incidence of voiding in the upper plenum and hot leg riser. Voiding in these regions could have significant impact on the stability of the NuScale power module. However, the panel considered this phenomenon to be of medium importance as mixing of the core flow both in the core (due to cross-flow) and in the riser will tend to average out any effects from radial peaking. The panel also considered the state of the knowledge with respect to steady-state assembly-by-assembly radial peaking and based on extensive applicable operating measurements and analysis in existing LWRs agreed on ranking the knowledge level as high.

7.1.4.15 Steady-State Axial Peaking

The panel reached a consensus that initial, steady-state axial peaking as applied to core kinetics is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered the importance of axial power distribution on the primary system flow. As with other phenomena discussed in this section, the total heat deposited in the coolant is, in general, the key contribution to stability performance, rather than local details. The panel also considered the state of the knowledge with respect to steady-state axial peaking and, based on extensive applicable operating measurements and analysis in existing LWRs, agreed on ranking the knowledge level as high.

7.1.4.16 Time in Fuel Cycle

The panel reached a consensus that the time in fuel cycle as applied to core kinetics is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered the implications of different times in fuel cycle. Time in cycle primarily affects stability performance through reactivity feedback coefficients; depending on the fuel isotopes and the coolant boron concentration, there can be a range of possible feedback coefficients. Therefore, the stability behavior of the system will likely depend on when in cycle the analysis takes place. The panel also considered the state of the knowledge with respect to time in fuel cycle and, based on the fact that the time in fuel cycle to evaluate stability is a user input to an analysis (and therefore well-known), agreed on ranking the knowledge level as high.

7.1.4.17 Transient Change in Radial Assembly-by-Assembly Radial Peaking

The panel reached a consensus that the transient change in radial assembly-wise peaking as applied to core kinetics is not applicable during normal operation, is of low importance during startup and shutdown, and of medium importance during AOOs. In determining this importance ranking, the panel considered the differences in importance of transient radial power distribution in relation to the scenarios under consideration. Clearly under normal operation transient changes are not expected. Under startup/shutdown operations, and more importantly under AOO-type conditions, radial power changes could potentially lead to greater incidence of subcooled boiling in the core, and therefore, could affect the void distribution in the primary system. The panel also considered the state of the knowledge with respect to transient change in radial assembly-wise peaking and, based on the underlying confidence in the numerical methods used to simulate the transient power shape, agreed on ranking the knowledge level as high.

7.1.4.18 Transient Change in Axial Power Peaking

The panel reached a consensus that transient change in axial power peaking as applied to core kinetics is not applicable during normal operation, and of low importance during startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered the differences in importance of transient axial power distribution in relation to the scenarios under consideration. Clearly, under normal operation, transient changes are not expected. As described elsewhere in this section, the integrated heat transferred to the coolant are more important than the power distribution; and unlike the radial changes, changes in the axial distribution are not as likely to impact the propensity for subcooled boiling (which is sensitive to the axially integrated power). The panel also considered the state of the knowledge with respect to transient change in axial power and, based on underlying confidence in the numerical methods used to compute the transient power shape, agreed on ranking the knowledge level as high.

7.1.4.19 Withdrawn Control Rod Bank Worth

The panel reached a consensus that withdrawn control rod bank worth as applied to core kinetics is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered the expected condition of control rods during operation of the NuScale reactor. As with most PWRs, NuScale is expected to operate with almost fully withdrawn control rods, so their worth would not be important under normal operation and as a precursor to AOO events. During startup/shutdown operations, control rods may be inserted into the core, but changes in their alignment are typically performed in conjunction with maneuvers in coolant boron concentration, to minimize the possibility of rapid reactivity insertion. The panel also considered the state of the knowledge with respect to withdrawn control rod bank worth and, based on extensive neutronic validation, agreed on ranking the knowledge level as high.

7.1.4.20 Xenon/Samarium Concentrations

The panel reached a consensus that Xenon and Samarium concentrations within the fuel as applied to core kinetics is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the NuScale reactor core is quite small and therefore tightly coupled. The likelihood for neutronic oscillation to occur as a result of shifting xenon and/or samarium concentrations is low as this generally requires a reactor core to be loosely coupled. The panel also considered the state of the knowledge with respect to Xenon and Samarium concentrations and based on extensive validation of these important fission products within existing code suites agreed on ranking the knowledge level as high.

7.1.5 Subchannel

7.1.5.1 Boron Blockage in Subchannels

The panel reached a consensus that blockage to flow in the core due to boron precipitation will not occur during normal operation, startup and shutdown, or during during AOOs. Prevention of boron precipitation is precluded by a reactor protection function to avoid void formation in the reactor coolant system (RCS). Boric acid concentration levels are expected to remain low and no precipitation would be possible at the temperatures expected. As a result, it was given a “N/A” ranking indicating the process will not occur. The panel also considered the state of the knowledge with respect to boron precipitation and blockage formation and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.1.5.2 Clad Ballooning

The panel reached a consensus that clad ballooning would not occur during normal operation, and that was of low importance during startup, shutdown, and during AOOs. The panel considered it was unlikely that the transients would not produce a large difference in the rod internal pressure and system pressure that would result in expansion of the cladding. The panel also considered the state of the knowledge with respect to rod deformation based on its experience with the current state of the art agreed on ranking the knowledge level as high.

7.1.5.3 Core Pressure Drop

The panel reached a consensus that the pressure drop across the core was a highly important process affecting stability during normal operation, startup and shutdown, and also during AOOs. In determining this importance ranking, the panel considered that the pressure drop resulting from form and friction loss would be significant contributors to the overall pressure drop across the core. Pressure drop has a direct effect on the natural circulation flow patterns and the dynamic response of flow to changing conditions in the reactor system. The panel also considered the state of the knowledge with respect to determination of pressure drop and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.1.5.4 Critical Heat Flux

The panel reached a consensus that reaching the critical heat flux (CHF) will be highly unlikely. During normal operation, startup and shutdown, and AOOs, the incidence of CHF is limited or precluded by SAFDL acceptance criteria. The panel also considered the state of the knowledge with respect to CHF and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high (assuming that fuel specific CHF testing is performed for the NuScale design).

7.1.5.5 Cross Flow / Mixing

The panel reached a consensus that cross flow and mixing in the core is of low importance during normal operation, startup and shutdown, and during AOOs. Most important to stability is the average coolant temperature and density, which impacts the natural circulation flow rate. Cross flow and mixing act to prevent significant maldistribution of temperature in the core. The panel also considered the state of the knowledge with respect to cross flow and mixing based on its experience with the current state of the art agreed on ranking the knowledge level as medium.

7.1.5.6 Density Wave Propagation

The panel reached a consensus that density wave propagation is of medium importance during normal operation, but of low importance during startup and shutdown. During AOOs density wave propagation was again considered to be of medium importance. This phenomenon is not ranked high as a significant contribution to a potential instability and is unlikely to play an important role without a larger degree of density difference (e.g., phase transition). While the flow remains strictly single phase, the effect of density waves should be small. However, in events or during normal operation if subcooled boiling occurs, a greater density difference may make it possible for a significant density wave to propagate. The panel also considered the state of the knowledge with respect to pressure wave propagation and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.1.5.7 Entrance Effects / Developing Length

The panel reached a consensus that the developing length (~10D) is expected to be small relative to the size of the component. The effect on dynamic flow behavior and pressure drop is expected to be moderate, at best. Therefore, the process was considered to be of medium importance during normal operation, low importance during startup and shutdown, and medium importance during AOOs. The panel also considered the state of the knowledge with respect to entrance length effects and, based on its experience with the current state of the art, agreed on ranking the knowledge level as medium.

7.1.5.8 Flashing

The panel reached a consensus that flashing is of low importance during normal operation, startup and shutdown, and during AOOs. Significant void formation is precluded by a reactor protection function, and during AOOs significant voids are not expected to occur due to rapid depressurization of the primary because a significant depressurization AOO would likely result in an automatic reactor protection system function to trip the reactor. The panel considered the state of the knowledge with respect to flashing and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.1.5.9 Flow Distribution

The panel reached a consensus that the core flow distribution is of medium importance during normal operation, low importance during startup and shutdown, and of medium importance during AOOs. The flow distribution in the core is expected to have a minor impact on the core pressure drop. The flow distribution, like the detailed power distribution, may impact local subcooled boiling in the core, these effects will be averaged out at the core outlet due to mixing. The panel also considered the current state of knowledge with respect to flow distribution and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.1.5.10 Flow Regime Transition

The panel reached a consensus that flow regime transitions are of low importance during normal operation, startup and shutdown, and for AOOs. Flow regime transition is not expected in the core, especially since significant void formation is precluded by a reactor protection function. The panel also considered the current state of knowledge with respect to flow regime transition and, based on its experience with the current state of the art, agreed on ranking the knowledge level as medium.

7.1.5.11 Spacer Grid Effects (Entrainment/De-entrainment)

Spacer grid effects on entrainment and de-entrainment will not occur since the flow will remain single phase. The panel reached a consensus that this process is not applicable during normal operation, startup and shutdown, and for AOOs. The panel did not determine a knowledge ranking for this phenomenon.

7.1.5.12 Spacer Grid Effects (Heat Transfer)

The panel reached a consensus that the spacer grid effect on heat transfer is low during normal operation, startup and shutdown, and for AOOs. The flow is single phase, and any impact on heat transfer is expected to be very small. The panel also considered the state of the knowledge with respect to spacer grid heat transfer effects and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.1.5.13 Heat Capacitance of Primary Coolant

The panel reached a consensus that the heat capacitance of the primary coolant is medium during normal operation, startup and shutdown, and for AOOs. The heat capacitance affects the storage of energy within the coolant and the rate at which the primary heats up and cools down. The panel also considered the state of the knowledge with respect to heat capacitance of the primary coolant and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.1.5.14 Interfacial Drag / Relative Motion of the Phases

The panel reached a consensus that interfacial drag the relative motion between phases is of low importance during normal operation, startup and shutdown, and for AOOs. Significant voiding is not expected, and similar to flow regime transition the process of interfacial drag is unlikely to occur. The panel also considered the current state of knowledge with respect to interfacial drag/relative motion of the phases and, based on its experience with the current state of the art, agreed on ranking the knowledge level as medium.

7.1.5.15 Natural Circulation

The panel reached a consensus that vertical/radial natural circulation occurring in the core is of high importance during normal operation, startup and shutdown, and for AOOs. In determining this importance ranking, the panel considered that natural circulation flow is the primary mechanism of coolant flow under the majority of operating and anticipated conditions and that a key driver for potential instability (or damping of instability) is the nature of the feedback between pressure drop, core power, and primary loop flow rate under natural circulation conditions. Based on these considerations, the panel collectively decided on ranking the importance of vertical/radial natural circulation as high. The panel also considered the current state of knowledge with respect to natural circulation and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.1.5.16 Pressure Wave Propagation

The panel reached a consensus that pressure wave propagation in the core is of low importance during normal operation, startup and shutdown, and for AOOs. The speed of sound ensures pressure waves propagate with a time frame much smaller compared to natural period of the reactor system, meaning that they could be felt essentially instantaneously with no impact on stability performance. The panel also considered the current state of knowledge with respect to natural circulation and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.1.5.17 Single Phase Convection

The panel reached a consensus that single phase convection in the core is of high importance during normal operation, startup and shutdown, and for AOOs. Convection heat transfer is the primary mechanism for the removal of heat from the fuel assemblies and the heating of the primary coolant. Heating of the coolant contributes to natural circulation, which has a strong effect on stability. The panel considered the current state of knowledge with respect to single phase convection and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.1.5.18 Single Phase Pressure Drop

The panel reached a consensus that single phase pressure drop in the core is of high importance during normal operation, startup and shutdown, and for AOOs. Pressure drop has a direct effect on the natural circulation flow patterns and the dynamic response of flow to changing conditions in the reactor system. The panel considered the current state of knowledge with respect to single phase pressure drop and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.1.5.19 Subcooled Boiling

The panel reached a consensus that subcooled boiling in the core is of medium importance during normal operation, startup and shutdown, but of high importance for AOOs. Subcooled boiling can contribute to voiding in the core and downstream in the hot leg riser. Subcooled boiling in the core can have the effect of heating the coolant downstream in the hot leg riser, which can decrease the margin to flashing or enable limited flashing. This may be more pronounced during startup conditions where the reactor core flow rate is very low. Subcooled boiling will generate possibly more bubbles at the lower core flow conditions where the power/flow ratio is higher. These bubbles will collapse downstream of the core in the riser section heating the fluid in the riser. As the fluid flows upward, the decrease in pressure reduces saturation temperature. Voiding in the hot leg riser can significantly affect the core flow rate. However, the degree of subcooled boiling is expected to be relatively small during normal operation and during startup and shutdown. During transient conditions, such as AOO, the pressure may become lower or power higher, leading to a higher incidence of subcooled boiling, which may have an adverse influence on the stability margin of the reactor system. The panel considered the current state of knowledge with respect to subcooled boiling and, based on its experience with the current state of the art, agreed on ranking the knowledge level as medium.

7.1.5.20 Turbulent Mixing

The panel reached a consensus that turbulent mixing in the core is of low importance during normal operation, startup and shutdown, and for AOOs. Of greater importance is the average coolant temperature and density, which impacts the natural circulation flow rate. The panel considered the current state of knowledge with respect to turbulent mixing in the core and, based on its experience with the current state of the art, agreed on ranking the knowledge level as medium.

7.1.5.21 Two-Phase Convection

The panel reached a consensus that two phase convection in the core is of low importance during normal operation, startup and shutdown, and for AOOs. Significant void formation is precluded by a reactor protection function. The panel considered the current state of knowledge with respect to two-phase convection and, based on its experience with the current state of the art, agreed on ranking the knowledge level as medium.

7.1.5.22 Two-Phase Pressure Drop

The panel reached a consensus that two-phase pressure drop in the core is of low importance during normal operation, startup and shutdown, and for AOOs. Significant void formation is precluded by a reactor protection function. The panel considered the current state of knowledge with respect to two-phase pressure drop and, based on its experience with the current state of the art, agreed on ranking the knowledge level as medium.

7.1.5.23 Void Distribution

The panel reached a consensus that void distribution in the core is of low importance during normal operation, startup and shutdown, and for AOOs. Significant void formation is precluded by a reactor protection function. The panel considered the current state of knowledge with respect to void distribution and, based on its experience with the current state of the art, agreed on ranking the knowledge level as medium.

7.2 Instrumentation and Controls

7.2.1 Primary and Secondary Side Control Systems: Signal Delay

The panel reached a consensus that signal delay is of low importance during normal operation, but of medium importance during startup and shutdown, and for AOOs. During normal operation, control systems should not respond as the reactor is stable and minor, damped oscillations would not result in activation of significant control features. During startup, it is assumed that much of the plant is under manual operator control. During AOOs, the signal delay can affect the protective function. Potentially adverse conditions for stability will persist after being detected by the reactor protection system based on the signal delay, but this is expected to be a small amount of time compared to the natural period of the reactor system. The panel considered the knowledge level of the signal delay to be high.

7.2.2 Primary Pressurizer Control System: Pressure Control System Feedback

The panel reached a consensus that the (primary side) pressure control system feedback is of low importance during normal operation, but of medium importance during startup and shutdown, and for AOOs. Changes in RCS temperature are expected to be sufficiently small during oscillatory conditions and the availability of mixing of the pressurizer water with the primary system flow circuit is also sufficiently small, so that the heater would not respond during conditions of normal operation or AOOs. During startup, pressurization may be achieved by a combination of nuclear power, pressurizer heaters, and the chemical and volume control system. In that case, during startup, the operation of the pressure control systems will have a direct effect on the degree of subcooled boiling in the core and riser, which would have a significant impact on stability. One could imagine an AOO related to operation of the pressurizer heaters, in cases where the heater activates, system pressure would increase, which is expected to be favorable from a stability perspective. Changes in RCS pressure are not expected to be significant as a result of potential oscillations initiated from conditions of normal operation, therefore, the pressurizer spray is not expected to respond. During startup, pressure can be expected to be increased, so spray would not be active. However, during AOOs, operation of the sprays may lead to lower pressure and hence smaller margin to voiding in the core and riser, which would be adverse from a stability perspective. The panel considered the knowledge level of the pressure control feedback system to be high.

7.2.3 Reactor protection: Detector Response

The panel reached a consensus that detector response is of medium importance during normal operation, during startup and shutdown, and for AOOs. This phenomenon description is intended to capture the influence of the local flow field on the performance of the detector as it applies to downstream control functions. As an example, the detector may register and produce a signal for a locally low temperature in the fluid field based on its position in the flow while the bulk fluid temperature is higher. During normal operation and startup, the reactor does not undergo a trip, so these phenomena do not occur. In AOOs, any adverse, unstable conditions are mitigated by a reactor trip, which relies on insertion of the shutdown banks to trip the reactor before SAFDLs are exceeded. The panel considered the knowledge level of the detector response to be high.

7.2.4 Secondary Side Control Systems: Pressure Control System Feedback

The panel reached a consensus that the (secondary side) pressure control system feedback is of medium importance during normal operation, during startup and shutdown, and for AOOs. This phenomenon is ranked as medium importance because controllers typically control behavior through valve positioning, the dynamic behavior of which is expected to be fast relative to the natural period of the reactor system, leading to significant damping of any oscillations caused by controllers on the primary system response. The panel considered the knowledge level of the secondary side pressure control feedback system to be high.

7.2.5 Secondary Side Control Systems: Resonant Interaction

The panel reached a consensus that resonant interaction is of medium importance during normal operation, but of low importance during startup and shutdown, and medium for AOOs. This phenomenon is not expected to occur because controllers typically change valve positions, a process expected to occur at a time frame much shorter than the natural period of the reactor system. There would need to be some similarity in the control system rate or frequency and the natural frequency of the reactor for resonance to occur. The panel considered the knowledge level of the resonant interaction to be medium.

7.2.6 Secondary Side Control Systems: Superheat Control System Feedback

The panel reached a consensus that super heat control on the secondary side is of medium importance during normal operation, during startup and shutdown, and for AOOs. This phenomenon is not ranked as high importance because controllers typically control behavior through valve positioning, the dynamic behavior of which is expected to be fast relative to the natural period of the reactor system, leading to significant damping of any oscillations caused by controllers on the primary system response. The panel considered the knowledge level of the superheat control system feedback to be high.

7.3 Primary System

7.3.1 Baffle Plate

7.3.1.1 Density Wave Propagation

The panel reached a consensus that density wave propagation occurring near the baffle plate is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that while the baffle plate is expected to have a dampening effect on density wave propagation, it should have a large impact on system dynamics by affecting flow rate and direction. The panel also considered the state of the knowledge with respect to density wave propagation and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.1.2 Entrance Effects/Developing Length

The panel reached a consensus that entrance effects/developing length occurring near the baffle plate is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the additional resistance caused by these effects should be small compared to the overall pressure drop of the system. The panel also considered the state of the knowledge with respect to entrance effects/developing length and, based on its experience with the current state of the art, agreed on ranking the knowledge level as medium.

7.3.1.3 Pressure Drop/Local Losses

The panel reached a consensus that pressure drop/local losses occurring near the baffle plate are of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that there should be significant flow losses in this region and that the pressure losses directly affect natural circulation flow rate. The panel also considered the state of the knowledge with respect to pressure drop/local losses and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.1.4 Pressure Wave Propagation

The panel reached a consensus that pressure wave propagation occurring near the baffle plate is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that pressure waves travel at a much faster rate than the natural period of the reactor system. This means that pressure changes are effectively felt instantaneously throughout the reactor system so the oscillations from the waves shouldn't significantly contribute to stability events. The panel also considered the state of the knowledge with respect to pressure wave propagation and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.1.5 Stagnation and Momentum Change

The panel reached a consensus that stagnation and momentum change occurring near the baffle plate is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the flow orientation change in this region has a large impact on system pressure drop which directly affects system flow rate. The panel also considered the state of the knowledge with respect to stagnation and momentum change and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.2 Downcomer

7.3.2.1 Convection Heat Transfer to the Shroud/Riser

The panel reached a consensus that convection heat transfer to the shroud/riser occurring in the downcomer is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the temperature difference between structures and coolant will likely be low, leading to a small amount of total heat transfer. The panel also considered the state of the knowledge with respect to convection heat transfer and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.2.2 Convection Heat Transfer to the Vessel

The panel reached a consensus that convection heat transfer to the vessel occurring in the downcomer is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the temperature difference between structures and coolant will likely be low, leading to a small amount of total heat transfer. The panel also considered the state of the knowledge with respect to convection heat transfer and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.2.3 Density Wave Propagation

The panel reached a consensus that density wave propagation occurring in the downcomer is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the density distribution of the fluid within the flow circuit will have an impact on the natural circulation flow rate, however, without void formation the density differences due to temperature are not as key in driving dynamic flow response as would be the case in a boiling channel. Furthermore, in the NuScale natural circulation flow loop, the integral density differences in vertical components are more significant than local density differences. The panel also considered the state of the knowledge with respect to density wave propagation and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.2.4 Entrance Effects/Developing Length

The panel reached a consensus that entrance effects and developing length occurring in the downcomer is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the pressure drop resulting from the entrance effects/developing length would be minor compared to more significant contributors, such as local form losses, and that any impact on heat transfer would be related to heat transfer between the coolant and structures (with a low temperature difference) which is also insignificant. The panel also considered the state of the knowledge with respect to entrance effects and developing length and, based on its experience with the current state of the art, agreed on ranking the knowledge level as medium. The panel identified this gap in knowledge due to a lack of understanding of the local flow patterns that will develop in the specific geometry of the NuScale design.

7.3.2.5 Flashing

The panel reached a consensus that flashing will be highly unlikely to occur in the downcomer during normal operation, startup, and shutdown. The panel reaches this conclusion based on the design of the stability solution to protect subcooling margin in the riser section as well as consideration of a startup procedure that pressurizes the vessel prior to control rod withdrawal operations. The panel also reached a consensus that the importance of flashing occurring in the downcomer is of low importance during AOOs. In determining this importance ranking, the panel considered that there is generally margin to flashing prior to AOO initiation and that the downcomer fluid is expected to have even greater margin compared to the riser section due to heat removal by the secondary system. If flashing were to occur in the downcomer it would be to a significantly smaller degree than would occur in the riser. The panel also considered the state of the knowledge with respect to flashing and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.2.6 Interfacial *Drag/Relative Motion of the Phases*

The panel reached a consensus that interfacial drag and relative motion of the phases occurring in the downcomer is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that subcooling margin is maintained in the primary loop, which would result in very low void fraction during normal plant operations and AOOs. The panel also considered the state of the knowledge with respect to interfacial drag/relative motion of the phases and, based on its experience with the current state of the art, agreed on ranking the knowledge level as medium, which is consistent with the ranking identified in the TRACE applicability report for integral PWRs.

7.3.2.7 Pressure *Wave Propagation*

The panel reached a consensus that pressure wave propagation occurring in the downcomer is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the speed of sound ensures that pressure waves will propagate through the primary flow loop with a time that is much smaller compared to the natural period of the reactor system. In essence, if pressure changes were felt instantaneously throughout the primary system, this would have little to no impact on the stability characteristics of the reactor system (which depends on the dynamic response and feedback of a natural circulation loop). The panel also considered the state of the knowledge with respect to pressure wave propagation and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.2.8 Radiation *Heat Transfer from Shroud/Riser*

The panel reached a consensus that radiation heat transfer from the shroud/riser occurring in the downcomer is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the temperature of the structures would be sufficiently low that radiation would be negligible compared to other heat transfer mechanisms (i.e., convection). The panel also considered the state of the knowledge with respect to radiation heat transfer and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.2.9 Radiation *Heat Transfer from Vessel*

The panel reached a consensus that radiation heat transfer from the vessel occurring in the downcomer is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the temperature of the structures would be sufficiently low that radiation would be negligible compared to other heat transfer mechanisms (i.e., convection). The panel also considered the state of the knowledge with respect to radiation heat transfer and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.2.10 Single *Phase Pressure Drop*

The panel reached a consensus that single phase pressure drop occurring in the downcomer is of medium importance during normal operation, startup, and shutdown. In determining this importance ranking, the panel considered that the single phase pressure losses are the dominant losses in this component affecting the natural circulation flow rate. The phenomenon was ranked medium as losses in this component are expected to be smaller than in other portions of the flow loop, such as the core and steam generator annulus. The panel reached a consensus that single phase pressure drop occurring in the downcomer is of high importance during AOOs. In determining this importance ranking, the panel considered that the changes in single phase loses through this component of the primary flow loop may have a significant impact on the dynamic response of the core flow rate, depending on the nature of the AOO. The panel also considered the current state of knowledge with respect to single phase pressure drop and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.2.11 Stored *Energy Release/Conduction of the Riser*

The panel reached a consensus that stored energy release/conduction of the riser occurring in the downcomer is of low importance during normal operation, startup, and shutdown. In determining this importance ranking, the panel considered the relatively low temperature difference between the coolant and structures, which would limit the amount of heat transfer, and similarly limit the importance of the stored energy. During AOOs, the panel reached a consensus that stored energy/conduction of the riser is of medium importance. In determining this importance ranking, the panel considered that stored energy release may have a slight damping effect on thermal transients, which could contribute mildly to the stability characteristics of the system, depending on the specific AOO under consideration. The panel also considered the current state of knowledge with respect to stored energy release/conduction of the riser and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.2.12 Stored *Energy Release/Conduction of the Vessel*

The panel reached a consensus that stored energy release/conduction of the vessel occurring in the downcomer is of low importance during normal operation, startup, and shutdown. In determining this importance ranking, the panel considered the relatively low temperature difference between the coolant and structures, which would limit the amount of heat transfer, and similarly limit the importance of the stored energy. During AOOs, the panel reached a consensus that stored energy/conduction of the vessel is of medium importance. In determining this importance ranking, the panel considered that stored energy release may have a slight damping effect on thermal transients, which could contribute mildly to the stability characteristics of the system, depending on the specific AOO under consideration. The panel also considered the current state of knowledge with respect to stored energy release/conduction of the vessel and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.2.13 Two Phase Level Swell

The panel reached a consensus that two phase level swell will be highly unlikely to occur during normal operation, startup, and shutdown. The panel reaches this conclusion based on the design of the stability solution to protect subcooling margin in the riser section as well as consideration of a startup procedure that pressurizes the vessel prior to control rod withdrawal operations. The panel also reached a consensus that the importance of two phase level swell occurring in the downcomer is of low importance during AOOs. In determining this importance ranking, the panel considered that there is generally margin to flashing prior to AOO initiation and that the downcomer fluid is expected to have even greater margin compared to the riser section due to heat removal by the secondary system. If voiding were to occur in the downcomer, it would be to a significantly smaller degree than would occur in the riser – limiting any effect of swell. The panel also considered the state of the knowledge with respect to flashing and, based on its experience with the current state of the art, agreed on ranking the knowledge level as medium, which is consistent with the ranking identified in the TRACE applicability report for integral PWRs.

7.3.2.14 Two Phase Pressure Drop

The panel also reached a consensus that the importance of two phase pressure drop occurring in the lower plenum is of low importance during normal operation, startup and shutdown, and AOOs. In determining this importance ranking, the panel considered that there is generally margin to voiding in the downcomer prior to AOO initiation due to heat removal by the secondary system. If voiding were to occur in the downcomer it would be to a significantly smaller degree than would occur in the riser. This means any impact from two phase pressure drop on the flow could be expected to be negligible compared to the effect of void formation in the riser. The panel also considered the state of the knowledge with respect to flashing and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.2.15 Vertical/Radial Natural Circulation

The panel reached a consensus that vertical/radial natural circulation occurring in the downcomer is of high importance during normal operation, startup and shutdown, and AOOs. In determining this importance ranking, the panel considered that natural circulation flow is the primary mechanism of coolant flow under the majority of operating and anticipated conditions and that a key driver for potential instability (or damping of instability) is the nature of the feedback between pressure drop, core power, and primary loop flow rate under natural circulation conditions. The panel also considered the current state of knowledge with respect to vertical/radial natural circulation and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.3 Downcomer-to-Lower Plenum

7.3.3.1 Density Wave Propagation

The panel reached a consensus that density wave propagation occurring in the downcomer-to-lower plenum region is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the density distribution of the fluid within the flow circuit will have an impact on the natural circulation flow rate, however, without void formation the density differences due to temperature are not as key in driving dynamic flow response as would be the case in a boiling channel. Furthermore, in the NuScale natural circulation flow loop, the integral density differences in vertical components are more significant than local density differences. The panel also considered the state of the knowledge with respect to density wave propagation and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.3.2 Entrance Effects/Developing Length

The panel reached a consensus that entrance effects and developing length occurring in the downcomer-to-lower plenum region is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the pressure drop resulting from the entrance effects/developing length would be minor compared to more significant contributors, such as local form losses, and that any impact on heat transfer would be related to heat transfer between the coolant and structures (with a low temperature difference) which is also insignificant. The panel also considered the state of the knowledge with respect to entrance effects and developing length and, based on its experience with the current state of the art, agreed on ranking the knowledge level as medium. The panel identified this gap in knowledge due to a lack of understanding of the local flow patterns that will develop in the specific geometry of the NuScale design.

7.3.3.3 Pressure Drop/Local Losses

The panel reached a consensus that pressure drop/local losses occurring in the downcomer-to-lower plenum region is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that form losses in this component contribute to the overall flow path resistance and therefore plays a role in determining the natural circulation flow rate, and the dynamic response of the flow rate. The phenomenon was ranked medium as losses in this component are expected to be smaller than in other portions of the flow loop, such as the core and steam generator annulus. The panel also considered the current state of knowledge with respect to pressure drop/local losses and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.3.4 Pressure Wave Propagation

The panel reached a consensus that pressure wave propagation occurring in the downcomer-to-lower plenum region is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the speed of sound ensures that pressure waves will propagate through the primary flow loop with a time that is much smaller compared to the natural period of the reactor system. In essence, if pressure changes were felt instantaneously throughout the primary system, this would have little to no impact on the stability characteristics of the reactor system (which depends on the dynamic response and feedback of a natural circulation loop). The panel also considered the state of the knowledge with respect to pressure wave propagation and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.4 Hot Leg Riser

7.3.4.1 Conduction

The panel reached a consensus that conduction occurring in the hot leg riser is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the temperature difference between the metal components in the hot leg riser and the fluid will be small and that the thermal inertia of the metal components would respond to dynamic changes in heat load much slower than the natural period of the reactor system. The panel also considered the state of the knowledge with respect to conduction and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.4.2 Control Rod Drives/Supports Structures Impact on Flow

The panel reached a consensus that control rod drives/supports structures impact on flow occurring in the hot leg riser is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the structures would cause a significant pressure drop in the system which would result in a lower system flow rate. The panel also considered the state of the knowledge with respect to control rod drives/supports structures impact on flow and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.4.3 Convection Heat Transfer to Shroud/Riser

The panel reached a consensus that convection heat transfer to shroud/riser occurring in the hot leg riser is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the total heat transfer to the shroud is expected to be small in these transients because the difference in temperature between the metal components and fluid is small. The panel also considered the state of the knowledge with respect to convection heat transfer to shroud/riser and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.4.4 Density Wave Propagation

The panel reached a consensus that density wave propagation occurring in the hot leg riser is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that while large significant differences in density from a steam/water mixture are unlikely, small amounts of void in the hot leg riser from subcooled boiling in the core could cause flow rate perturbations if they are able to propagate through the riser before collapsing. The panel also considered the state of the knowledge with respect to density wave propagation and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.4.5 Entrance Effects/Developing Length

The panel reached a consensus that entrance effects/developing length occurring in the hot leg riser is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that entrance effects are expected to be present throughout the entire hot leg riser based on the small development length in the region. However, these effects are not expected to be the dominant pressure loss in the hot leg riser section. The panel also considered the state of the knowledge with respect to entrance effects/developing length and, based on its experience with the current state of the art, agreed on ranking the knowledge level as medium. In determining this knowledge level, the panel considered that due to inherent uncertainties in the local flow and energy distribution, empirical correlations may be unable to accurately predict the phenomenon.

7.3.4.6 Flashing

The panel reached a consensus that flashing occurring in the hot leg riser is of high importance during AOOs, medium importance during startup and shutdown, and low importance during normal operation. In determining this importance ranking, the panel considered that while flashing is highly unlikely during normal operation, its potential occurrence during startup, shutdown, and AOOs would significantly reduce the stability margin of the reactor system. The temperature based trip based on hot leg riser temperature and pressurizer pressure ensures that no initial condition of normal operation could be operated without subcooling margin (though some limited and localized flashing may occur due to subcooled boiling or hot channel effects). The panel also considered the state of the knowledge with respect to flashing and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high. In determining this knowledge level, the panel considered that the conditions which lead to flashing are well understood and models which attempt to capture the flashing affect in reactor safety analysis codes have been used with success with other LWR plants.

7.3.4.7 Interfacial Drag/Relative Motion of the Phases

The panel reached a consensus that interfacial drag/relative motion of the phases occurring in the hot leg riser is of medium importance during AOOs and normal operation and low importance during startup and shutdown. In determining this importance ranking, the panel considered that the additional pressure drop induced by the relative motion of the phases is likely to have a detrimental effect on reactor stability margin. The panel also considered the state of the knowledge with respect to interfacial drag/relative motion of the phases and, based on its experience with the current state of the art, agreed on ranking the knowledge level as medium. In determining this knowledge level, the panel considered that while models exist which attempt to describe the phenomena, they are highly empirical and often require the use of flow regime maps which may result in discontinuities and erroneous predictions.

7.3.4.8 Ledinegg Instability

The panel reached a consensus that Ledinegg Instability occurring in the hot leg riser is of high importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that that this mode of instability can result in undamped flow oscillations which result in undamped reactor power oscillations. The panel also considered the state of the knowledge with respect to Ledinegg Instability and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high. In determining this knowledge level, the panel considered that the Ledinegg Instability is a well understood process in the scientific literature and that any uncertainty in the predictions should be due to an issue with an underlying physical mechanism.

7.3.4.9 Pressure Wave Propagation

The panel reached a consensus that pressure wave propagation occurring in the hot leg riser is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that pressure waves travel at a much faster rate than the natural period of the reactor system. This means that pressure changes are effectively felt instantaneously throughout the reactor system so the oscillations from the waves shouldn't significantly contribute to stability events. The panel also considered the state of the knowledge with respect to pressure wave propagation and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.4.10 Radiation Heat Transfer from Shroud/Riser

The panel reached a consensus that radiation heat transfer from shroud/riser occurring in the hot leg riser is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that since no significant voiding is expected for these transients and the temperature of the fluid and shroud is relatively low, the effect of radiation heat transfer from the shroud to the fluid is negligible compared to the convection heat transfer occurring in the system. The panel also considered the state of the knowledge with respect to radiation heat transfer from shroud/riser and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.4.11 Riser Bypass Flow

The panel reached a consensus that riser bypass flow occurring in the hot leg riser is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that riser bypass flow will be small when compared to the main flow for stability transients so the bypass flow should not have a significant impact on overall system dynamics. The panel also considered the state of the knowledge with respect to riser bypass flow and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.4.12 Stored Energy Release/Conduction of the Riser

The panel reached a consensus that stored energy release/conduction of the riser occurring in the hot leg riser is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that considered that the temperature difference between the metal components in the hot leg riser and the fluid will be small and that the thermal inertia of the metal components would respond to dynamic changes in heat load much slower than the natural period of the reactor system so they should not have a significant impact on stability events. The panel also considered the state of the knowledge with respect to stored energy release/conduction of the riser and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.4.13 Subcooled Boiling

The panel reached a consensus that subcooled boiling occurring in the hot leg riser is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that that for the stability transients considered, it is highly unlikely that the shroud would be hotter than the hot leg fluid so there would be no driving force to initiate subcooled boiling. Thus, the phenomena should have a negligible effect on stability transients. The panel also considered the state of the knowledge with respect to subcooled boiling and, based on its experience with the current state of the art, agreed on ranking the knowledge level as medium.

7.3.4.14 Turbulent Mixing (e.g. Hot Streaking)

The panel reached a consensus that turbulent mixing occurring in the hot leg riser is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that turbulent mixing in the hot leg riser is expected to be high which will help homogenize the temperature distribution in the core. However, in the event of poor turbulent mixing, differences between assemblies could arise which would lead to in-core instabilities. The panel also considered the state of the knowledge with respect to turbulent mixing and, based on its experience with the current state of the art, agreed on ranking the knowledge level as medium.

7.3.4.15 Two-Phase Level Swell

The panel reached a consensus that two-phase level swell occurring in the hot leg riser is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that since the stability transients considered occur with the reactor safety system still in operation, significant two-phase level swell in the hot leg riser region is highly unlikely so the phenomena's impact should be negligible. The panel also considered the state of the knowledge with respect to two-phase level swell and, based on its experience with the current state of the art, agreed on ranking the knowledge level as medium.

7.3.4.16 Two-Phase Pressure Drop

The panel reached a consensus that two-phase pressure drop occurring in the hot leg riser is of medium importance during AOOs and normal operation and low importance during startup and shutdown. In determining this importance ranking the panel considered that any voids that form will increase the overall system pressure drop which directly affects the natural circulation flow rate and stability characteristics of the primary system. The panel also considered the state of the knowledge with respect to two-phase pressure drop and, based on its experience with the current state of the art, agreed on ranking the knowledge level as medium.

7.3.4.17 Vertical/Radial Natural Circulation

The panel reached a consensus that vertical/radial natural circulation occurring in the hot leg riser is of high importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that since there are no pumps in the RCS, the primary mechanism for heat removal from the core is through natural circulation flow. Therefore, any disruption to the natural circulation could cause or exacerbate a stability event. The panel also considered the state of the knowledge with respect to vertical/radial natural circulation and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.4.18 Vortexing

The panel reached a consensus that vortexing occurring in the hot leg riser is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that vortexing is unlikely to occur in the hot leg riser due to the control rod structures which would disrupt the formation of any large scale flow phenomena in the radial direction. However, in the event that vortexing did occur in the hot leg riser, a significant impact to flow rate and pressure drop would be expected which may affect stability characteristics in the reactor coolant system. The panel also considered the state of the knowledge with respect to vortexing and, based on its experience with the current state of the art, agreed on ranking the knowledge level as medium.

7.3.5 Lower Plenum

7.3.5.1 Convection Heat Transfer to the Vessel

The panel reached a consensus that convection heat transfer to the vessel occurring in the lower plenum is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the temperature difference between structures and coolant will likely be low, leading to a small amount of total heat transfer. The panel also considered the state of the knowledge with respect to convection heat transfer and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.5.2 Flashing

The panel reached a consensus that flashing occurring in the lower plenum is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that there is generally margin to flashing prior to AOO initiation and that the lower plenum fluid is expected to have a large margin compared to the riser section due to heat removal by the secondary system. If flashing were to occur in the lower plenum, it would be to a significantly smaller degree than would occur in the riser. The panel also considered the state of the knowledge with respect to flashing and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.5.3 Interfacial Drag/Relative Motion of the Phases

The panel reached a consensus that interfacial drag and relative motion of the phases occurring in the lower plenum is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that subcooling margin is maintained in the primary loop, which would result in very low void fraction during normal plant operations and AOOs. The panel also considered the state of the knowledge with respect to interfacial drag/relative motion of the phases and, based on its experience with the current state of the art, agreed on ranking the knowledge level as medium, which is consistent with the ranking identified in the TRACE applicability report for integral PWRs.

7.3.5.4 Single Phase Pressure Drop

The panel reached a consensus that single phase pressure drop occurring in the lower plenum is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the single phase pressure losses are the dominant losses in this component affecting the natural circulation flow rate. The phenomenon was ranked medium as losses in this component are expected to be smaller than in other portions of the flow loop, such as the core and steam generator annulus. During AOOs, the contribution from the single phase pressure drop in the lower plenum is expected to be smaller than from other components that may become more important during certain anticipated transients, such as the downcomer. The panel also considered the current state of knowledge with respect to single phase pressure drop and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.5.5 Stored Energy Release/Conduction of the Vessel

The panel reached a consensus that stored energy release/conduction of the vessel occurring in the lower plenum is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered the relatively low temperature difference between the coolant and structures, which would limit the amount of heat transfer, and similarly limit the importance of the stored energy. The panel also considered that stored energy release may have a slight damping effect on thermal transients, which could contribute mildly to the stability characteristics of the system, depending on the specific AOO under consideration, however, that the effect of this phenomenon in the lower plenum is minor compared to that in other components (i.e., the riser). The panel also considered the current state of knowledge with respect to stored energy release/conduction of the vessel and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.5.6 Two Phase Level Swell

The panel reached a consensus that two phase level swell will be highly unlikely to occur in the lower plenum during normal operation, startup, and shutdown. The panel reaches this conclusion based on the design of the stability solution to protect subcooling margin in the riser section as well as consideration of a startup procedure that pressurizes the vessel prior to control rod withdrawal operations. The panel also reached a consensus that the importance of two phase level swell occurring in the lower plenum is of low importance during AOOs. In determining this importance ranking, the panel considered that there is generally margin to flashing prior to AOO initiation and that the lower plenum fluid is expected to have even greater margin compared to the riser section due to heat removal by the secondary system. If voiding were to occur in the lower plenum it would be to a significantly smaller degree than would occur in the riser – limiting any effect of swell. The panel also considered the state of the knowledge with respect to two phase level swell and, based on its experience with the current state of the art, agreed on ranking the knowledge level as medium, which is consistent with the ranking identified in the TRACE applicability report for integral PWRs.

7.3.5.7 Two Phase Pressure Drop

The panel reached a consensus that two phase pressure drop will be highly unlikely to occur in the lower plenum during normal operation and startup and shutdown. The panel reaches this conclusion based on the design of the stability solution to protect subcooling margin in the riser section as well as consideration of a startup procedure that pressurizes the vessel prior to control rod withdrawal operations. The panel also reached a consensus that the importance of two phase pressure drop occurring in the lower plenum is of low importance during AOOs. In determining this importance ranking, the panel considered that there is generally margin to flashing prior to AOO initiation and that the lower plenum fluid is expected to have even greater margin compared to the riser section due to heat removal by the secondary system. If voiding were to occur in the lower plenum it would be to a significantly smaller degree than would occur in the riser. This means any impact from two phase pressure drop on the flow could be expected to be negligible compared to the effect of void formation in the riser. The panel also considered the state of the knowledge with respect to two phase pressure drop and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.5.8 Vertical/Radial Natural Circulation

The panel reached a consensus that vertical/radial natural circulation occurring in the lower plenum is of high importance. In determining this importance ranking, the panel considered that natural circulation flow is the primary mechanism of coolant flow under the majority of operating and anticipated conditions and that a key driver for potential instability (or damping of instability) is the nature of the feedback between pressure drop, core power, and primary loop flow rate under natural circulation conditions. The panel also considered the current state of knowledge with respect to vertical/radial natural circulation and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.6 Pressurizer

7.3.6.1 Surge Line Flow

The panel reached a consensus that surge line flow occurring in the pressurizer is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that surge line flow is expected to be a small component of overall RCS flow for the stability transients considered. Additionally, the fluid in the surge line may only act to dampen rather than exacerbate any instability event. The panel also considered the state of the knowledge with respect to surge line flow and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.6.2 Convection Heat Transfer to the Vessel

The panel reached a consensus that convection heat transfer to the vessel occurring in the pressurizer is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the convection heat transfer to the vessel should be relatively constant during stability events because much of the pressurizer is exposed to saturated steam. Additionally, large oscillations in pressurizer level are not expected to have a large impact on the temperature of the vessel wall because of the thermal inertia of the metal components. The panel also considered the state of the knowledge with respect to convection heat transfer to the vessel and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.6.3 Flashing

The panel reached a consensus that flashing occurring in the pressurizer is of medium importance during AOOs and of low importance during normal operation and startup and shutdown. In determining this importance ranking, the panel considered that during some AOOs, pressure in the pressurizer could drop to the point where flashing is significant enough in the pressurizer to cause a perturbation in the RCS. However, during normal operation and startup and shutdown flashing is not expected to cause any significant perturbation in the RCS. Based on these considerations, the panel collectively decided on ranking the importance of flashing as medium importance during AOOs and of low importance during normal operation and startup and shutdown. The panel also considered the state of the knowledge with respect to flashing and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high. In determining this knowledge level, the panel considered that the conditions which lead to flashing are well understood and models which attempt to capture the flashing affect in reactor safety analysis codes have been used with success with other light water reactor plants.

7.3.6.4 Flooding at Baffle Plate

The panel reached a consensus that flooding at baffle plate occurring in the pressurizer is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that since the reactor coolant pressure boundary is expected to be maintained for all of the stability transients considered and void formation from boiling is expected to be minimal, flooding at the baffle plate is thought to be highly unlikely. Based on these considerations, the panel collectively decided on ranking the importance of flooding at baffle plate as low. The panel also considered the state of the knowledge with respect to flooding at baffle plate and, based on its experience with the current state of the art, agreed on ranking the knowledge level as medium.

7.3.6.5 Heater

The panel reached a consensus that heater operation occurring in the pressurizer is of medium importance during AOOs and startup and shutdown and low importance during normal operation. In determining this importance ranking, the panel considered that the heater is not expected to have a significant impact on RCS flow because of the limited mass and heat transfer between the pressurizer and the main RCS. However, since the heaters help control overall system pressure which directly relates to subcooling margin, their ability to maintain system pressure may be more important during AOOs and startup and shutdown. Based on these considerations, the panel collectively decided on ranking the importance of heater operation as medium importance during AOOs and startup and shutdown and low importance during normal operation. The panel also considered the state of the knowledge with respect to heater operation and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.6.6 Interfacial Drag/Relative Motion of the Phases

The panel reached a consensus that interfacial drag/relative motion of the phases occurring in the pressurizer is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that since flow rates in the pressurizer are low, the phases are expected to be separated within the pressurizer. The separated fluid would result in a significantly lower interfacial drag compared to a system where the fluids are mixed which means that any impact on the primary RCS flow should be small. Based on these considerations, the panel collectively decided on ranking the importance of interfacial drag/relative motion of the phases as low. The panel also considered the state of the knowledge with respect to interfacial drag/relative motion of the phases and, based on its experience with the current state of the art, agreed on ranking the knowledge level as medium.

7.3.6.7 Nitrogen Overpressure

The panel reached a consensus that nitrogen overpressure occurring in the pressurizer is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that any nitrogen in the system would tend to migrate to the top of the pressurizer which would isolate it from the main RCS flow. The panel also considered the state of the knowledge with respect to nitrogen overpressure and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.6.8 Noncondensable Gas Effects

The panel reached a consensus that noncondensable gas effects occurring in the pressurizer are of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that noncondensable gases would tend to migrate to the top of the pressurizer which would isolate them and their effects from the main RCS flow. The panel also considered the state of the knowledge with respect to noncondensable gas effects and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.6.9 Phase Separation

The panel reached a consensus that phase separation occurring in the pressurizer is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that under most circumstances the fluid in the pressurizer is expected to be stratified and any disruption of that configuration is expected to have a minimal effect on the RCS flow because of the small flow path that exists between the pressurizer and the main RCS. The panel also considered the state of the knowledge with respect to phase separation and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.6.10 Radiation Heat Transfer from Reactor Vessel to Containment Vessel

The panel reached a consensus that radiation heat transfer from reactor vessel to containment vessel occurring in the pressurizer is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that radiation effects are negligible for the stability transients considered because the structures are at a relatively low temperature. The panel also considered the state of the knowledge with respect to radiation heat transfer from reactor vessel to containment vessel and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.6.11 Single Phase Pressure Drop

The panel reached a consensus that single phase pressure drop occurring in the pressurizer is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that because the flow between the pressurizer and the RCS is small that the impact of single phase pressure drop is expected to have a minimal impact on the primary flow. The panel also considered the state of the knowledge with respect to single phase pressure drop and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.6.12 Spray

The panel reached a consensus that spray occurring in the pressurizer is of medium importance during AOOs and low importance during normal operation and during startup and shutdown. In determining this importance ranking, the panel considered that pressurizer spray is not expected to have a significant impact on RCS flow because of the limited mass and heat transfer between the pressurizer and the main RCS. However, since the spray system helps control overall system pressure which directly relates to subcooling margin, its ability to maintain system pressure may be more important during AOOs. The panel also considered the state of the knowledge with respect to spray and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.6.13 Two Phase Pressure Drop

The panel reached a consensus that two phase pressure drop occurring in the pressurizer is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that because the phases are expected to be separated and because flow between the pressurizer and the RCS is small, the impact of two phase pressure drop in the pressurizer is expected to have a minimal impact on the primary flow. The panel also considered the state of the knowledge with respect to single phase pressure drop and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.6.14 Water Thermal Expansion

The panel reached a consensus that water thermal expansion filling the pressurizer is of medium importance during startup, shutdown, and AOOs and low importance during normal operation. In determining this importance ranking, the panel considered that significant changes in RCS temperature will occur during startup and shutdown and may occur during some AOOs. The thermal expansion caused by these changes in temperature will cause pressure changes which will affect subcooling margin. However, during normal operation, large changes in RCS temperature are not expected thus the water volume is expected to remain relatively constant. The panel also considered the state of the knowledge with respect to water thermal expansion and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.7 Steam Generator Annulus

7.3.7.1 Convection Heat Transfer to the Riser

The panel reached a consensus that convection heat transfer to the riser occurring in the steam generator annulus is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the temperature difference between structures and coolant will likely be low, leading to a small amount of total heat transfer. The convective heat transfer outside of a cylinder has been well studied in the literature. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as high.

7.3.7.2 Convection Heat Transfer to the Steam Generator Tubes

The panel reached a consensus that convection heat transfer to the steam generator tubes occurring in the steam generator annulus is of high importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the heat transfer to the steam generator tubes is the main heat sink which cools down the coolant, which enables the driving force for natural circulation in the main path. This heat transfer mechanism mediates communication of fluctuations in either secondary or primary side flow to the other side of the module. Therefore, this phenomenon can play a highly important role in determining dampening or enhancement of perturbations on one side affecting the other. Due to the cross flow configuration in the annulus, the heat transfer model depends on empirical correlations which have great uncertainties. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as medium.

7.3.7.3 Convection Heat Transfer to the Vessel

The panel reached a consensus that convection heat transfer to the vessel occurring in the steam generator annulus is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the temperature difference between vessel wall and coolant will likely be low since the vessel is thermally insulated, leading to a small amount of total heat transfer. The convective heat transfer inside of a cylinder has been well studied in the literature. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as high.

7.3.7.4 Density Wave Propagation

The panel reached a consensus that density wave propagation occurring in the steam generator annulus is of low importance during normal operation. In determining this importance ranking, the panel considered that the effect of density waves on stability performance would likely be limited because the coolant is expected to remain in the liquid phase and therefore only small differences in density would develop. During startup, shutdown, and during AOOs, there is a possibility for void formation due to potentially lower pressure or higher power conditions in which the density wave propagation may contribute to the stability performance of the reactor system. The density wave propagation phenomena and theory have been well studied in the literature since the 1960s. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as high.

7.3.7.5 Entrance Effects/Developing Length

The panel reached a consensus that entrance effects occurring in the steam generator annulus are of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the entrance effects have to do with the boundary no-slip conditions. These effects affect the natural circulation and, therefore, the stability performance of the module. In this component, the helical coils make the flow area smaller and the developing length shorter. The entrance effects/developing length phenomena and theories in regular flow geometry have been well studied in the literature. However, with the complication of helical coils, the panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as medium.

7.3.7.6 Feed Header Effects on Flow

The panel reached a consensus that feed header effects on flow in the steam generator annulus is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the header provides significant form loss in the main natural circulation path. These effects affect the natural circulation and, therefore, the stability performance of the module. In addition, due to the existence of feed header, unbalanced tube flow may result in uneven heat transfer and fluid density. The feed header presents a special configuration in the flow path. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as medium.

7.3.7.7 Feed Header Stored Energy

The panel reached a consensus that feed header stored energy in the steam generator annulus is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the energy would be small due to its volume and the temperature difference between the structure and the coolant. The stored energy is well studied in the literature. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as high.

7.3.7.8 Flashing

The panel reached a consensus that flashing occurring in the steam generator annulus is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the possibility of liquid flashing will likely be low and could be excluded by protection system. The liquid flashing has been well studied in the literature. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as high.

7.3.7.9 Heat capacitance of primary coolant

The panel reached a consensus that heat capacitance of primary coolant in the steam generator annulus is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that heat capacitance of coolant directly affects the heat transfer from primary side to the secondary side. And the heat transfer will directly affect the stability characteristics of the system. The heat capacitance of primary coolant has been well studied in the literature. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as high.

7.3.7.10 Interfacial Drag/Relative Motion of the Phases

The panel reached a consensus that interfacial drag in the steam generator annulus is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the possibility of two phase flow will likely be low and could be excluded by the protection system. The interfacial drag has been well studied in the literature. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as medium.

7.3.7.11 Pressure Wave Propagation

The panel reached a consensus that pressure wave propagation occurring in the steam generator annulus is of low importance during normal operation, startup, shutdown, and during AOOs. The speed of sound ensures pressure waves propagate with a time frame much smaller compared to natural period of the reactor system, meaning that they could be felt essentially instantaneously with no impact on stability performance. The pressure wave propagation phenomena and theory have been well studied in the literature since the 1960s. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as high.

7.3.7.12 Single Phase Pressure Drop

The panel reached a consensus that single phase pressure drop in the steam generator annulus is of high importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the single phase pressure drop is one of the major pressure drops to affect the driving force for natural circulation in the main path. Due to the cross flow configuration in the annulus, single phase pressure drop is more complicated than the parallel flow. However, the theory and experimental data in this area are sufficiently mature to facilitate accurate modeling in an analysis. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as high.

7.3.7.13 Steam Header Effect on Flow

The panel reached a consensus that steam header effects on flow in the steam generator annulus is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the header provides significant form loss in the main natural circulation path. These effects affect the natural circulation flow and directly affect the stability characteristics of the primary loop. In addition, due to the existence of steam header, unbalanced tube flow may result in uneven heat transfer and fluid density. The feed steam presents a special configuration in the flow path. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as medium.

7.3.7.14 Steam Header Stored Energy

The panel reached a consensus that steam header stored energy in the steam generator annulus is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the energy would be small due to its volume and the temperature difference between the structure and the coolant. The stored energy is well studied in the literature. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as high.

7.3.7.15 Stored Energy Release/Conduction of the Riser

The panel reached a consensus that stored energy released from the riser in the steam generator annulus is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the energy would be small due to its temperature difference between the structure and the coolant. The rate of energy release compared to the natural circulation period is too slow to affect the decay ratio. The stored energy is well studied in the literature. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as high.

7.3.7.16 Stored Energy Release/Conduction of the Vessel

The panel reached a consensus that stored energy released of the vessel wall in the steam generator annulus is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the energy would be small due to its temperature difference between the structure and the coolant. The rate of energy release compared to the natural circulation period is too slow to affect the decay ratio. The stored energy is well studied in the literature. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as high.

7.3.7.17 Tube Bypass Flow (i.e. Outside of the SG Helix, Inside of the Vessel ID)

The panel reached a consensus that tube bypass flow in the steam generator annulus is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the tube bypass flow would be a small fraction of main natural circulation flow. The amount is too small to affect the decay ratio. The tube bypass flow geometry compared to the geometry of cross flow in the main annulus section is relatively simple. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as high.

7.3.7.18 Two Phase Level Swell

The panel reached a consensus that two phase level swell in the steam generator annulus is of low importance during normal operation and AOOs, and not possible in startup and shutdown condition. In determining this importance ranking, the panel considered that the possibility of two phase flow will likely be low and could be excluded by the protection system. Two phase level swell is not likely to happen in these scenarios. But due to the complexity of interfacial drag in helical coils cross flow geometry, the panel agreed on ranking the knowledge level as medium.

7.3.7.19 Two Phase Pressure Drop

The panel reached a consensus that two phase pressure drop in the steam generator annulus is of low importance during normal operation and AOOs, and not possible in startup and shutdown condition. In determining this importance ranking, the panel considered that the possibility of two phase flow will likely be low and could be excluded by the protection system. Two phase pressure drop is well studied in the literature. But the cross flow geometry may complicate the modeling. The panel agreed on ranking the knowledge level as medium.

7.3.7.20 Vertical/Radial Natural Circulation

The panel reached a consensus that vertical/radial natural circulation in the steam generator annulus is of high importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the natural circulation in the annulus is the main driving mechanism for natural circulation in the main path. Flow perturbations on the primary side can be damped or enhanced by this mechanism. Due to the cross flow configuration in the annulus, natural circulation is more complicated than that in a parallel tube flow environment due to its multidimensional flow nature. However, there exists enough theory and data in the literature to model the phenomenon in the analysis. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as medium.

7.3.8 Upper Plenum

7.3.8.1 Convection Heat Transfer to the Vessel

The panel reached a consensus that convection heat transfer to the vessel occurring in the upper plenum is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the temperature difference between structures and coolant will likely be low, leading to a small amount of total heat transfer. The panel also considered the state of the knowledge with respect to convection heat transfer and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.8.2 Density Wave Propagation

The panel reached a consensus that density wave propagation occurring in the upper plenum is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the density distribution of the fluid within the flow circuit will have an impact on the natural circulation flow rate, however, without void formation the density differences due to temperature are not as key in driving dynamic flow response as would be the case in a boiling channel. Furthermore, in the NuScale natural circulation flow loop, the integral density differences in vertical components are more significant than local density differences. The panel also considered the state of the knowledge with respect to density wave propagation and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.8.3 Downcomer Bypass Flow

The panel reached a consensus that downcomer bypass flow occurring in the upper plenum is of low importance. In determining this importance ranking, the panel considered that the bypass flow fraction is small. The panel also considered the current state of knowledge with respect to downcomer bypass flow and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.8.4 Entrance Effects/Developing Length

The panel reached a consensus that entrance effects and developing length occurring in the upper plenum is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the pressure drop resulting from the entrance effects / developing length would be minor compared to more significant contributors, such as local form losses, and that any impact on heat transfer would be related to heat transfer between the coolant and structures (with a low temperature difference) which is also insignificant. The panel also considered the state of the knowledge with respect to entrance effects and developing length and, based on its experience with the current state of the art, agreed on ranking the knowledge level as medium. The panel identified this gap in knowledge due to a lack of understanding of the local flow patterns that will develop in the specific geometry of the NuScale design.

7.3.8.5 Flashing

The panel reached a consensus that flashing occurring in the upper plenum is of low importance during normal operation, startup, and shutdown. In determining this importance ranking, the panel considered that there is generally margin to flashing as afforded by the design of the stability solution to protect subcooling margin in the riser section as well as consideration of a startup procedure that pressurizes the vessel prior to control rod withdrawal operations. However, pressure is lower in the upper plenum compared to the riser, lower plenum, and downcomer, leading to lower subcooling margin in this region of the primary side. While subcooling margin is expected prior to AOO initiation, flashing may occur in the upper plenum during particular AOO scenarios. Therefore, the panel considers flashing to be of higher importance during AOOs. However, the impact of voiding in the upper plenum is expected to have a smaller impact on the natural circulation core flow rate and stability characteristics compared to void formation in the riser section. Based on these considerations, the panel collectively decided on ranking the importance of flashing as low during normal operation and startup and shutdown and medium during AOOs. The panel also considered the state of the knowledge with respect to flashing and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.8.6 Interfacial Drag/Relative Motion of the Phases

The panel reached a consensus that interfacial drag and relative motion of the phases occurring in the upper plenum is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that subcooling margin is maintained in the primary loop, which would result in very low void fraction during normal plant operations and AOOs. If voiding were to occur in the upper plenum, the effect of the interfacial drag would be insignificant compared to the effect of void in the riser. The panel also considered the state of the knowledge with respect to interfacial drag/relative motion of the phases and, based on its experience with the current state of the art, agreed on ranking the knowledge level as medium, which is consistent with the ranking identified in the TRACE applicability report for integral PWRs.

7.3.8.7 Pressure Wave Propagation

The panel reached a consensus that pressure wave propagation occurring in the upper plenum region is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the speed of sound ensures that pressure waves will propagate through the primary flow loop with a time that is much smaller compared to the natural period of the reactor system. In essence, if pressure changes were felt instantaneously throughout the primary system, this would have little to no impact on the stability characteristics of the reactor system (which depends on the dynamic response and feedback of a natural circulation loop). The panel also considered the state of the knowledge with respect to pressure wave propagation and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.8.8 Radiation Heat Transfer from the Reactor Vessel to Containment Vessel

The panel reached a consensus that radiation heat transfer from the reactor vessel to the containment vessel occurring in the upper plenum is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the temperature of the structures would be sufficiently low that radiation would be negligible compared to other heat transfer mechanisms (i.e., convection). The panel also considered the state of the knowledge with respect to radiation heat transfer and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.8.9 Single Phase Pressure Drop

The panel reached a consensus that single phase pressure drop occurring in the upper plenum is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the single phase pressure losses are the dominant losses in this component affecting the natural circulation flow rate. The phenomenon was ranked medium as losses in this component are expected to be smaller than in other portions of the flow loop, such as the core and steam generator annulus. During AOOs, the contribution from the single phase pressure drop in the upper plenum is expected to be smaller than from other components that may become more important during certain anticipated transients, such as the downcomer. The panel also considered the current state of knowledge with respect to single phase pressure drop and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.8.10 Stored Energy Release/Conduction of the Vessel

The panel reached a consensus that stored energy release/conduction of the vessel occurring in the upper plenum is of low importance during normal operation, startup, and shutdown. In determining this importance ranking, the panel considered the relatively low temperature difference between the coolant and structures, which would limit the amount of heat transfer, and similarly limit the importance of the stored energy. During AOOs, the panel reached a consensus that stored energy/conduction of the lower plenum is of low importance. In determining this importance ranking, the panel considered that stored energy release may have a slight damping effect on thermal transients, which could contribute mildly to the stability characteristics of the system, depending on the specific AOO under consideration. However, the effect of this phenomenon in the upper plenum is minor compared to that in other components (i.e., the riser). The panel also considered the current state of knowledge with respect to stored energy release/conduction of the vessel and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.8.11 Two Phase Level Swell

The panel reached a consensus that two phase level swell occurring in the upper plenum is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that two phase conditions are not expected in the upper plenum, but may occur to a limited extent. If two phase conditions develop perhaps during certain AOOs, given this limited nature, they are not expected to have a significant impact on the overall natural circulation flow patterns that develop, overall loop flow resistance, or flow feedback characteristics. The panel also considered the current state of knowledge with respect to two phase level swell and, based on its experience with the current state of the art, agreed on ranking the knowledge level as medium, which is consistent with the ranking identified in the TRACE applicability report for integral PWRs.

7.3.8.12 Two Phase Pressure Drop

The panel reached a consensus that two phase pressure drop occurring in the upper plenum is of low importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that two phase conditions are not expected in the upper plenum, but may occur to a limited extent. If two phase conditions develop perhaps during certain AOOs, given this limited nature, they are not expected to have a significant impact on the overall natural circulation flow patterns that develop, overall loop flow resistance, or flow feedback characteristics. The panel also considered the current state of knowledge with respect to two phase pressure drop and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.3.8.13 Vertical/Radial Natural Circulation

The panel reached a consensus that vertical/radial natural circulation occurring in the upper plenum is of high importance. In determining this importance ranking, the panel considered that natural circulation flow is the primary mechanism of coolant flow under the majority of operating and anticipated conditions and that a key driver for potential instability (or damping of instability) is the nature of the feedback between pressure drop, core power, and primary loop flow rate under natural circulation conditions. The panel also considered the current state of knowledge with respect to vertical/radial natural circulation and, based on its experience with the current state of the art, agreed on ranking the knowledge level as high.

7.4 Secondary System

7.4.1 Steam generator tubes

7.4.1.1 Asymmetric Loading

The panel reached a consensus that asymmetric loading in the steam generator tubes is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the imbalance operation of the two steam generators (SGs) could affect the heat transfer patterns and flow regimes. The SGs are intertwined, and therefore, an asymmetric loading on the SG does not inherently produce any discernable effect on the primary side – in essence two SGs operating at 100 percent each would be indistinguishable from in terms of the primary flow as one SG operating at 200 percent heat removal. Possible asymmetries would be limited to a smooth azimuthal gradient that could appear over a length limited by the pitch between tube centers, which would be small compared to the axial height of the downcomer. However, plugging could result in asymmetric loading that would result in one SG bearing more of the heat removal burden relative to the other, resulting in a difference in the average boiling length for the more heavily burdened SG. In that case, one of the SGs may become more susceptible to Ledinegg or density wave instability owing to the difference in average heat load. The asymmetric loading of steam generator is typical in

PWR operation. However, due to the complex heat transfer modes in the steam generator tubes to maintain a balanced operating condition on both primary and secondary sides, some uncertainties are expected. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as medium.

7.4.1.2 Conduction through the Tube Wall

The panel reached a consensus that conduction through the tube wall is of high importance during normal operation and during AOOs. In determining this importance ranking, the panel considered that the heat conduction transfer to the steam generator tubes is the main heat sink which enables the driving force for natural circulation in the main path. Phenomena significantly affecting the natural circulation flow pattern in the primary loop are highly important to the stability characteristics of the reactor system. However, in the startup and shutdown operation, the heat transfer amount is relatively small because the power is lower, and this led the panel to the medium ranking. The heat conduction heat transfer has been well studied in the literature. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as high.

7.4.1.3 Density Wave Propagation

The panel reached a consensus that density wave propagation in the steam generator tubes is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that in a flow channel with high void fraction, density wave propagation could vary the local void significantly enough to shift the flow and heat transfer boundaries. With any disturbances or parallel channel oscillation existing in the secondary system, this phenomenon could enhance the disturbance. In reaching its final importance determination, the panel assumed that the SG would be designed with adequate orificing of the helical coils to ensure that density wave oscillations are inherently damped. Such a design would ensure that unstable oscillations could only persist when further enhanced by other feedback contributions (e.g., from the secondary side control systems, or primary side interactions). The density wave propagation is a well-studied phenomenon. However, there exist some degrees of uncertainty in the helical coil flow geometry and two phase heat transfer modes. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as medium.

7.4.1.4 Feedwater Inlet Temperature/Feedwater Heating

The panel reached a consensus that feedwater inlet temperature/feedwater heating in the steam generator tubes is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that in a flow channel with high void fraction, feedwater inlet temperature (or the subcooling) could affect the local void significantly enough to shift the flow and heat transfer mode boundaries. If any disturbances or parallel channel oscillation occurs in the secondary system, this parameter could enhance the disturbance. The importance of this phenomenon may be considered more highly important if it was later determined that density wave driven instability were likely to occur on the secondary side, however, the panel assumed in its determination that the SG would be designed in such a manner (e.g., through coil inlet orificing) as to be inherently stable. The feedwater temperature is a boundary condition of the secondary system. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as high.

7.4.1.5 Flashing

The panel reached a consensus that flashing in the steam generator tubes is of low importance during normal operation, startup, and shutdown. In determining this importance ranking, the panel considered that the flashing is not likely to occur during normal operation, startup, or shutdown because pressure on the secondary side is not expected to rapidly decrease. However, in the AOO operations, the steam line pressure and the feedwater inlet temperature could swing, which led the panel to rank this phenomenon as being of medium importance during AOOs. The flashing has been well studied in the literature. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as high.

7.4.1.6 Heat Capacitance of Secondary Coolant

The panel reached a consensus that the heat capacitance in the steam generator tubes is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that in a flow channel with high void fraction, the heat capacitance could affect the local void significantly enough to shift the flow and heat transfer mode boundaries. Any perturbations on the primary side may be enhanced or dampened by a moderate degree by the induced fluctuations that could occur in the secondary side as a result of the heat capacity of the secondary side coolant. The heat capacitance is determined by the heat transfer mode and flow regime. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as high.

7.4.1.7 Inlet Losses/Orificing

The panel reached a consensus that the inlet loss/orifcing in the steam generator tubes is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that any disturbance or instability (e.g., parallel channel instability) could be affected by the pressure drop caused by the inlet loss or orifice position. In reaching its determination, the panel assumed that the SG would be designed in such a way to ensure that the inlet losses through coil orifices would be sufficient to damp density wave oscillations. The inlet losses/orificing is well studied in the literature. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as high.

7.4.1.8 Ledinegg Instability

The panel reached a consensus that the Ledinegg instability in the steam generator tubes is of high importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the likelihood of this instability is high due to the complex fluid state in the steam generator tubes due to the existence of multiple heat transfer modes and flow regimes. This instability mode is not easily dampened and it could result in oscillation. The Ledinegg instability mechanism is well understood through many studies in the literature. However, due to the existence of multiple two phase heat transfer modes in the same tube, the prediction capability of this instability could involve uncertainties associated with other two phase phenomena (e.g., such as interfacial drag). The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as high.

7.4.1.9 Minimum Stable Film Boiling

The panel reached a consensus that minimum stable film boiling in the steam generator tubes is of low importance during normal operation, startup, and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the minimum stable film boiling is not likely to occur in the scenarios considered by the panel. The minimum stable film boiling temperature has been a popular research interest in the literature. Current modeling still depends on empirical formulation. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as medium.

7.4.1.10 Parallel Channel Effects

The panel reached a consensus that the parallel channel effects in the steam generator tubes is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the parallel channel effects could mostly affect the flows in the low flow scenario and it could lead to a channel or steam generator wide instability. However, in reaching its ranking, the panel assumed that the SG has been designed in such a way as to ensure density wave driven oscillations are damped (e.g., through coil inlet orifice design). The parallel channel effects are well studied in the literature. Due to the helical coil arrangement, there could be some uncertainties. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as medium.

7.4.1.11 Secondary Side Pressure

The panel reached a consensus that the secondary side pressure in the steam generator tubes is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the secondary side pressure could affect the heat transfer modes and void distribution in the tubes. Any pressure oscillation in the secondary side could affect the heat transfer and any oscillations would propagate into primary side, albeit with a damped magnitude. The secondary side pressure effects on the heat transfer modes in secondary side are well studied and secondary pressure is likely to be controlled during all normal and anticipated operational conditions. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as high.

7.4.1.12 Single Phase Heat Transfer to Liquid

The panel reached a consensus that the single phase heat transfer to liquid in the steam generator tubes is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that single phase heat transfer to liquid could be the limiting heat resistance. However, the length of this heat transfer mode is relatively shorter than the single phase vapor. The single phase heat transfer to liquid in secondary side has to do with the boiling length which has uncertainty in the helical tubes. With many applications of helical coils in industry and studies in academia, the panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as high.

7.4.1.13 Single Phase Heat Transfer to Vapor

The panel reached a consensus that the single phase heat transfer to vapor in the steam generator tubes is of medium importance during normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that single phase heat transfer to vapor contributes a significant part of the overall heat transfer. However, the length of this heat transfer mode depends on the boiling length. The single phase heat transfer to vapor in secondary side has to do with the boiling length which has uncertainty in the helical tubes. With many applications of helical coils in industry and studies in academia, the panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as high.

7.4.1.14 Stored Energy of the Tubes

The panel reached a consensus that the stored energy in the steam generator tubes is of medium importance during the startup, shutdown, and during AOOs. In determining this importance ranking, the panel considered that the heat capacitance and stored energy could dampen the communication of any perturbation between the primary and secondary sides under transient conditions where the total core power is changing. However, in the steady state normal operating condition, the stored energy is ranked as being of low importance due to the small temperature difference between the coolant and structure. Stored energy in metal tubes is well studied in the literature. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as high.

7.4.1.15 Transition Boiling

The panel reached a consensus that the transition boiling is of low importance during the normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the transition boiling itself is not a stable heat transfer mode. If it exists in the secondary tubes, the amount of heat transfer is small relative to other modes. The transition boiling is not as well studied in the literature as other heat transfer modes, particularly in the helical coil tubes. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as medium.

7.4.1.16 Two Phase Heat Transfer

The panel reached a consensus that two phase heat transfer is of high importance during the normal operation and during AOOs. In determining this importance ranking, the panel considered that two phase heat transfer is a major part of the heat transfer from primary to secondary side. Any instability in the secondary side could be affected by this mode of heat transfer. In startup and shutdown operation, the panel reduced the importance ranking to medium because this mode of heat transfer is less important at lower reactor power levels. The two phase heat transfer is well studied in the literature; there exist some complexities in the helical coil tubes. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as medium.

7.4.1.17 Void Distribution

The panel reached a consensus that void distribution is of medium importance during the normal operation, startup and shutdown, and during AOOs. In determining this importance ranking, the panel considered that the void distribution determines the partition of different heat transfer modes and the overall heat transfer from the primary side to the secondary side. The void distribution is a well-studied subject in the literature; however there exist some complexities in the interfacial drag in helical coil tubes due to the centrifugal force. The panel considered the state of the knowledge and experience and agreed on ranking the knowledge level as medium.

Table 2: PIRT Importance and Knowledge Level Rankings

			Importance Ranking			
System	**Component**	**Process/Phenomenon**	**Normal Operation (100% Power)**	**During Startup / Shutdown**	**During AOO**	**Knowledge Level**
core	barrel/baffle	bypass flow	L	L	L	H
core	barrel/baffle	density wave propagation	L	L	L	H
core	barrel/baffle	entrance effects/developing length	L	L	L	H
core	barrel/baffle	pressure wave propagation	L	L	L	H
core	barrel/baffle	stored energy	L	L	L	H
core	barrel/baffle	water thermal expansion	M	M	M	H
core	control rods and guide tubes	effects on flow	L	L	L	H
core	control rods and guide tubes	effects on heat transfer	L	L	L	H
core	fuel rods	assembly burnup distribution	L	L	L	H
core	fuel rods	boron precipitation	N/A	N/A	N/A	H
core	fuel rods	cladding conductivity	M	L	M	H
core	fuel rods	cladding oxidation	L	L	L	H
core	fuel rods	cladding strain	L	L	L	H
core	fuel rods	core pin-by-pin burnup distribution	L	L	L	H
core	fuel rods	fission power	H	H	H	H
core	fuel rods	fuel conductivity and density	M	M	M	H
core	fuel rods	fuel heat capacity	M	M	M	H
core	fuel rods	gap conductance	M	M	M	M
core	fuel rods	initial gap pressure	L	L	L	H
core	fuel rods	pellet radial power distribution	L	L	L	H
core	fuel rods	stored energy	M	M	M	H

			Importance Ranking			
System	**Component**	**Process/Phenomenon**	**Normal Operation (100% Power)**	**During Startup / Shutdown**	**During AOO**	**Knowledge Level**
core	fuel rods	total peaking factor	L	L	L	H
core	kinetics	assembly interaction (e.g., through ADFs)	L	L	L	H
core	kinetics	axial/radial reflector representation	L	L	L	M
core	kinetics	decay heat	M	H	M	H
core	kinetics	delayed neutrons	H	H	H	H
core	kinetics	fuel temperature feedback	H	H	H	H
core	kinetics	moderator density feedback	H	H	H	H
core	kinetics	moderator temperature feedback	M	H	H	H
core	kinetics	pellet burnup distribution	L	L	L	H
core	kinetics	pellet/structure/coolant direct energy	L	L	L	H
core	kinetics	pin-to-pin power distribution	L	L	L	H
core	kinetics	shutdown bank speed	L	L	M	H
core	kinetics	shutdown bank worth	L	M	M	H
core	kinetics	solube boron reactivity feedback	M	M	M	H
core	kinetics	steady-state assembly-to-assembly radial peaking	M	M	M	H
core	kinetics	steady-state axial power peaking	L	L	L	H
core	kinetics	time in fuel cycle	M	M	M	H
core	kinetics	transient change in assembly-to-assembly radial peaking	N/A	L	M	H
core	kinetics	transient change in axial power peaking	N/A	L	L	H
core	kinetics	withdrawn control rod bank worth	L	L	L	H
core	kinetics	xenon/samarium concentrations	L	L	L	H
core	subchannel	boron blockage in subchannels	N/A	N/A	N/A	H
core	subchannel	clad ballooning	N/A	L	L	H
core	subchannel	core pressure drop	H	H	H	H

			Importance Ranking			
System	**Component**	**Process/Phenomenon**	**Normal Operation (100% Power)**	**During Startup / Shutdown**	**During AOO**	**Knowledge Level**
core	subchannel	critical heat flux	L	L	L	H
core	subchannel	cross flow / mixing	L	L	L	M
core	subchannel	density wave propagation	M	L	M	H
core	subchannel	entrance effects/developing length	M	L	M	M
core	subchannel	flashing	L	L	L	H
core	subchannel	flow distribution	M	L	M	H
core	subchannel	flow regime transition	L	L	L	M
core	subchannel	grid spacer effects (entrainment/deentrainment)	N/A	N/A	N/A	N/A
core	subchannel	grid spacer effects (heat transfer)	L	L	L	H
core	subchannel	heat capacitance of primary coolant	M	M	M	H
core	subchannel	interfacial drag/relative motion of the phases	L	L	L	M
core	subchannel	natural circulation	H	H	H	H
core	subchannel	pressure wave propagation	L	L	L	H
core	subchannel	single phase convection	H	H	H	H
core	subchannel	single phase pressure drop	H	H	H	H
core	subchannel	subcooled boiling	M	M	H	M
core	subchannel	turbulent mixing	L	L	L	M
core	subchannel	two phase convection	L	L	L	M
core	subchannel	two phase pressure drop	L	L	L	M
core	subchannel	void distribution	L	L	L	M
instrumentation and controls	primary and secondary side control systems	signal delay	L	M	M	H

			Importance Ranking			
System	**Component**	**Process/Phenomenon**	**Normal Operation (100% Power)**	**During Startup / Shutdown**	**During AOO**	**Knowledge Level**
instrumentation and controls	primary pressurizer control system	pressure control system feedback	L	M	M	H
instrumentation and controls	reactor protection	detector response (including instrument response to local variations in flow fields)	M	M	M	H
instrumentation and controls	secondary side control systems	pressure control system feedback	M	M	M	H
instrumentation and controls	secondary side control systems	resonant interaction	M	L	M	M
instrumentation and controls	secondary side control systems	super heat control system feedback	M	M	M	H
primary	baffle plate	density wave propagation	M	M	M	H
primary	baffle plate	entrance effects/developing length	L	L	L	M
primary	baffle plate	pressure drop/local losses	M	M	M	H
primary	baffle plate	pressure wave propagation	L	L	L	H
primary	baffle plate	stagnation and momentum change	M	M	M	H
primary	downcomer	convection heat transfer to shroud/riser	L	L	L	H
primary	downcomer	convection heat transfer to the vessel	L	L	L	H
primary	downcomer	density wave propagation	M	M	M	H
primary	downcomer	entrance effects/developing length	L	L	L	M
primary	downcomer	flashing	N/A	N/A	L	H
primary	downcomer	interfacial drag/relative motion of the phases	L	L	L	M
primary	downcomer	pressure wave propagation	L	L	L	H
primary	downcomer	radiation heat transfer from shroud/riser	L	L	L	H
primary	downcomer	radiation heat transfer from vessel	L	L	L	H

			Importance Ranking			
System	**Component**	**Process/Phenomenon**	**Normal Operation (100% Power)**	**During Startup / Shutdown**	**During AOO**	**Knowledge Level**
primary	downcomer	single phase pressure drop	M	M	H	H
primary	downcomer	stored energy release/conduction of the riser	L	L	M	H
primary	downcomer	stored energy release/conduction of the vessel	L	L	M	H
primary	downcomer	two phase level swell	N/A	N/A	L	M
primary	downcomer	two phase pressure drop	L	L	L	H
primary	downcomer	vertical/radial natural circulation	H	H	H	H
primary	downcomer-to-lower plenum	density wave propagation	M	M	M	H
primary	downcomer-to-lower plenum	entrance effects/developing length	L	L	L	M
primary	downcomer-to-lower plenum	pressure drop/local losses	M	M	M	H
primary	downcomer-to-lower plenum	pressure wave propagation	L	L	L	H
primary	hot leg riser	conduction	L	L	L	H
primary	hot leg riser	control rod drives/supports structures affect on flow	M	M	M	H
primary	hot leg riser	convection heat transfer to shroud/riser	L	L	L	H
primary	hot leg riser	density wave propagation	M	M	M	H
primary	hot leg riser	entrance effects/developing length	M	M	M	M
primary	hot leg riser	flashing	L	M	H	H
primary	hot leg riser	interfacial drag/relative motion of the phases	M	L	M	M
primary	hot leg riser	Ledinegg instability	H	H	H	H

			Importance Ranking			
System	**Component**	**Process/Phenomenon**	**Normal Operation (100% Power)**	**During Startup / Shutdown**	**During AOO**	**Knowledge Level**
primary	hot leg riser	pressure wave propagation	L	L	L	H
primary	hot leg riser	radiation heat transfer from shroud/riser	L	L	L	H
primary	hot leg riser	riser bypass flow	L	L	L	H
primary	hot leg riser	stored energy release/conduction of the riser	L	L	L	H
primary	hot leg riser	subcooled boiling	L	L	L	M
primary	hot leg riser	Turbulent mixing (e.g., hot streaking)	M	M	M	M
primary	hot leg riser	two phase level swell	L	L	L	M
primary	hot leg riser	two phase pressure drop	M	L	M	M
primary	hot leg riser	vertical/radial natural circulation	H	H	H	H
primary	hot leg riser	vortexing	L	L	L	M
primary	lower plenum	convection heat transfer to the vessel	L	L	L	H
primary	lower plenum	flashing	L	L	L	H
primary	lower plenum	interfacial drag/relative motion of the phases	L	L	L	M
primary	lower plenum	single phase pressure drop	M	M	M	H
primary	lower plenum	stored energy release/conduction of the vessel	L	L	L	H
primary	lower plenum	two phase level swell	N/A	N/A	L	M
primary	lower plenum	two phase pressure drop	N/A	N/A	L	H
primary	lower plenum	vertical/radial natural circulation	H	H	H	H
primary	pressurizer	"surge line" flow	L	L	L	H
primary	pressurizer	convection heat transfer to the vessel	L	L	L	H
primary	pressurizer	flashing	L	L	M	H
primary	pressurizer	flooding at baffle plate	L	L	L	M
primary	pressurizer	heater	L	M	M	H

System	Component	Process/Phenomenon	Importance Ranking: Normal Operation (100% Power)	During Startup / Shutdown	During AOO	Knowledge Level
primary	pressurizer	interfacial drag/relative motion of the phases	L	L	L	M
primary	pressurizer	nitrogen overpressure	L	L	L	H
primary	pressurizer	noncondensable gas effects	L	L	L	H
primary	pressurizer	phase separation	L	L	L	H
primary	pressurizer	radiation heat transfer from reactor vessel to containment vessel	L	L	L	H
primary	pressurizer	single phase pressure drop	L	L	L	H
primary	pressurizer	spray	L	L	M	H
primary	pressurizer	two phase pressure drop	L	L	L	H
primary	pressurizer	water thermal expansion	L	M	M	H
primary	steam generator annulus	convection heat transfer to the riser	L	L	L	H
primary	steam generator annulus	convection heat transfer to the steam generator tubes	H	H	H	M
primary	steam generator annulus	convection heat transfer to the vessel	L	L	L	H
primary	steam generator annulus	density wave propagation	L	M	M	H
primary	steam generator annulus	entrance effects/developing length	M	M	M	M
primary	steam generator annulus	feed header effect on flow	M	M	M	M

			Importance Ranking			
System	**Component**	**Process/Phenomenon**	**Normal Operation (100% Power)**	**During Startup / Shutdown**	**During AOO**	**Knowledge Level**
primary	steam generator annulus	feed header stored energy	L	L	L	H
primary	steam generator annulus	flashing	L	L	L	H
primary	steam generator annulus	heat capacitance of primary coolant	M	M	M	H
primary	steam generator annulus	interfacial drag/relative motion of the phases	L	L	L	M
primary	steam generator annulus	pressure wave propagation	L	L	L	H
primary	steam generator annulus	single phase pressure drop	H	H	H	H
primary	steam generator annulus	steam header effect on flow	M	M	M	M
primary	steam generator annulus	steam header stored energy	L	L	L	H
primary	steam generator annulus	stored energy release/conduction of the riser	L	L	L	H
primary	steam generator annulus	stored energy release/conduction of the vessel	L	L	L	H

			Importance Ranking			
System	**Component**	**Process/Phenomenon**	**Normal Operation (100% Power)**	**During Startup / Shutdown**	**During AOO**	**Knowledge Level**
primary	steam generator annulus	tube bypass flow (i.e. outside of the SG helix, inside of the vessel ID)	L	L	L	H
primary	steam generator annulus	two phase level swell	L	N/A	L	M
primary	steam generator annulus	two phase pressure drop	L	N/A	L	M
primary	steam generator annulus	vertical/radial natural circulation	H	H	H	M
primary	upper plenum	convection heat transfer to the vessel	L	L	L	H
primary	upper plenum	density wave propagation	M	M	M	H
primary	upper plenum	downcomer bypass flow	L	L	L	H
primary	upper plenum	entrance effects/developing length	L	L	L	M
primary	upper plenum	flashing	L	L	M	H
primary	upper plenum	interfacial drag/relative motion of the phases	L	L	L	M
primary	upper plenum	pressure wave propagation	L	L	L	H
primary	upper plenum	radiation heat transfer from reactor vessel to containment vessel	L	L	L	H
primary	upper plenum	single phase pressure drop	M	M	M	H
primary	upper plenum	stored energy release/conduction of the vessel	L	L	L	H
primary	upper plenum	two phase level swell	L	L	L	M
primary	upper plenum	two phase pressure drop	L	L	L	H
primary	upper plenum	vertical/radial natural circulation	H	H	H	H

System	Component	Process/Phenomenon	Importance Ranking: Normal Operation (100% Power)	During Startup / Shutdown	During AOO	Knowledge Level
secondary	steam generator tubes	asymmetric loading	M	M	M	M
secondary	steam generator tubes	conduction through the tube wall	H	M	H	H
secondary	steam generator tubes	density wave propagation	M	M	M	M
secondary	steam generator tubes	feedwater inlet temperature/feedwater heating	M	M	M	H
secondary	steam generator tubes	flashing	L	L	M	H
secondary	steam generator tubes	heat capacitance of secondary coolant	M	M	M	H
secondary	steam generator tubes	inlet losses/orificing	M	M	M	H
secondary	steam generator tubes	Ledinegg instability	H	H	H	H
secondary	steam generator tubes	minimum stable film boiling	L	L	L	M
secondary	steam generator tubes	parallel channel effects	M	M	M	M
secondary	steam generator tubes	secondary side pressure	M	M	M	H
secondary	steam generator tubes	single phase heat transfer to liquid	M	M	M	H
secondary	steam generator tubes	single phase heat transfer to vapor	M	M	M	H

			Importance Ranking			
System	**Component**	**Process/Phenomenon**	**Normal Operation (100% Power)**	**During Startup / Shutdown**	**During AOO**	**Knowledge Level**
secondary	steam generator tubes	stored energy of the tubes	L	M	M	H
secondary	steam generator tubes	transition boiling	L	L	L	M
secondary	steam generator tubes	two phase heat transfer	H	M	H	M
secondary	steam generator tubes	void distribution	M	M	M	M

8 Phenomena Importance / Knowledge Level Issues

In performing this PIRT, the panel identified several phenomena with high importance, but less than high knowledge levels. These phenomena are listed in this section for follow-up activities associated with determining TRACE applicability. These phenomena are:

- Convection heat transfer to the steam generator tubes occurring in the steam generator annulus of the primary side was considered to be of high importance, but the knowledge level was ranked as medium.
- Vertical/radial natural circulation occurring in steam generator annulus of the primary side was considered to be of high importance, but the knowledge level was ranked as medium.
- Two phase heat transfer occurring on the secondary side of the steam generator tubes was considered to be of high importance, but medium knowledge level.

These highly important phenomena should be further evaluated as a part of future work to determine the applicability of TRACE to evaluate stability for NuScale. Similar to what has been done previously in Ref. 5, the panel rated these three highly important phenomena according to a category system, summarized below (the panel only categorized the three phenomena with high importance and less than high knowledge ranking):

- Category A - TRACE and/or PARCS is considered fully applicable and can be expected to accurately simulate associated processes and phenomena.
- Category B - TRACE and/or PARCS is expected to be applicable and should be capable of simulating the associated processes and phenomena with only limited code development or additional assessment.
- Category C - TRACE and/or PARCS models/correlations are not designed to simulate these phenomena. However, the effects of these phenomena can be bounded using existing TRACE capabilities (i.e., code work-around) and the appropriate well scaled integral effects data representing the SMR geometry.
- Category D - Additional TRACE and/or PARCS model development and assessment is considered necessary to demonstrate TRACE/PARCS applicability for the phenomena in this category. Also, the use of well-scaled integral and/or separate effects data representing the SMR geometry is required.

In evaluating these phenomena and the capabilities of TRACE, the panel concludes that these three phenomena fall into category B. With additional assessment of TRACE against appropriate and relevant test data, it should be possible to make adjustments to input parameters to bring TRACE into reasonable agreement in simulating these phenomena. However, final determination of TRACE applicability to analyze NuScale stability is the subject of future work.

9 Summary and Conclusions

The panel concluded its ranking and identified several phenomena important to NuScale stability. In performing the ranking, the panel considered the decay ratio as the relevant figure of merit for analysis. Further, the panel considered stability performance of the NuScale power module during 100% power, normal operation, during startup and shutdown, and during AOOs. The phenomena ranked as highly important (during any condition) is listed in Table 3.

The panel also ranked the knowledge level for each phenomena. Of these highly ranked phenomena, the panel found three highly important phenomena with a knowledge level lower than high (in all three cases, the panel identified the knowledge level as medium). These phenomena are:

- Convection heat transfer to the steam generator tubes occurring in the steam generator annulus of the primary side was considered to be of high importance, but the knowledge level was ranked as medium.
- Vertical/radial natural circulation occurring in steam generator annulus of the primary side was considered to be of high importance, but the knowledge level was ranked as medium.
- Two phase heat transfer occurring on the secondary side of the steam generator tubes was considered to be of high importance, but medium knowledge level.

The panel concluded that these phenomena fall under category B with respect to TRACE applicability. In other words, the panel concluded that with a small effort in terms of assessment and code development, TRACE should be made applicable to analyze the associated phenomena. However, these issues will be addressed more fully in future work as TRACE applicability determination is the subject of future work.

Table 3: Highly Important Phenomena for NuScale Stability

System	Component	Process/Phenomenon
core	fuel rods	fission power
core	kinetics	decay heat
core	kinetics	delayed neutrons
core	kinetics	fuel temperature feedback
core	kinetics	moderator density feedback
core	kinetics	moderator temperature feedback
core	subchannel	core pressure drop
core	subchannel	natural circulation
core	subchannel	single phase convection
core	subchannel	single phase pressure drop
core	subchannel	subcooled boiling
primary	downcomer	single phase pressure drop
primary	downcomer	vertical/radial natural circulation
primary	hot leg riser	flashing
primary	hot leg riser	Ledinegg instability
primary	hot leg riser	vertical/radial natural circulation
primary	lower plenum	vertical/radial natural circulation
primary	steam generator annulus	convection heat transfer to the steam generator tubes
primary	steam generator annulus	single phase pressure drop
primary	steam generator annulus	vertical/radial natural circulation
primary	upper plenum	vertical/radial natural circulation
secondary	steam generator tubes	conduction through the tube wall
secondary	steam generator tubes	Ledinegg instability
secondary	steam generator tubes	two phase heat transfer

10 References

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5. ERI/NRC 12-203, “APPLICABILITY OF THE TRACE AND PARCS COMPUTER CODES TO INTEGRAL PRESSURIZED WATER REACTORS,” May 2012 (ADAMS Accession NO. ML120610573).
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