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Instrumentation and Control to Prevent and Mitigate Severe Accident Conditions

SAMG-D Toolkit, Module 3, Chapter 3

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Agenda

- Background
- Approach of evaluation of instrument availability
- Possible severe accident sequences
- Severe accident conditions
- Accident management information assessment
- Instrument availability during severe accidents
  - Instrument Qualification
  - Harsh environment
- Diagnostic Assessment
- Conclusions
- References

Background

- Bases for instrumentation used in generic SAMGs are summarised in NUREG-5691 (1991) where U.S. Nuclear Regulatory Commission (NRC) has identified accident management as an essential element of the Integration Plan for the closure of severe accident issues.
- One of the areas affecting the capability of plant personnel to successfully manage a severe accident is the availability of timely and accurate information that will assist in determining the status of the plant, selecting preventative or mitigative actions, and monitoring the effectiveness of these actions.

Approach to evaluation of instrument availability (1/3)

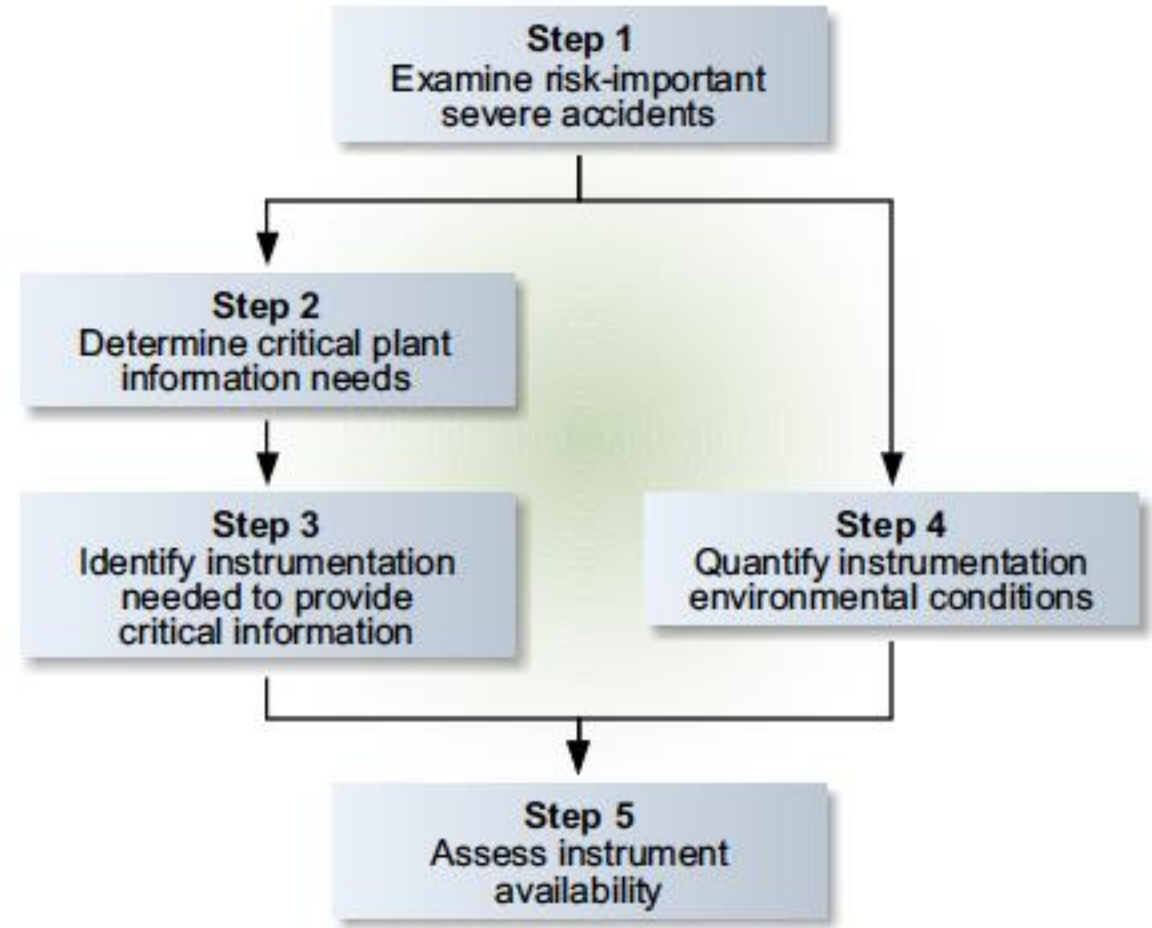
- 4 step process:
  - 1. **Identify a set of possible severe accident sequences** that have the potential of influencing the risk for a PWR with a large dry containment.
  - 2. **Define the expected conditions** within the **reactor coolant system** and **containment** for important accident sequences, and identify phases of the sequences that correspond with the phenomena occurring and challenges to different instruments. **Define envelopes bounding the range of parameters** that would be expected to impact instrument performance for the severe accidents identified in Step 1.

Approach to evaluation of instrument availability (2/3)

- 4 step process:
  - **3. Assess instrument availability during each phase** of the severe accident sequences, based on the location of the instrument and conditions that would influence instrument performance.
  - **4. Provide** an accident management information assessment **discussing the information needs** and the **instruments that are available**. Identify potential limitations on the information available for assessing the status of plant safety functions .

Approach to evaluation of instrument availability (3/3)

- The most recent approach:



Step 1 - Identification of risk-important SA sequences (1/5)

- To accomplish Step 1, the types of **severe accident sequences that have the potential of influencing risk should be identified**.
  - Generic SAMGs were based on the probabilistic risk assessment results presented in NUREG-1150 for the Surry and Zion PWRs.
  - Although the results are specific to these two plants, the sequence categories identified in this document are sufficiently broad that they would apply to most PWRs.
- However, plant specific analyses and evaluations are highly recommended.

Step 1 - Identification of risk-important SA sequences (2/5)

- SA accident sequence phases:
  - **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 during this phase. Fuel heatup results from the lack of adequate cooling. This phase ends when fuel melting begins.

Step 1 - Identification of risk-important SA sequences (3/5)

- SA accident sequence phases:
  - **Phase 3** - Fuel melting occurs during this phase. Fuel and cladding relocation and the formation of debris beds occur. The phase ends when relocation of a significant amount of core material to the reactor vessel lower plenum begins.
  - **Phase 4 -** Molten core debris accumulates in the lower head of the reactor vessel during this phase. The phase ends with the failure of the lower head.

Step 1 - Identification of risk-important SA sequences (4/5)

- SA accident sequence phases:
  - **Phase 5** - This phase is initiated when 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 due to direct containment heating is also possible, depending on the reactor coolant system pressure when lower head failure occurred.

Step 1 - Identification of risk-important SA sequences (5/5)

- Separation of the sequences into five phases allows for segregation of the information needs and instrument availability.

- **Information needs** and **instrument availability differ from phase to phase**, as **different plant safety functions** are challenged and **harsh environmental conditions** develop in various portions of the reactor coolant system, containment, and, in some sequences, the auxiliary and turbine buildings.

- Instrument availability evaluations were based primarily on the pressure and temperature qualification, location, and source of backup power for each instrument.

- **PSA insights should be used in the identification of risk-important SA sequences.**

Step 2 – Critical plant information needs (1/4)

- The Safety Functions information needs to be identified for each mechanism are summarized as follows:
  - Determination of the status of the safety function in the plant, that is, whether the safety functions are being adequately maintained within predetermined limits.
  - Identification of plant behaviour (mechanisms) or precursors to this behaviour that indicate that a challenge to plant safety is occurring or is imminent.

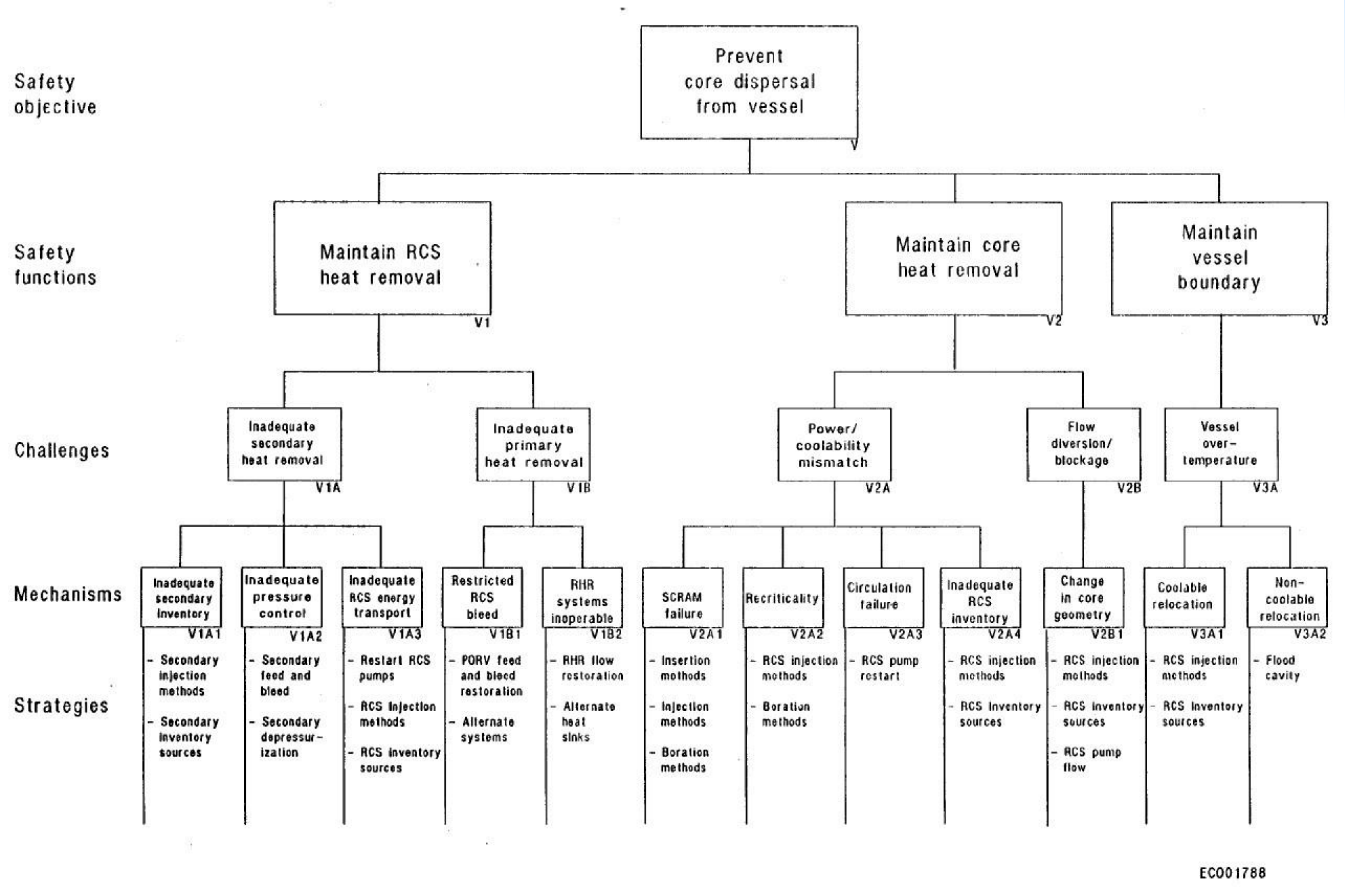
Step 2 – Critical plant information needs (2/4)

- The Safety Functions information needs to be identified for each mechanism are summarized as follows:
  - Selection of strategies that will prevent or mitigate plant behavior that is challenging plant safety .
  - Monitoring the implementation and effectiveness of the selected strategy.

Step 2 – Critical plant information needs (3/4)

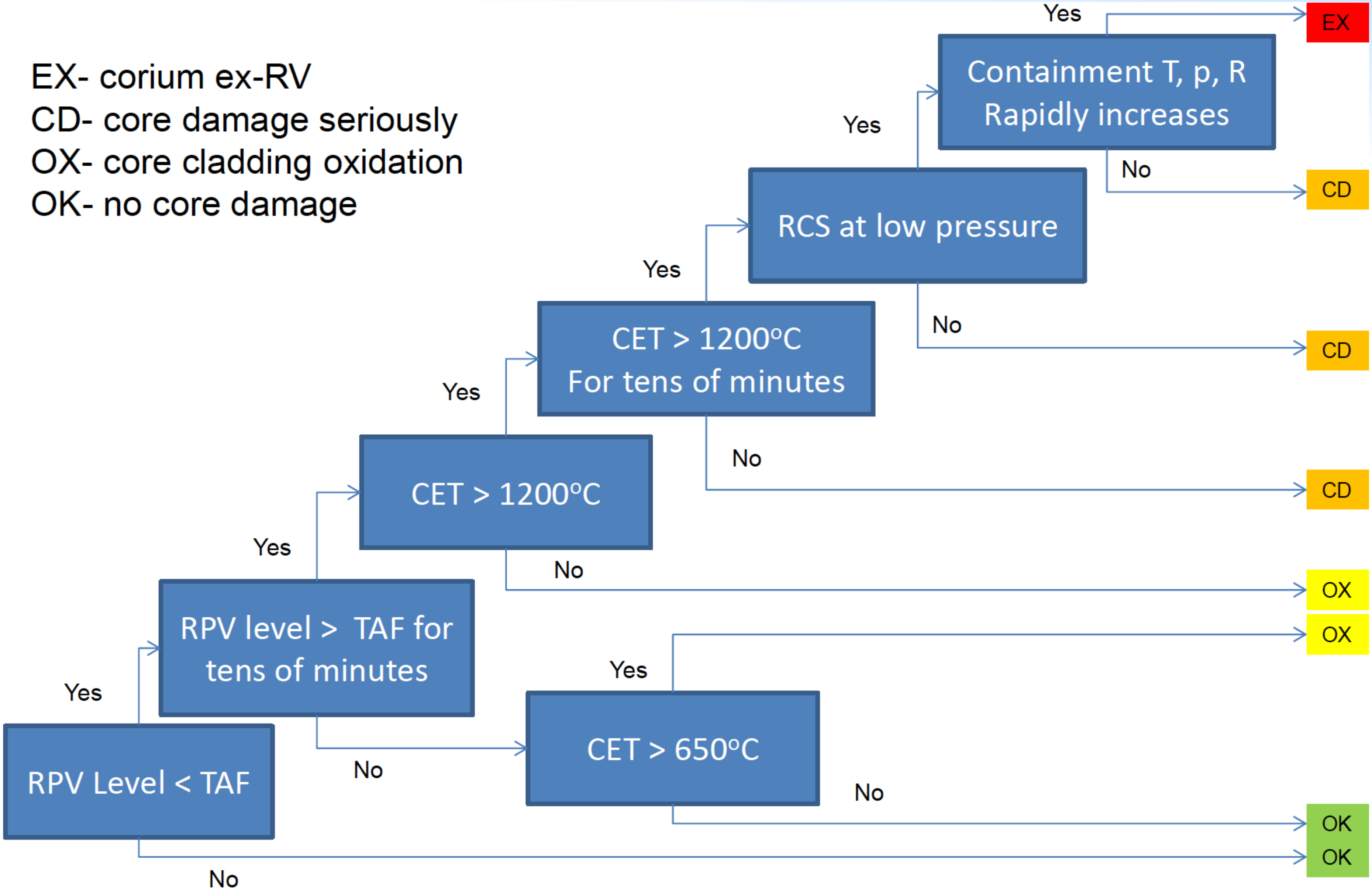
- Generic SAMGs accident management information assessment relies principally on the safety objective trees (e.g. prevent core dispersal from vessel, prevent containment failure and mitigate fission product release from containment) and information needs tables developed in NUREG/CR-5513.

Step 2 – Critical plant information needs (4/4)



Step 3 – Identification of necessary instrumentation (1/10)

EX- corium ex-RV
CD- core damage seriously
OX- core cladding oxidation
OK- no core damage



Step 3 – Identification of necessary instrumentation (2/10)

Generic Instrumentation Group Number	Information
1	Core temperature (as indicated by core exit thermocouples)
2	Core outlet temperature (as indicated by a variety of measuring devices)
3	RPV upper internals / structure temperature (inferred from water temperature or control rod drive temperature)
4	Core water level
5	Hot leg temperature
6	Core external power monitors
7	Pressurizer water level
8	Reactor system pressure
9	Containment pressure
10	Containment temperature
11	Containment radiation levels
12	Containment hydrogen levels
13	Suppression / refueling pool temperature
14	Valve position indication

Step 3 – Identification of necessary instrumentation (3/10)

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Damage Condition		Possible Symptoms
ID	Description	
OX	Intact fuel (clad ballooning, oxidation, or collapse might have occurred; no core structural materials—fuel, clad, or steel—molten) or RCS damage	• Core outlet temperature (where appropriate) > 650 °C (1200°F). • Considerable superheat [> 93 °C (200°F]measured in hot legs. • Core water level: collapsed water height at or below core mid-plane. • Loss of pressurizer level (for PWRs without loop seal). • External core power monitors increasing. • Some or increasing hydrogen measured in containment. • Hot leg and/or surge line temperature at or near maximum measured value along with indications of damage condition OX. • RCS pressure at or near nominal operating value along with indications of damage condition OX. • Hydrogen measured in containment • Limited radiation in containment, perhaps due to primary coolant activity and the release of fission product gases from fuel clad gap, as well as limited diffusion from the fuel matrix.
BD	Core significantly oxidized and not intact (core structural components have melted and are relocating downward); RCS pressure boundary (hot leg, surge line, and/or SG tube failure)	• High radiation in containment with indications of BD. • Increasing hydrogen measured in containment with RCS at or near operating pressure • Core outlet temperatures (where appropriate) > 1090 ° C (2000°F)/ • Loss of pressurizer level (in PWRs without loop seal) with indications of damage condition BD • External core power monitors increasing. • Collapsed water level at or below 40% core height for 10 minutes or longer. • Hot leg and/or surge line temperature at or near maximum measured value. • High radiation in steam generator

Step 3 – Identification of necessary instrumentation (4/10)

Damage Condition ID	Damage Condition Description	Possible Symptoms
EX/CH	Core debris relocated ex-vessel into the primary containment (RPV failed); Containment is closed but challenged; Core concrete attack	• Core outlet temperatures (where appropriate) > 1090 ° C (2000°F)/ • RCS depressurization combined with containment pressurization. • RCS pressure essentially equal to the containment pressure. • High radiation in containment. • Hydrogen measured in containment (>20% of the active fuel cladding reacted). • Continually increasing containment pressure • Continually increasing containment temperatures (more than saturation temperature). • No indication of water injection or containment heat removal • CO and/or CO_2 measured in containment and increasing. • Indication from heat balance on RCS and containment that the removal rate is less than decay heat.
I	Containment boundary impaired (containment isolation function not complete).	• Isolation not complete. • Steam release detected outside containment. • High radiation detected outside containment. • Decrease in containment pressure in absence of containment heat removal.
B	Containment bypassed (RCS isolation function not complete).	• Indication that containment isolation is not complete. • High pressure or ruptured disk in the pressurized quench tank (for systems with relief valves on the low-pressure systems piped to the quench tank). • High humidity or flooding detected in the secondary containment/auxiliary building. • High temperatures detected in the secondary containment/auxiliary building. • High radiation detected outside containment. • High RCS pressure (near nominal operating condition) and condition BD. • Water accumulation detected in secondary containment/auxiliary building. • Activation of fire suppression system or isolation dampers in secondary containment/auxiliary building. • High radiation detected in the standby gas treatment system. • High radiation detected in steam generators

Step 3 – Identification of necessary instrumentation (5/10)

Damage Condition		Possible Symptoms
ID	Description	
SC-CC	Secondary containment undamaged, closed, and cooled.	• Building ventilation system is available. • Releases from the building are monitored and filtered or released at a high elevation.
SC-CH	Secondary containment closed but challenged.	• Releases from the building are un-monitored or at ground level. • Conditions in the RCS pose potential for containment bypass. • Containment pressure and temperature high and increasing. • Building atmospheric temperature high and increasing. • The concentration of hydrogen, if measured, is potentially increasing in the secondary containment/auxiliary building. The concentration of CO and CO_2, if measured is potentially increasing in the secondary containment/auxiliary building.
SC-F	Secondary containment has failed with large path to the environment.	• Secondary containment pressure at ambient environmental conditions. • Visual inspection of the exterior of the building could indicate the failure location (for example, a failed blowout panel). • Increase in measured dose rates at the site boundary

Step 3 – Identification of necessary instrumentation (6/10)

- Parameter table - State OX:

Functional Need	Range of Interest	Generic Instrumentation Group Providing Data[a]
Core outlet temperature	> 650 °C (1200 °F)	1,2
Core temperature	not listed	1,2
Average core temperature	635 - 1270 °C (1175-2335 °F)	1,2
Core exit gas temperature	1260 °C (2300 °F)	1,2
Upper plenum structure temperature	620 °C (1150 °F)	1,2
Maximum reactor system pressure	17.8 MPa (2550 psia)	8
Minimum reactor system pressure	0.25 - 0.28 MPa (36-40 psia)	8
RPV exit gas temperature	680 ° C (1250 °F)	1,2
Hot leg temperature	> 110 °C (200 °F) superheat; 427 ° C(800 °F)	5,8
Containment pressure (with and without hydrogen burns)	0.18 to 0.20 MPa (26 to 29 psia)	9
Containment temperature (with and without hydrogen burns)	99 - 119 °C (211- 246 °F)	10
Containment radiation levels	limited	11
Core water level	at or below core mid-plane	4
Pressurizer water level	lowering	7
External core power monitors	"increasing"	6
Containment hydrogen levels	"present or increasing"	12
Location of core material	in-vessel or ex-vessel	11

Step 3 – Identification of necessary instrumentation (7/10)

- Parameter table - State BD:

Functional Need	Range of Interest	Generic Instrumentation Group Providing Data[a]
Average core temperature	2360 °C (4285 °F)	2
Core outlet temperature	> 1090 ° C (2000 °F)	1,2
Core exit gas temperature	2040-2150 ° C (3700-3900 °F)	1,2
Upper plenum structure temperature	982-1900 ° C (1800-3450 °F)	1,2
Maximum reactor system pressure	15.5 MPa (2550 psia)	8
Minimum reactor system pressure	0.22 to 0.23 MPa (32-34 psia)	8
RPV exit gas temperature	816-982 ° C (1500-1800 °F)	1,2
Hot leg temperature	>110 °C (200 °F) superheat; 427 ° C(800 °F)	1,2,5
Containment pressure (with and without hydrogen burns)	0.26 to 1.1 MPa (37 to 149 psia)	9
Containment temperature (with and without hydrogen burns)	93-1100 ° C (200-2031 °F)	10
Containment radiation levels	limited	11
Core water level	at or below 40% core height	4
Pressurizer water level	zero	7
External core power monitors	"increasing"	6
Containment hydrogen levels	"present or increasing"	12
Location of core material	in-vessel or ex-vessel	11

Step 3 – Identification of necessary instrumentation (8/10)

- Parameter table - State EX:

Functional Need	Range of Interest	Generic Instrumentation Group Providing Data[a]
Core water level	lost	4,6
Containment pressure (with and without hydrogen burns)	0.79 to 1.0 MPa (114 to 150 psia)	9, trend
Containment temperature (with and without hydrogen burns)	362-2400 °F	10, trend
Containment radiation levels	high	11
Containment hydrogen levels	"substantial"	12

Step 3 – Identification of necessary instrumentation (9/10)

PWR - CHLA Information Needs (Ref: TBR)

CHLA	Measures of Effectiveness (Information Needs)
Inject into RCS	Decreasing Core exit thermocouples Increasing Reactor vessel level indication Decreasing containment pressure Decreasing containment temperatures Decreasing hot or cold leg temperature
Depressurize RCS	Decreasing RCS pressure Decreasing Core exit thermocouples Increasing containment hydrogen concentration Increasing containment radiation Increasing containment pressure Decreasing hot or cold leg temperature

DIAGNOSTIC FLOW CHART/SEVERE CHALLENGE STATUS TREE INSTRUMENTATION

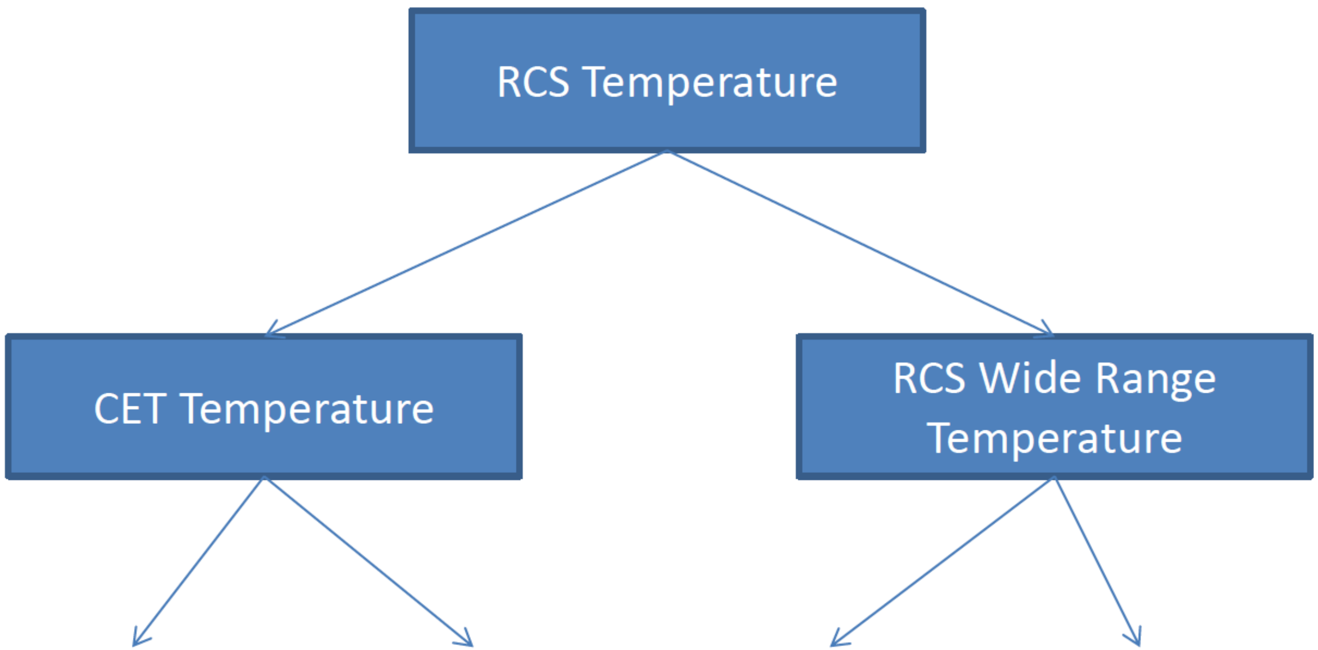
Parameter	Instrumentation	Number of Channels	Instrument I.D. or TAG Number	Instrument Range
RCS Pressure	Wide Range RCS Pressure	1/loop (hot leg)	PT405 [PT406[Note 1]]	0-2[illegible]0kp/cm²
	Pressurizer Pressure	4	PT455, PT456, PT457, PT458	120-180kp/cm²
	Accumulator Pressure	2/accumulator	PT960, PT961 [PT962, PT963]	0 - [illegible] kp/cm²
	SI Header Pressure			
	Charging Pumps	1/pump	MDP01: PI28[illegible] M[illegible]02: P[illegible]8B [illegible]DP: [illegible]286B PI204 [illegible]eader)	0 - 250 kp/cm²
	SI Pumps	1/pump	P[illegible]04 [PI905]	0 - 210 kp/cm²
	RHR Pumps	1/p[illegible]	PI861 [PI862]	0 - 50 kp/cm²

Instrument	Typical Range	Usefulness	Comments
Pressurizer Pressure	1700-2500 psig	Limited in usefulness during core damage	Lower indication range (1700 psig) limits usefulness during severe accidents.

Step 3 – Identification of necessary instrumentation (10/10)

Necessary Information

Parameters

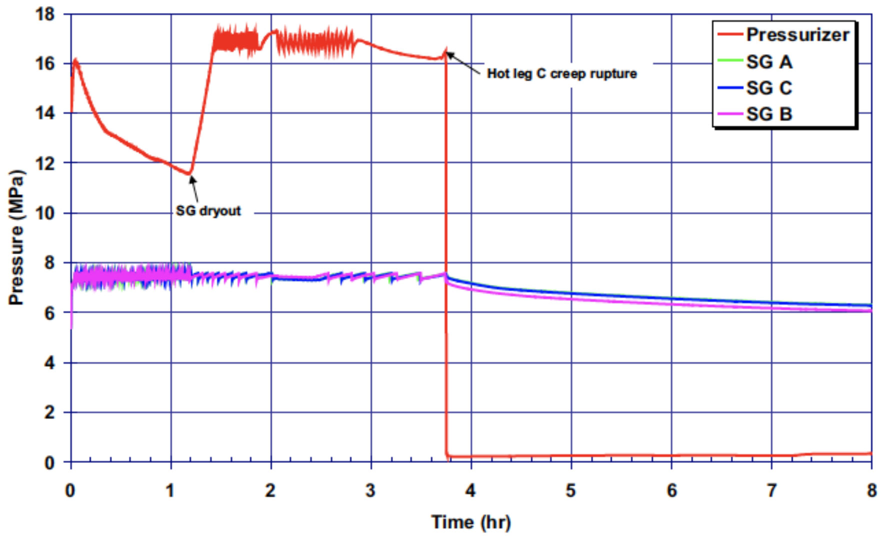


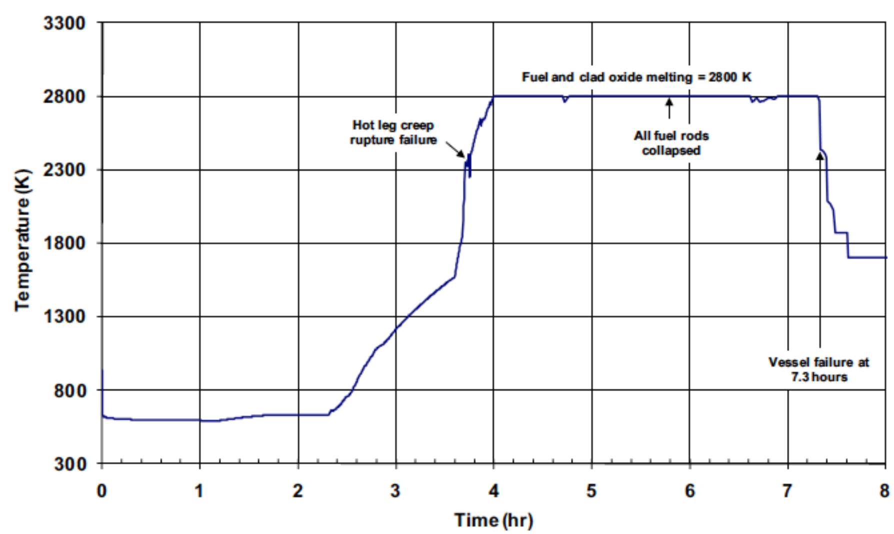
Instrument Loops	**TCAxxx**	**TCBxxx**	**TRCAxxx**	**TRCBxxx**
Loop Components	TLAyyyy	TLByyyy	TLAzzz	TLBzzz
	TQAyyy	TQByyy	TQAzzz	TQBzzz
	TIAyyy	TIByyy	TIAzzz	TIBzzz

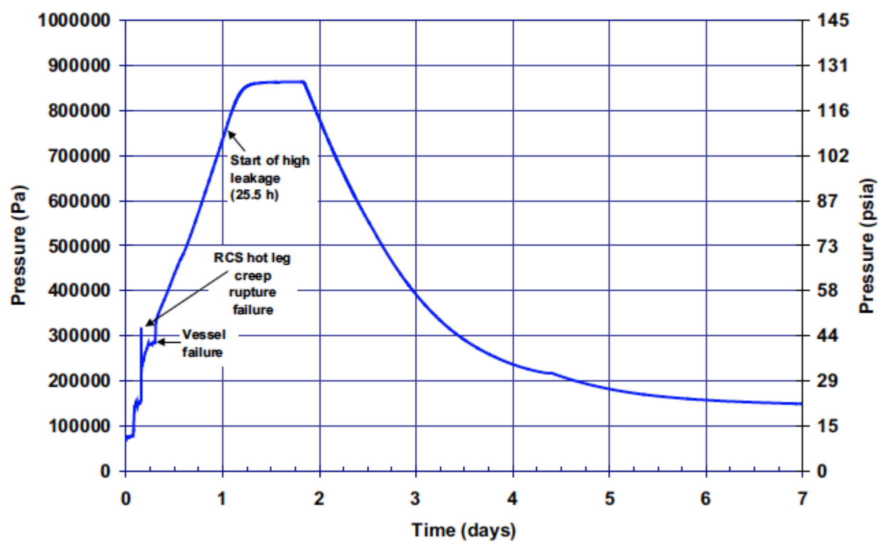
Step 4 – Quantification of plant parameters during SA (1/3)

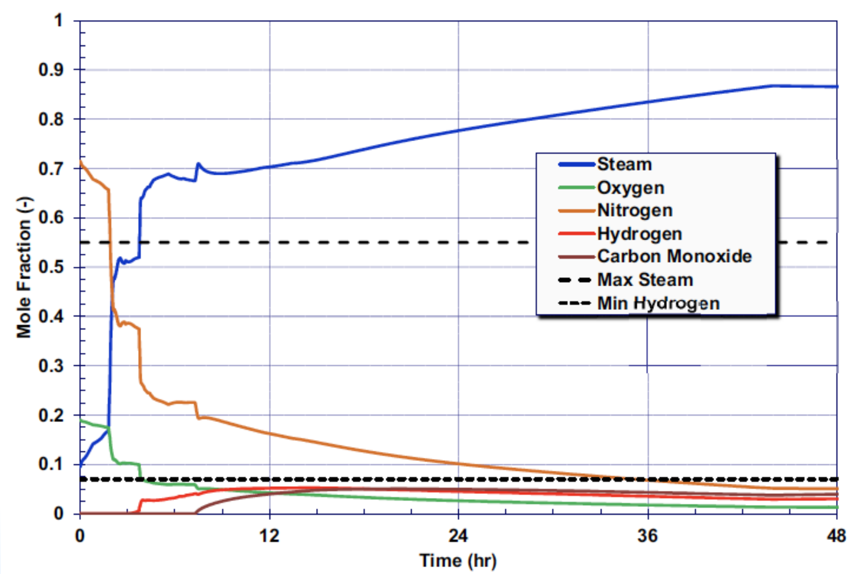
- Based on the set of identified risk-significant SA, the bounding plant conditions should be defined.
- In general, **temperature, humidity, pressure and radiation environmental conditions** are of the utmost interest when evaluating equipment availability in accident conditions.
- Plant parameters should be developed by plant-specific SA analyses.

Step 4 – Quantification of plant parameters during SA (2/3)









Step 4 – Quantification of plant parameters during SA (3/3)

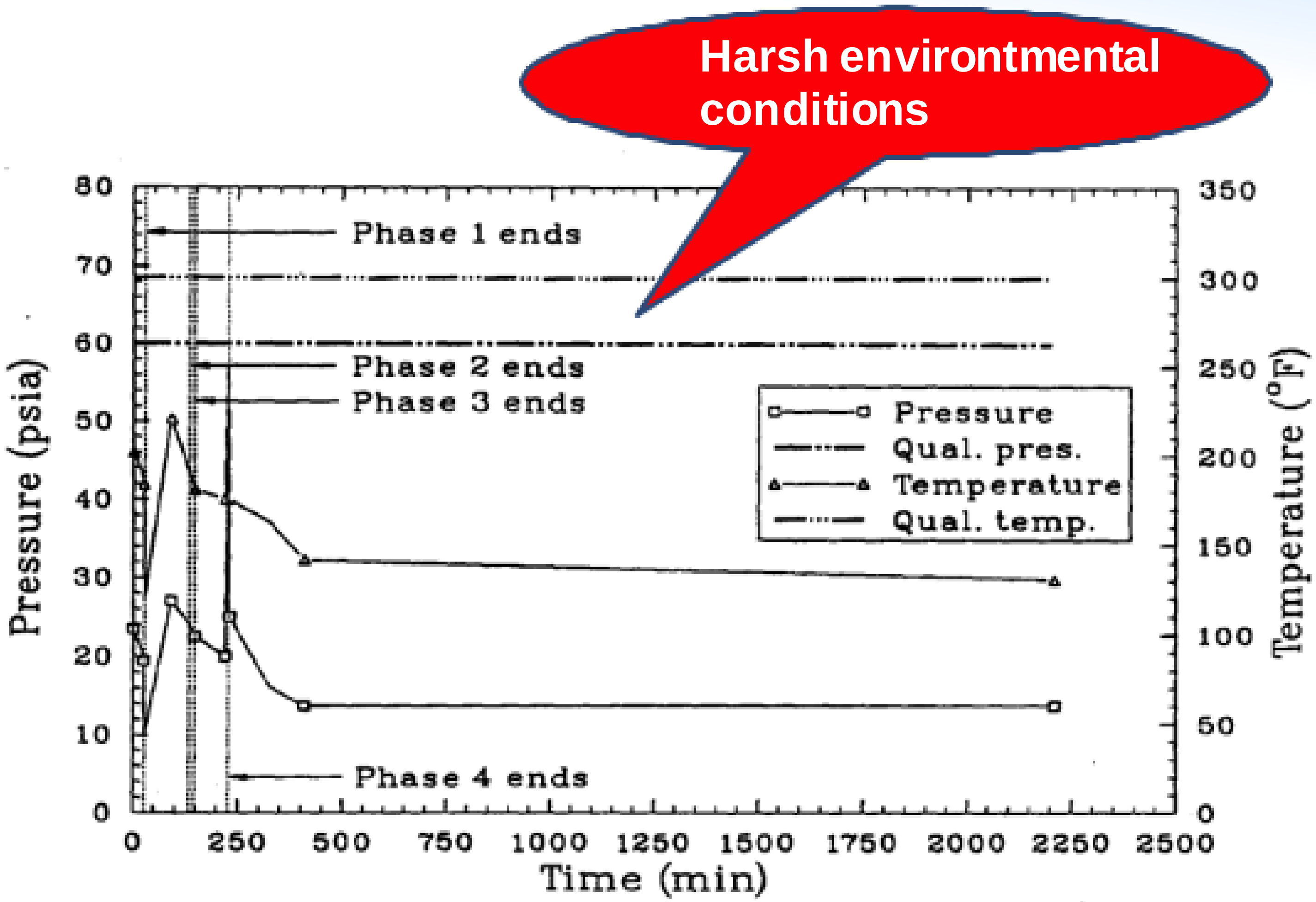


Figure B-4. Surry S_2D, basemat melt, containment data.

Step 5 – Assessment of instrument availability (1/10)

- The conditions affecting instrument availability are:
  - **Harsh pressure, temperature, humidity and radiation containment environments**, causing instrument performance to degrade.
  - **Electrical power failure** resulting from station blackout, loss of a dc bus, or other power interruptions, causing instruments to be unavailable.
  - **High radiation fields** resulting from an interfacing system LOCA or steam generator tube rupture, impeding access to instruments or sampling stations located in the auxiliary building or turbine building.

Step 5 – Assessment of instrument availability (2/10)

- Instrumentation should be adequately qualified and classified, e.g. according to the US NRC RG 1.97.
- Typical instrument systems consist of transducers, cabling, electronics, and other instrument system components:
  - For instruments located in the reactor coolant system, evaluation is focused on the sensors, because of the harsh temperature conditions that these sensors could be exposed to during a severe accident.
  - For instruments located in the containment, consideration is given to cabling, splices, and other components of the instrument systems.

Step 5 – Assessment of instrument availability (3/10)

- The basic instrument system performance is not well known when qualification conditions are exceeded!
  - An assessment of the relationship between the instrument uncertainties and the timing and degree to which the qualification conditions are exceeded would require a detailed study of basic instrument capabilities and failure modes.

Step 5 – Assessment of instrument availability (4/10)

- The basic instrument system performance is not well known when qualification conditions are exceeded!
  - It should be noted that operators may not recognize that instrument performance has degraded. One possibility is that an instrument reading appears to be normal or the trends may be plausible, when, in actuality, the plant conditions and trends are different.
  - Cabling is expected to be particularly vulnerable to the high-temperature conditions that develop during multiple hydrogen burns.

Step 5 – Assessment of instrument availability (5/10)

- There is little uncertainty in the conclusion of degraded performance or failure of instruments located:
  - In the reactor vessel if exposed to the temperatures expected during a core melt, which are well in excess of the qualification temperatures.
  - In the reactor cavity which would be subjected to temperature conditions well in excess of their qualification limit upon lower head failure.

Step 5 – Assessment of instrument availability (6/10)

- There is more uncertainty in assessing the performance of instruments located in the reactor coolant system outside the reactor vessel, because of hot gases being transported through the reactor coolant system due to PORV actuation or natural circulation. The uncertainty here is in the temperature predictions in the reactor coolant system, which are sensitive to the analytical assumptions made.

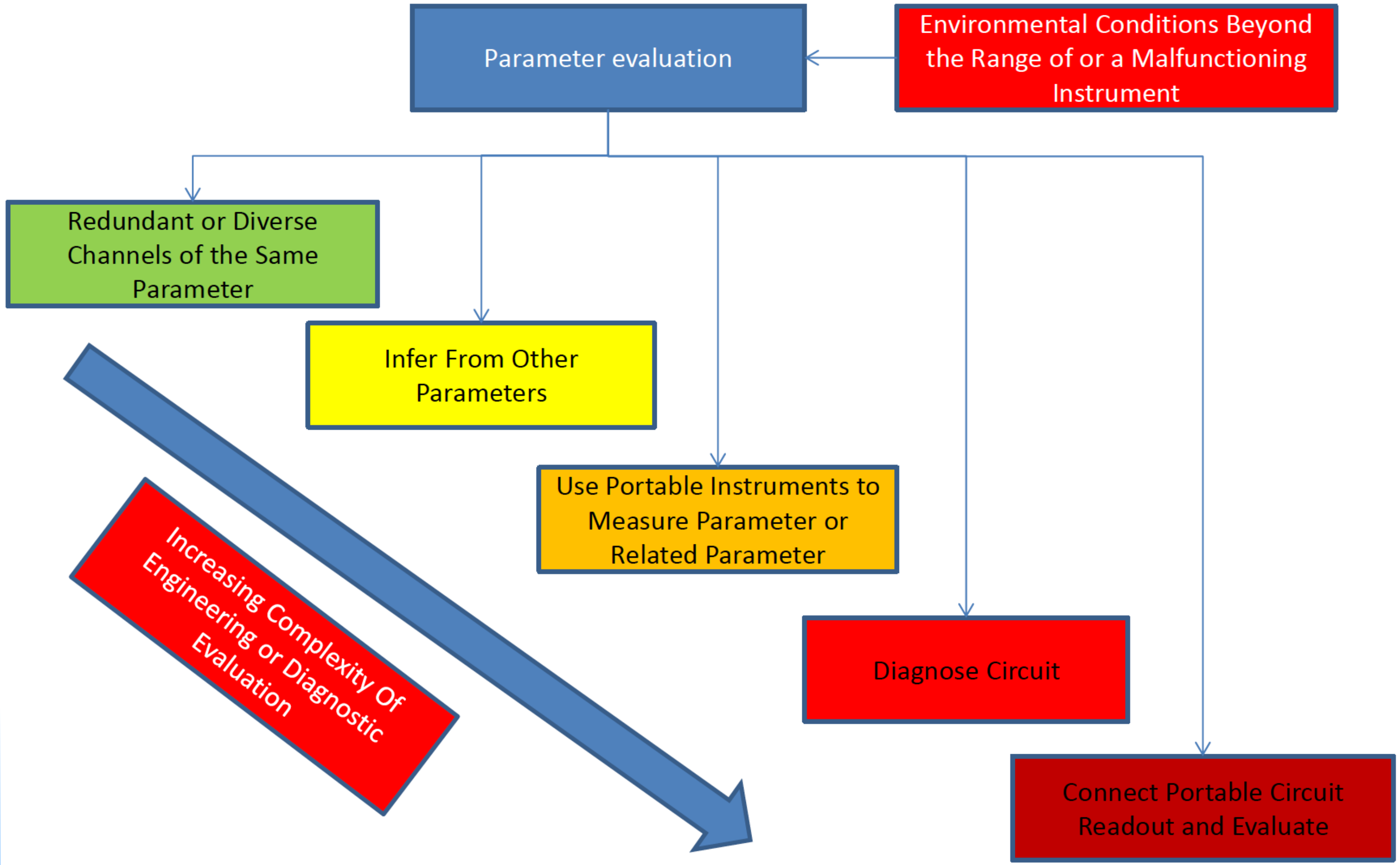
Step 5 – Assessment of instrument availability (7/10)

- The occurrence and timing of **hydrogen burns** or **direct containment heating** can produce temperatures well in excess of qualification limits of instruments located in the containment.
- Evaluation of instrument performance during hydrogen burns or direct containment heating should be evaluated on a plant specific basis.

Step 5 – Assessment of instrument availability (8/10)

- Analytical uncertainties have great impact on predicted temperature distribution because of the dynamics of hydrogen transport and ignition in containment:
  - The uncertainty issue regarding hydrogen burns in the containment is the location and magnitude of these burns.
  - If hydrogen bums occur near the top of the containment, instruments located in the reactor cavity or near the containment floor may survive because of dissipation of the thermal energy.
  - The occurrence of hydrogen bums in the containment does not automatically mean that the performance of instruments located in the containment will degrade. The issues are similar for direct containment heating.

Step 5 – Assessment of instrument availability (9/10)



Step 5 – Assessment of instrument availability (10/10)

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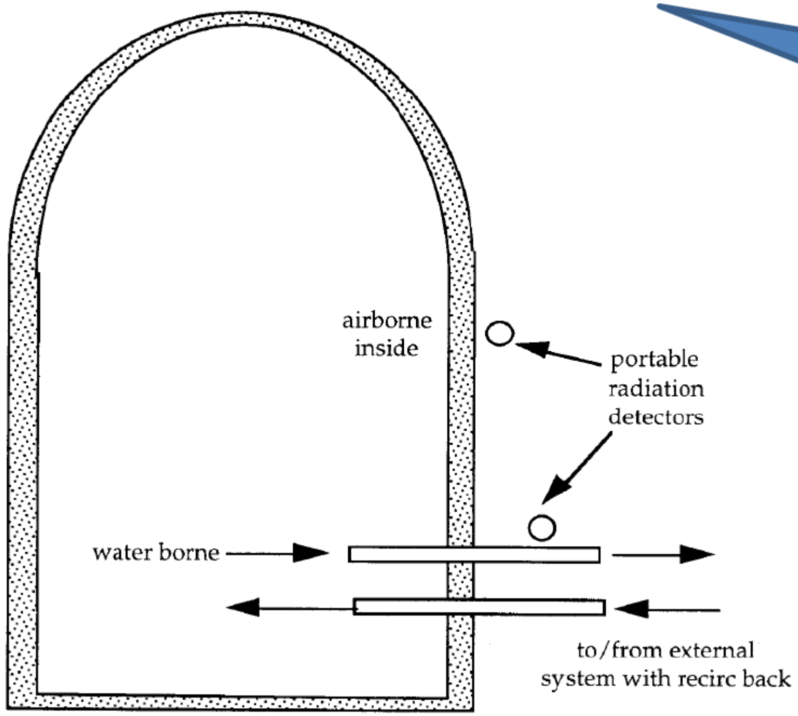
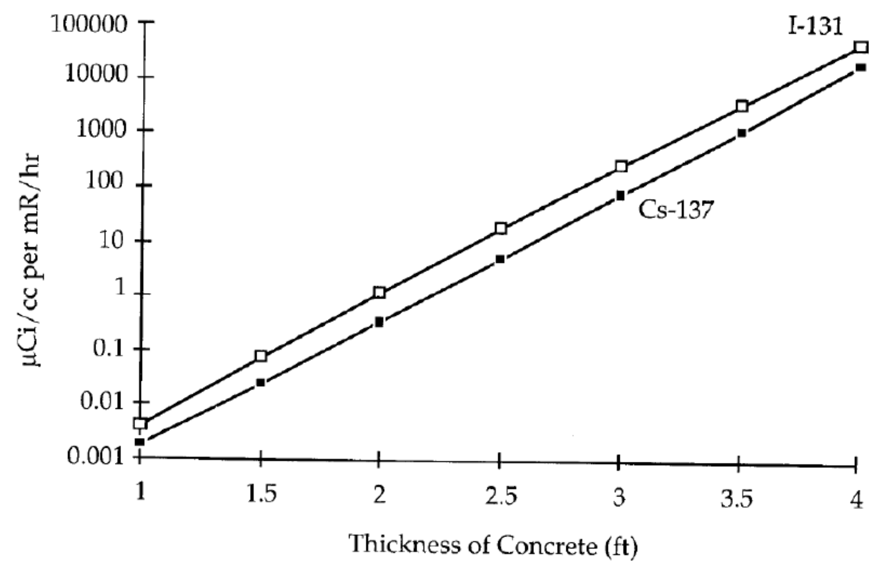
Example: Portable Radiation Detection of Containment Internal Radiation and Necessary Correction due to the Thickness of Concrete

Necessity for Technical Support Centre (TSC) and Operational Support Centre (OPC) training and drills!

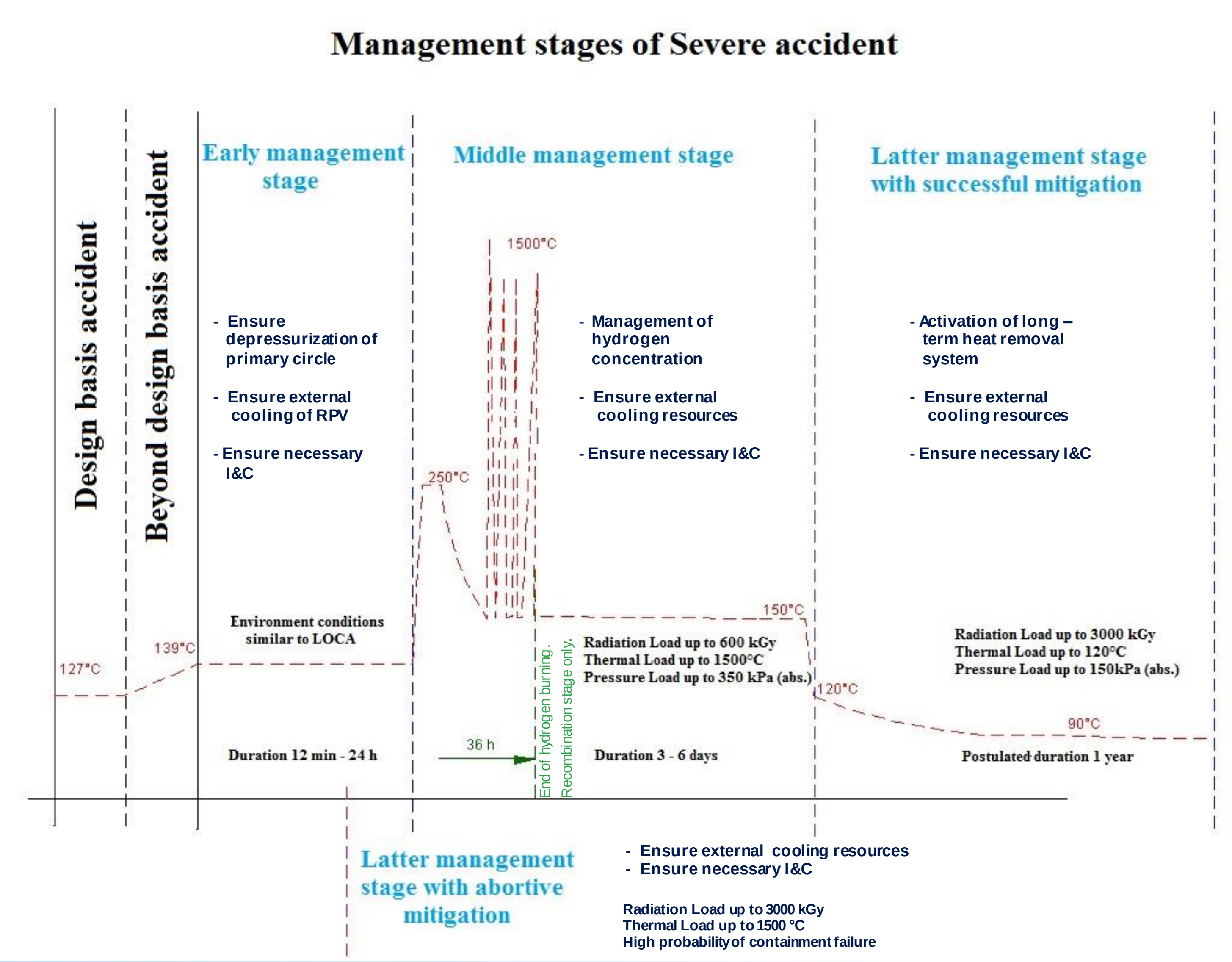




Example
Bohunice NPP SA graded I&C (1/5)

- A limited set of dedicated SA graded I&C was installed in Bohunice NPP during the implementation of SAM project.
- In general, step 1 – 4 were followed to:
  - Identify necessary instrumentation,
  - Identify bounding plant parameters for all SA phases,
  - To qualify instrumentation needed for specific SA phase.

Example
Bohunice NPP SA graded I&C (2/5)



Example
Bohunice NPP SA graded I&C (3/5)

- **Mitigation strategies**
  - Ensure depressurization of primary circle
  - Ensure external cooling of RPV

- **Necessary equipment**

Required environmental conditions for early management stage of SA

Equipment	Location	Thermal load (°C)	Pressure load (kPa^{abs})	Relative humidity (%)	Flooding of system	Radiation (kGy)
Depressurization system of primary circle	SG box A527	140 / 10min 160 / 2min	250	100	no	124 30
Drainage of bubble tower water trays	SG box A263	140/ 2 min	250	100	no	124 15
Reactor cavity flooding system	SG box A004	140 / 10min 150 / 2min	250	100	yes	124 -

- **Another equipment , which must preserve their functionality during this stage of SA**
  - External cooling resources
  - Hydrogen management system
  - Vacuum breaker
  - Long – term heat removal system
  - I&C system for SA
  - Alternative power – supply system for SA

Example
Bohunice NPP SA graded I&C (4/5)

- **Mitigation strategies**
  - ➢ Ensure management of hydrogen in containment
  - ➢ Ensure external cooling resources
- **Necessary equipment**

Equipment	Location	Thermal load (°C)	Pressure load (kPa^{abs})	Relative humidity (%)	Flooding of system	Radiation (kGy)
		Required environmental conditions for middle management stage of SA				
Hydrogen management system	SG box	250* / 30 min 150	350	100	no	124
Vacuum breaker	SG box A263	150	350	100	no	124 15
External cooling resources	Auxiliary building	42	100	100	no	<0.00024

* Local temperature during hydrogen burning should exceeds 1500°C

- **Another equipment , which must preserve their functionality during this stage of SA**
  - ➢ Long – term heat removal system
  - ➢ I&C system for SA
  - ➢ Alternative power – supply system for SA

Example
Bohunice NPP SA graded I&C (5/5)

- **Mitigation strategies**
  - Activation of long – term heat removal system
  - Ensure external cooling resources

- **Necessary equipment**

Required environmental conditions for latter management stage of SA

Equipment	Location	Thermal load (°C)	Pressure load (kPa^abs)	Relative humidity (%)	Flooding of system	Radiation (kGy)
Long – term heat removal system	A203 A001	120 50	120 100	100 100	yes no	237 13
External cooling resources	Auxiliary building	42	100	100	no	<0.0017

- **Another equipment , which must preserve their functionality during this stage of SA**
  - I&C system for SA
  - Alternative power – supply system for SA

Conclusions

- The **role of plant instrumentation is significant** and has to be carefully evaluated in the process of the development of the SAMGs.
- The plant instrumentation provides the **vital link** between:
  - the **severe accident conditions inside the plant** and
  - the **decision making process for severe accident management activities**.
- Because the correct **use and interpretation of instrumentation** is fundamental to the **successful diagnosis and management** of a severe accident, instrumentation should be an **integral part of severe accident training**.

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Questions?