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Accident Information Needs[a]

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ABSTRACT

A five-step methodology has been developed to evaluate information needs for nuclear power plants under accident conditions and the availability of plant instrumentation during severe accidents. Step 1 examines the credible accidents and their relationships to plant safety functions. Step 2 determines the information personnel involved in accident management will need to understand plant behavior. Step 3 determines the capability of the instrumentation to function properly under severe accident conditions. Step 4 determines the conditions expected during the identified severe accidents. Step 5 compares the instrument capabilities and the severe accident conditions to evaluate the availability of the instrumentation to supply needed plant information.

1. INTRODUCTION

Nuclear power plant personnel currently have the capability to manage a broad range of accidents. Severe accidents at these plants will occur only if there are multiple failures of safety related equipment, serious human errors, or some combination of these two conditions. Successful management of this complex severe accident behavior requires that plant personnel diagnose the occurrence of an accident, determine the extent of challenge to plant safety, monitor the performance of automatic systems, select strategies to prevent or mitigate the safety challenge, implement the strategies, and monitor their effectiveness. The capability of personnel to effectively carry out these actions is directly influenced by the availability of timely and accurate plant status information. Plant instrumentation is relied upon to supply this information.

Safety-related instrumentation installed in a nuclear power plant is primarily designed and qualified for preventing and mitigating accidents that have a severity less than or equal to the severity of a design-basis accident. The ability of the instrumentation to supply the information needed for severe accident management has not been comprehensively investigated for conditions typical of a broad range of severe accidents. This paper discusses a methodology for assessing information needs and instrument availability during severe accidents.

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2. METHODOLOGY

We have developed a five-step methodology to identify the information needs of nuclear power plant personnel during accidents and to assess the availability of instruments to fulfill these needs during severe accidents. Figure 1 shows the relationship of the steps to one another. A brief description of each step follows.

2.1 Step 1: Examine Potential Severe Accidents

The objective of Step 1 is to use existing information to identify and examine the credible accidents, including accidents that progress beyond core damage (severe accidents). Information needed to prevent accidents from progressing to the point where core damage will occur is generally well defined in the plant safety analysis reports. However, information needed to understand and mitigate the effects of severe accidents may not be well defined in plant procedures or licensing documents. You can find material to define severe accident information needs in plant Probabilistic Safety Assessments (PSAs), Individual Plant Examinations (in the United States), or other similar documents where the contributors to plant risk are examined and discussed. Broad categories of severe accident sequences are generally defined in these documents using plant damage states. Although the plant damage states may differ from plant to plant, common examples are station blackout, small and large break loss-of-coolant accidents, and anticipated transients without scram. Sufficient information should be available to understand the status of plant safety and support systems for the sequences that compose these categories. You should also obtain material on the progression of the accident beyond core damage. The PSA accident progression bins, for example, collate sequences with similar vessel or containment failure conditions. This material will aid in understanding the information needs for mitigating events such as steam explosions, hydrogen detonations, direct containment heating, and other severe accident behavior that occurs late in an accident.

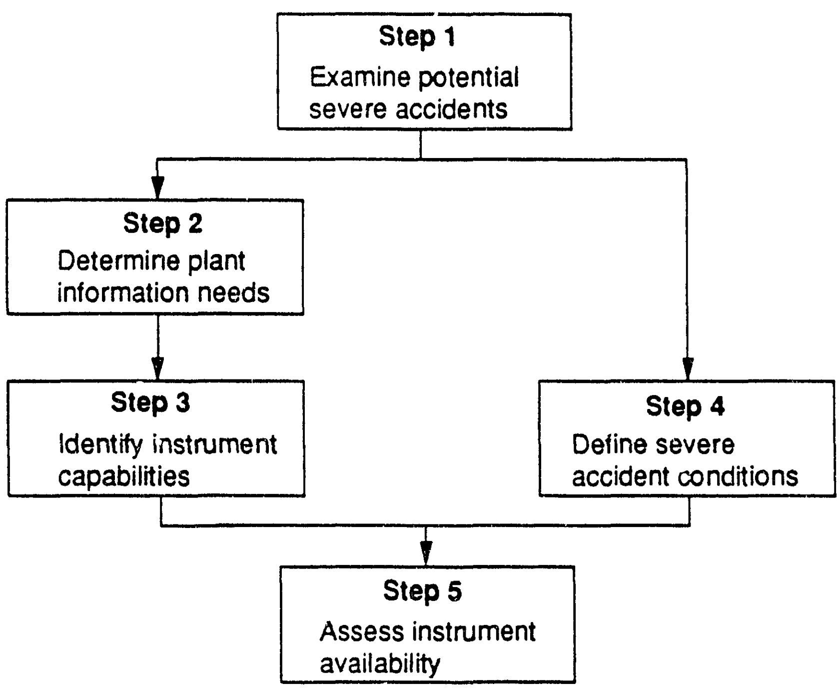

Figure 1. Methodology to assess instrument availability.

2.2 Step 2: Determine Plant Information Needs

Since there is a good understanding of the information needs for plant behavior prior to core damage, the objective of Step 2 is to determine the information that personnel involved in accident management will need to understand plant behavior for a broad range of severe accident conditions. We have identified two methods that potentially can be used to accomplish this objective. The first is to use accident sequences from the PSA; the second is to use a safety function approach.

The first method evaluates selected accident sequences from the PSA to "systematically determine the plant instrumentation required to supply the operator with the necessary and sufficient information to allow him to unambiguously determine the status of the plant under accident conditions, and thereby allow him to take the most effective action to bring the plant to successful shutdown" [1]. To ensure all necessary plant instrumentation is identified using this method, a detailed examination of a large number of severe accident sequences is required.

We prefer the second method, which uses a safety function approach, because it is structured to provide a more comprehensive evaluation of the information needs. It uses a functional "top down" approach that starts with the overall objectives of accident management and relates these objectives to the accident management strategies using a hierarchical tree structure. Once the relationship between the safety objectives and the strategies is clearly understood, the information can be identified that is needed by accident management personnel to ensure that the safety objectives can be accomplished. Examples for carrying out this method are summarized in the following discussion. Additional details are presented in References 2 and 3.

The role of personnel involved in the management of a severe accident is to ensure that certain safety objectives are met. In order to meet these safety objectives, certain critical plant safety functions must be maintained within acceptable limits. An accident will present challenges to the safety functions, caused by various mechanisms. Finally, plant personnel will select and implement various strategies for preventing or mitigating the mechanisms that challenge the safety function. These actions form a natural hierarchy that can be arranged in a tree structure for each plant safety objective.

The first step in developing a tree structure is to define the high level safety objectives. As an example, for a pressurized water reactor with a large dry containment we subdivided severe accident management issues into those associated with in-vessel accident management and those associated with containment and release management. This categorization of issues corresponds with the barriers to fission products that remain once the fuel has been damaged and recognizes that strategies can be implemented to reduce the inventory of fission products readily available for release to the environment. Based on this subdivision, the safety objectives for a plant during a severe accident can be defined as (a) prevent core dispersal from vessel, (b) prevent containment failure, and (c) mitigate fission product release from containment.

Figure 2 shows an example safety objective tree developed for the first of the three safety objectives. The information used to develop this tree was not based on a specific plant, but on information generally typical of some Combustion Engineering and Westinghouse PWRs. Personnel with expertise in severe accidents and PWR operations were consulted to develop and review the trees. Note that the strategies shown are only examples and are not a complete set for preventing

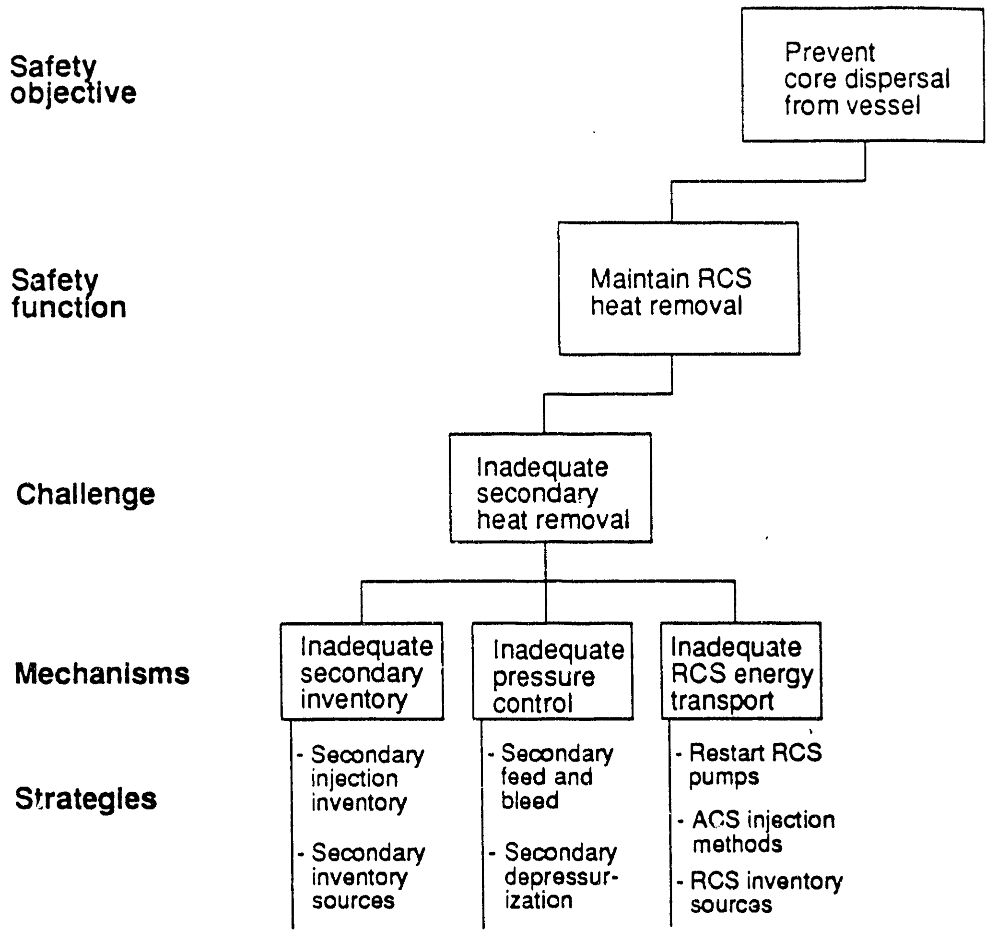

Figure 2. Example of a branch of a safety objective tree for one safety objective.

or mitigating the mechanisms and maintaining the safety functions. Some strategies may not be practical under certain circumstances but are included to illustrate that there may be conflicting requirements for some plant safety functions. Most strategies presented are general and require further evaluation to determine whether they would adequately maintain the appropriate safety functions for a specific plant configuration. Further descriptions of the structure of these trees and the rationale used in their development are presented in Reference 2.

Safety Objective Trees can be used as tools to systematically determine an operating crew's information needs. This is accomplished by examining the branch points of the tree to decide what information is necessary to

1. Determine the status of the safety functions in the plant, i.e., whether the safety functions are being adequately maintained

2. Identify plant behavior (mechanisms) or precursors to this behavior that will indicate a challenge to plant safety is occurring or is imminent

3. Select strategies that will prevent or mitigate this plant behavior and monitor the implementation and effectiveness of these strategies.

We developed a table to systematically determine and display accident management information needs. Table 1 shows the structure. The rows coincide closely with the safety functions, mechanisms, and strategies on the safety objective trees. In the safety function section, describe the information needed to determine whether a safety function is being maintained within the accepted safety limits. In the mechanism section, describe information necessary to identify the specific mechanisms that may challenge the safety function. Two different categories are defined for mechanisms: indicators and precursors. Indicators include information that identifies when a mechanism is actually occurring and challenging a safety function. Precursor information identifies whether a mechanism is expected to occur in the future based on currently available information.

The strategies section contains three categories of information that relate to strategy selection and evaluation. For selection criteria, identify information to determine which strategies should be selected for a given situation, including consideration of the plant conditions under which the strategy can operate and be effective. For strategy initiation, list the information needed for the operating

The columns in the table list the identified information needs, the sources of information that could supply these needs, and the available instrumentation that could supply the needed information. Information sources are either direct or indirect. A direct information source is one that can be used to provide information that will positively determine the presence or absence of a specific condition on the safety objective tree. For example, if the safety function addresses pressure control, a pressure measurement is a direct information source for understanding challenges to the safety function. An

Table 1. Structure of information needs for accident management.

		Information needs	Direct information source	Indirect information source	Available instruments
Safety function					
Mechanism					
	Indicator				
	Precursor				
Strategy					
	Selection criteria				
	Strategy initiation				
	Strategy effectiveness				

indirect information source can be used to infer the needed information, but there may be conditions where the information source may be ambiguous. For example, the core exit temperature measurement may provide accurate information on the temperature of the fuel rods for some system conditions but would not be accurate for all combinations of system flow and fluid state conditions.

Information needs tables may be extensive; see References 2 and 3 for a full description of the tables for a PWR and a Boiling Water Reactor (BWR) with a MARK I containment respectively. Table 2 displays an example of the initial section for the Prevent Core Dispersal from the PWR vessel safety objective tree shown in Figure 2. Included are the information needs for the Maintain RCS Heat Removal (V1) safety function, the Inadequate Secondary Inventory (V1A1) mechanism, and the RCS Injection Methods strategy. The format of the table enables us to quickly scan the columns to determine the information needs, identify the sources of information, and ascertain whether existing instruments will supply the information. The information need for the Maintain RCS Heat Removal safety function is the energy removal rate from the RCS. Since there are many ways that energy can be removed from the RCS, and many of these are not measured with sufficient accuracy to derive an energy removal rate, we conclude that a direct information source for energy removal rate does not exist. There are, however, numerous indirect information sources. Some of these, such as steam flow rate, could provide a reasonable measurement of energy removal rate; others, such as PORV flow, are not measured but are indicated indirectly by such devices as acoustic monitors or temperature measurements downstream of the PORV.

The inventory of fluid in the secondary sides of the steam generators is considered to be an information need indicator for the Inadequate Secondary Inventory mechanism (V1A1). There is a direct information source for this information need, secondary side liquid level, that indicates the inventory, and there is an instrument available to provide this information. An example of a precursor information need is feedwater flow status. A rapid reduction in feedwater flow, under certain plant conditions, provides early information that alerts the operator of the potential for an inadequate inventory to occur in the future.

The last section of the example table provides the information needs for the Injection Methods strategy. These information needs are relatively straightforward because all have direct information sources and available instruments.

Developing the information needs and instrumentation input to the table requires the expertise of personnel with diverse backgrounds. A team of personnel with operations, instrumentation, and severe accident experience is necessary.

2.3 Step 3: Identify Instrument Capabilities

The objective of Step 3 is to determine the existing plant instruments that can provide the information needs. Potential limitations on the capability of these instruments to function properly when exposed to severe accident conditions must be established to make this determination. Two limitations we consider important are the range of the instrument and the environmental qualification conditions. Such limitations may prevent the instruments from supplying the information needed to successfully manage potential severe accidents.

Table 2. Example information needs.

	Information needs	Direct information source	Indirect information source	Available instruments
Maintain RCS heat removal safety function (VI)	Energy removal rate	None		None
			RCS fluid temperature	Hot or cold leg RTD
			RCS pressure	Pressurizer pressure
			Steam generator steam flow	Steam flow indicators
			PORV discharge pipe noise	Acoustic monitor
			RHR heat removal	RHR flows, temperature
Inadequate secondary inventory mechanism (V1A1)	<u>Indicator</u> Secondary fluid inventory	Secondary liquid level		Secondary liquid level
	<u>Precursor</u> Feedwater flow status	Feedwater flow rate		Feedwater flow rate
Injection methods strategy	<u>Selection Criteria</u> Inventory availability	Tank inventories		Tank levels
	Pumping capability	Electrical power availability		
	Alignment capability	Valve alignments		Valve indicators
	<u>Strategy Initiation</u> Feedwater flow status	Feedwater flow rate		Feedwater flow rate
	Injection water inventory (decreasing)	Tank inventory		Tank level CST
	<u>Strategy Effectiveness</u> RCS fluid temperature	RCS fluid temperature		Hot or cold leg RTDs
	Secondary fluid inventory	Secondary liquid level		Secondary liquid level

Instruments having the potential to supply information needs can be identified from plant documentation such as piping and instrumentation diagrams, system instrument lists, and documentation showing compliance with regulatory requirements, for example Regulatory Guide 1.97 [4] in the United States. Potential limitations on instrument capability can be identified by examining possible conditions for which the instrumentation will fail to supply the information needs identified in Step 2. The following conditions should be identified:

- The physical location of the plant instrumentation and all cabling, splices, terminal blocks, and signal conditioning equipment that would be exposed to a harsh environment during the identified severe accident sequences.

- The range of the instrumentation.

- The qualification ranges of the instruments for temperature, pressure, humidity, and radiation levels. For our PWR example we used the following instrument qualification temperature and pressure conditions:

    1. Instrumentation within the reactor coolant system

        - Maximum temperature = 2300°F

        - Maximum pressure = 2500 psia

    2. Instruments within the containment building

        - Maximum temperature = 300°F

        - Maximum pressure = 60 psia

- All available information on the effect of exceeding the qualification ranges on the performance of the instruments

- The performance of the instruments if there is a failure of support systems such as site electrical power, emergency power, dc busses, service water, component cooling water, or instrument air

- All instruments or sampling stations that require access where such access could be impeded because of adverse environmental conditions, such as high radiation fields or high temperatures

- The information needs that existing plant instrumentation does not have the capability to supply.

These results will be used in Step 5, together with the severe accident conditions identified in Step 4, to evaluate instrument availability.

2.4 Step 4: Define Severe Accident Conditions

The objective of this step is to define the predicted severe accident conditions important for assessing instrument availability. These conditions include the following:

- Harsh environments that might occur in the reactor coolant system (RCS), containment, auxiliary building, or turbine building that could cause failure of the instrumentation or impede access to sampling stations. A minimum set of environmental conditions that should be defined are temperature, pressure, radiation levels, and humidity.

- Support systems failures that could result in the failure of instrumentation. Examples are failure of ac power, failure of service water, and failure of instrument air supplies.

To accomplish the objective, severe accident analysis for representative accident sequences must be selected for each of the severe accident sequence categories identified in Step 1. These sequences should have system behavior representing the categories identified. Applicable analyses include calculations to support the core damage analyses and consequence analyses for the PSA for your plant or calculations performed for other plants with similar design features, equipment, and operations. Realistic calculations must be used so that a reasonable estimate of plant behavior is obtained. Results should represent as much of the expected physical phenomena as is practical. For example, natural circulation in the hot leg might cause temperatures to be sufficiently high that the environmental qualification levels of the instrumentation is exceeded. If hot leg natural circulation is expected, calculations should be obtained that include these effects.

Plots of temperature and pressure typical of conditions at the approximate location of the plant instrumentation are needed to assess the magnitude and times of harsh conditions. Knowledge of the humidity at these locations may also be necessary, depending on the instrument qualification limits. Estimates of the integrated radiation dose at the location of the instrument are also needed.

The severe accident conditions that influence instrument availability for a plant will change as a severe accident progresses, different safety functions are challenged, and harsh conditions develop in various plant locations. To account for these changing conditions, it is convenient to divide the accident sequences into phases based on the timing of key events and the phenomena occurring in the reactor coolant system and the containment. As an example, we found the following five phases to be adequate for assessing the information needs of PWRs [5].

Phase 1. This phase begins with initiation of the sequence, including the blowdown/boiloff of water inventory in the reactor coolant system, and ends at the time of initial uncovery of the reactor core. Operator guidance for Phase 1 is included in the existing plant Emergency Operating Procedures.

Phase 2. Core uncovery begins. Fuel heatup results from the lack of adequate cooling. This phase ends when fuel melting begins.

Phase 3. Fuel melting occurs, including fuel and cladding relocation and the formation of debris beds. The phase ends with relocation of a significant amount of core material to the reactor vessel lower plenum. Hydrogen may burn during this phase, depending on the accident sequence.

Phase 4. Molten core debris accumulates in the lower head of the reactor vessel. The phase ends with failure of the lower head. Hydrogen may burn during this phase, depending on the accident sequence.

Phase 5. The core debris directly interacts with the containment after lower head failure. During this phase, containment failure could occur because of overpressure, hydrogen burns, or basemat meltthrough resulting from core-concrete interaction. Containment failure resulting from direct containment heating is also possible, depending on the reactor coolant system pressure when lower head failure occurs.

The accident phases for a PWR correspond to the time sequence of a severe accident. First the reactor system is affected followed by the containment. However, this time correspondence of the phases is not universal for all reactor types. For example, the following accident phases were determined to be adequate for defining when harsh accident conditions would affect the availability of instrumentation for a Boiling Water Reactor (BWR) with a MARK I containment [6]. Harsh accident conditions are those that exceed the environmental qualification conditions specified for plant instruments.

Phase 1. Harsh conditions only in the reactor system

Phase 2. Harsh containment conditions before core damage

Phase 3. Harsh containment conditions after core damage

Phase 4. Harsh reactor building conditions before core damage

Phase 5. Harsh reactor building conditions after core damage.

This approach for BWRs is used because of the possibility of harsh conditions in the containment and reactor building prior to core damage during an ATWS or accidents where the containment heat removal systems have failed.

The limiting conditions for the phases defined can be determined by examining the boundaries of each of the five phases on plots of the system conditions (temperatures, pressures, etc.) for selected accident sequences. A tabulation of the maximum and minimum values of these limiting conditions for each sequence phase is necessary to facilitate comparisons with the instrument failure conditions identified in Step 3.

2.5 Step 5: Assess Instrument Availability

The objective of this step is to assess instrument availability during each phase of the severe accident sequence, based on the results developed in Steps 3 and 4. The following conditions that would cause degraded instrument performance and restrict the information available during each phase should be considered:

- Exceeding environmental qualification conditions or conditions determined by testing or analysis

- Exceeding the instrument range

- Support system failure: electrical power, instrument air, service water, etc.

A comparison of the maximum conditions tabulated for each phase with the limiting harsh conditions specified for the instruments can be used to screen instruments into three categories: (a) instruments available because environmental qualification conditions are not exceeded, (b) instruments having the potential for degraded performance because environmental conditions are exceeded, but only by small amounts, and (c) instruments that will experience degraded performance because environmental conditions are exceeded by significant amounts. Instruments in the second category require additional analysis; for example, heat transfer calculations to determine the temperature distribution in pressure sensors are necessary before a definitive statement on degraded performance of sensors is possible.

Two different methods of display have been developed for the results. A table can be used when communication of detailed information is desired, for example, a list of the instruments, their location, and the status of the instrument during each phase. An example of this format [5] is presented in Table 3. When an overview of the instruments is desired, the table format can be simplified as shown in Table 4. The times when the instruments are not available are much more easily seen from this table.

3. CONCLUSIONS

The method discussed can be used to identify the information needed by plant personnel for management of severe accidents. The method will also identify areas in which information needs will not be met because there is insufficient instrumentation. Instrument availability can be determined using the methodology which can be used to determine where difficulties may occur in understanding plant status, evaluating strategy selection, and determining strategy effectiveness for severe accident sequences.

Table 3. Review of instrument performance during a severe accident.

Instrument description or measurement range	Instrument location	Status during each accident phase
Category 1 Instruments		
Source range monitor (10–1 to 105 CPS, 10–9 to 10–3% full power)	Reactor cavity	Available from accident initiation up to Phase 5. Degraded performance during Phase 5 due to harsh conditions in the cavity. Monitors qualified for DBA non-harsh environment. Diesel generator backup assumed.
Neutron flux wide range monitor (10–8 to 150% full power, power range 0.1 to 125% full power	Reactor cavity	Available during Phases 1 and 2. Degraded performance during Phase 5 due to harsh conditions in the cavity. Monitors qualified for DBA non-harsh environment. Diesel generator backup assumed.
Core exit thermocouples (200–2300°F)	Reactor	Available during Phases 1 and 2. Degraded performance due to high in-vessel temperature from core meltdown for all sequences. Failure of some or all of the thermocouples is possible. Diesel generator backup assumed.
RVLMS (0–100% water level above core)	Reactor	Available during Phases 1 and 2. Degraded performance during Phase 3 due to high in-vessel temperature from core meltdown for all sequences. Failure possible depending on the location of the RVLMS sensors. Diesel generator backup assumed.
Pressurizer level (0–360 in, 0–100%)	RCS and containment	Available during Phases 1 and 2. Degraded performance during Phase 3 due to high pressurizer temperatures resulting from natural circulation during core meltdown. Degraded performance also possible due to high temperatures from multiple hydrogen burns during Phases 3, 4, and 5 or due to direct containment heating at the end of Phase 4. Battery backup provided.
RCS pressure (pressurizer) (0–4000 psig)	RCS and containment	Available during Phases 1 and 2. Degraded performance during Phase 3 due to high pressurizer temperature resulting from natural circulation during core meltdown. Degraded performance is also possible due to high temperatures resulting from multiple hydrogen burns during Phases 3, 4, and 5 or direct containment heating at the end of Phase 4. Battery backup provided.
Cold leg temperature (0–600°F)	RCS and containment	Readings may be out of range for accidents where natural circulation causes high temperatures in the RCS outside the RPV. Degraded performance due to high temperature from multiple hydrogen burns during Phases 3, 4, or 5 or due to direct containment heating at the end of Phase 4. Battery backup provided.
Hot leg temperature (212–705°F)	RCS and containment	Readings may be out of range for accidents where natural circulation causes high temperatures in the RCS outside the RPV. Degraded performance is also possible due to hot leg temperature exceeding the qualification temperature. Degraded performance possible due to multiple hydrogen burns during Phases 3, 4, 5 or direct containment heating at the end of Phase 4. Battery backup provided.

Table 4. Example of instrument availability for PWR Category 1 instruments.

		Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Instruments	Safety functions	Core uncovery	Fuel heatup	Core relocation	Lower head failure	Containment failure
Neutron flux source range monitor	V2, V3, C1, C2	A	A	A	A	DPP
Neutron flux wide range monitor	V2	A	A	A	A	DPP
RCS pressure	V1, V2, V3, C1, C2	A	A	DPP	DPP	DPP
Pressurizer level	V2, V3, C3,	A	A	DPP	DPP	DPP
Core exit thermocouples	V1, V2, V3, C1, C2, C3, F1, F2	A	A	DPP	DPP	DPP
Hot leg RTDs	V1, V2, V3	A	A	DPP	DPP	DPP
Cold leg RTDs	V1, V2, V3	A	A	DPP	DPP	DPP
Subcooling monitor	V1, V2, V3, C3	A	A	DPP	DPP	DPP
Reactor vessel level system	V1, V2, V3, C1, C2, C3, F1, F2	A	A	DPP	DPP	DPP
Steam generator pressure	V1, V2, V3, C1, C3	A	A	DPP	DPP	DPP
Steam generator level	V1, V2, V3, C1, C3	A	A	DPP	DPP	DPP

A = Instrument available.

DPP = Degraded performance possible.

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