Pre-Application Review Meeting
Severe Accident Analysis

Objectives of Meeting

Objective of Meeting

- Introduce severe accident mitigation features and analysis methodologies of the APR1400

- It would be helpful to us if you provide comments following this presentation.

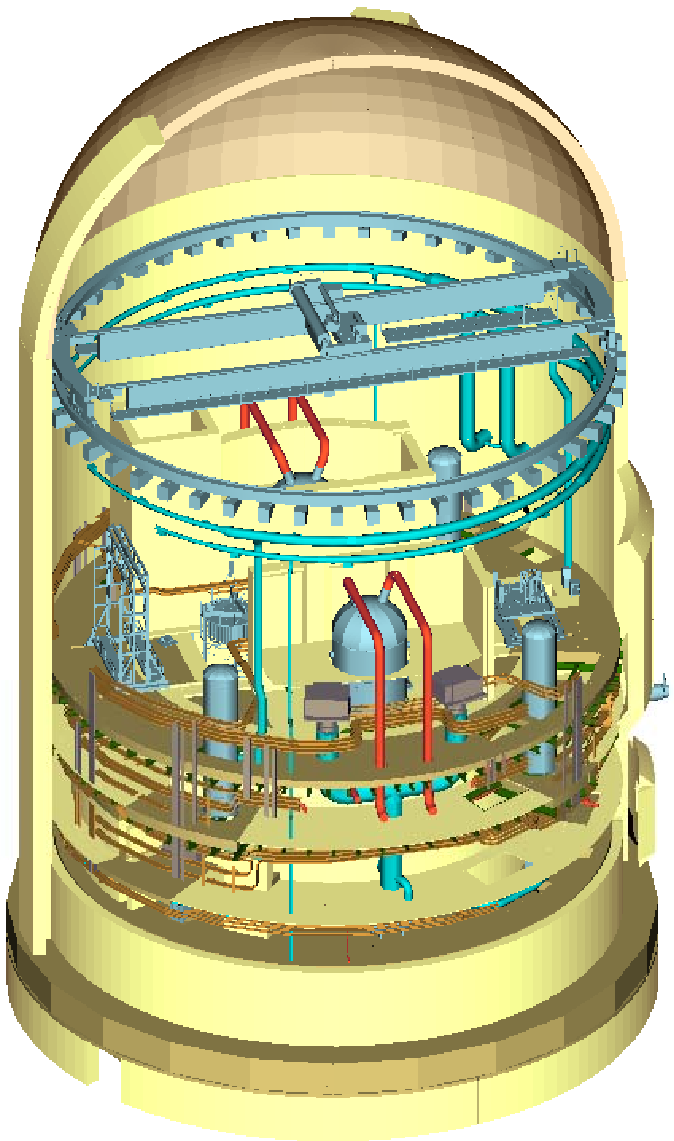
Overview of APR1400

Overview of APR1400 Design

- Evolutionary two-loop PWR with a large dry pre-stressed cylindrical concrete containment with a free volume of ~ 88,000 m^3
- In-containment refueling water storage tank (IRWST) with a large supply of borated water for cavity flooding
- Designed with severe accident mitigation features to meet licensing requirements and utility needs

7th Pre-application Review Meeting

APR1400 Design



Regulations

Regulations

- Requirements
  - 10CFR 50.34(f), Additional TMI requirements
  - 10CFR 50.44, Combustible gas control for nuclear power plants
  - SECY 90-016, Evolutionary LWR certification issues and their relationship to current regulatory requirements
  - SECY 93-087, Policy, technical, and licensing issues pertaining to evolutionary and advanced LWR design
- SECY 93-087 is used as a key basis for severe accident mitigation design features and evaluation

Hydrogen Control

- **SECY 93-087 and 10 CFR 50.44**
  - Accommodate hydrogen generation equivalent to a 100% metal water reaction of the fuel cladding
  - Limit containment hydrogen concentration to no greater than 10 volume %
  - Provide containment-wide hydrogen control

Core Debris Coolability

- **SECY 93-087**
  - Provide reactor cavity floor space to enhance debris spreading
  - Provide a means to flood the reactor cavity to assist in the cooling process
  - Protect the containment liner and other structural members with concrete, if necessary
  - Ensure that the best estimate environmental conditions (pressure & temperature) resulting from CCIs do not exceed FLC (Factored Load Category) for concrete containment for 24 hours. Also ensure that the containment capability has margin to accommodate uncertainties in the environmental conditions from CCIs

High-Pressure Core Melt Ejection

- **SECY 93-087**
  - Provide a reliable RCS depressurization system
  - Provide cavity design features to decrease the amount of ejected Core Debris that could reach the upper containment

Containment Performance

- **SECY 93-087**
  - Maintain its role as a reliable, leak-tight barrier by ensuring that containment stresses do not exceed FLC for a minimum period of 24 hours following the onset of core damage
  - Provide a barrier against the uncontrolled release of fission products following this period

Equipment Survivability

- **SECY 93-087**
  - Reasonable assurance that mitigation features will operate in the severe accident environment for which they are intended and over the time span for which they are needed
  - Guidance in Appendices A and B of RG 1.155, “Station Blackout”, is appropriate for equipment used to mitigate the consequences of severe accident

Severe Accident Mitigation Features

Severe Accident Mitigation Features

- **A severe accident is a low probability, high consequence event**
  - Prevention is more effective from the cost/benefit perspective
  - Predicting a scenario a priori is not clear-cut

Severe Accident Mitigation Features

- **With the defense-in-depth and risk-informed approach in mind, severe accident mitigation features are considered in two ways**
  - The evaluation of containment performance against severe accident phenomena
  - Development and implementation of Severe Accident Management Guidelines (SAMGs) Program
    - SAMG is one of the key element of the NRC 'Integration Plan for Closure of Severe Accident Issues'

Severe Accident Mitigation Features

- **APR1400 Severe Accident Mitigation Features**
  - Containment Design
  - Hydrogen Mitigation System (HMS)
  - Safety Depressurization and Vent System (SDVS)
  - Cavity Flooding System (CFS)
  - Reactor Cavity Structure Design
  - Emergency Containment Spray Backup System (ECSBS)

Severe Accident Mitigation Features

- **Containment Design**
  - Large dry pre-stressed cylindrical concrete containment with a steel liner plate
  - Reliable, leak-tight barrier for approximately 24 hours following the onset of core damage under the more likely severe accident challenges by ensuring that containment stresses do not exceed FLC

Severe Accident Mitigation Features

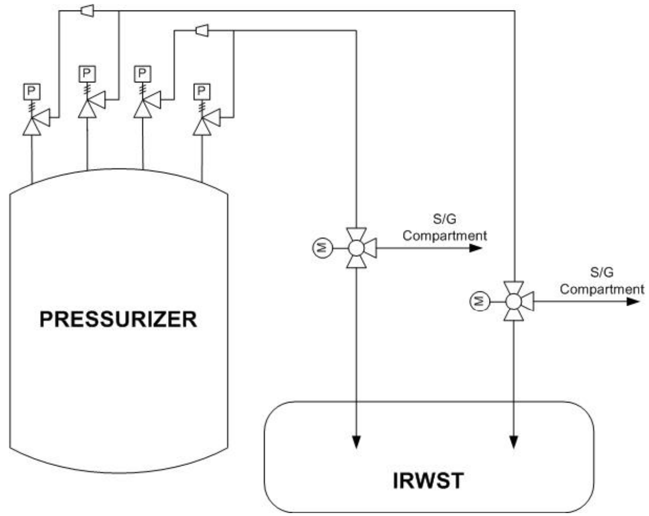
- **Hydrogen Mitigation System (HMS)**
  - Limits hydrogen concentration in containment, generated from a 100% fuel clad-coolant reaction, to less than 10 %
  - PARs (Passive Autocatalytic Recombiners) and igniters
    - PARs : Distributed throughout the containment and control the hydrogen concentration
    - Igniters : Installed near the hydrogen discharge locations and control the possible rapid hydrogen release

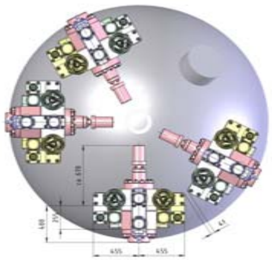
Igniter

PAR

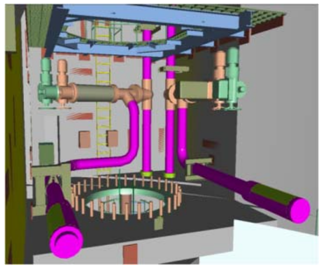
Severe Accident Mitigation Features

- **Safety Depressurization and Vent System (SDVS)**
  - Means to rapidly depressurize the primary system to 250 psia before reactor vessel breach to prevent DCH following a severe accident
  - Means to depressurize RCS for Feed & Bleed operation following a TLOFW (Total Loss Of Feed Water)
  - Elimination of flow of hydrogen into IRWST through the manually opening of POSRVs and 3-way valves
  - Four POSRVs, twelve spargers and two 3-way motor operated valves





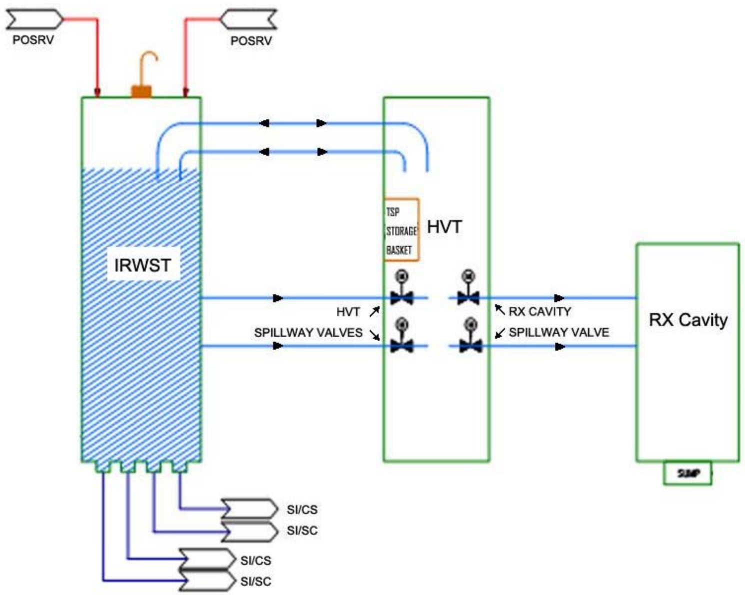
POSRV

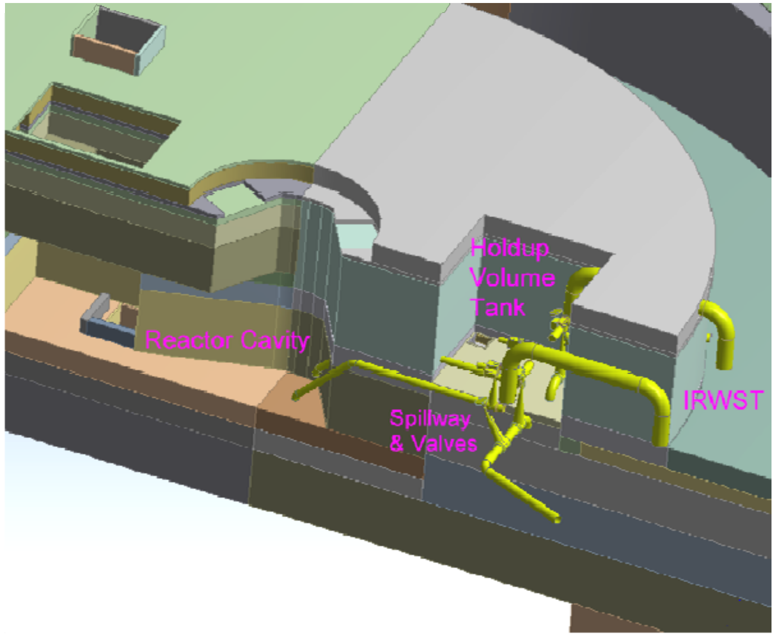


3-Way Valve

Severe Accident Mitigation Features

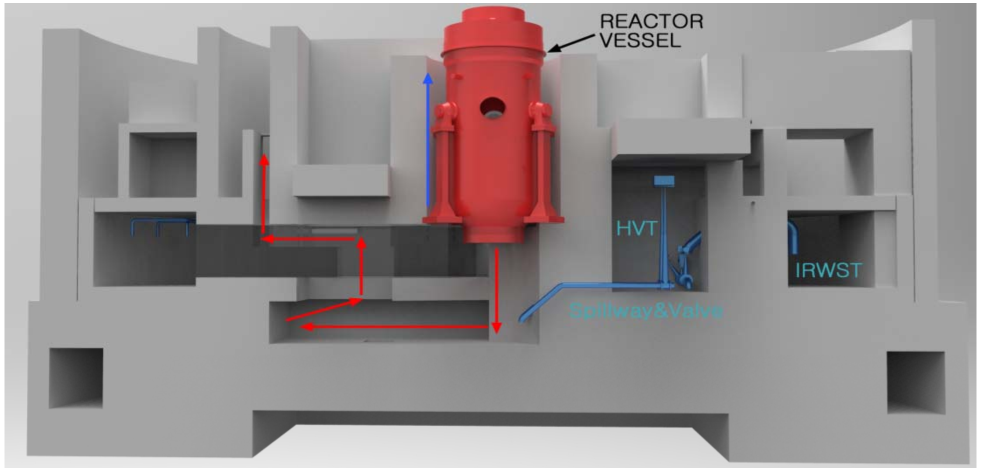
- **Cavity Flooding System (CFS)**
  - CFS is installed to minimize the corium-concrete attack and the generation of combustible gases (hydrogen & carbon monoxide)
  - CFS will assist with scrubbing fission products released from the core debris and molten corium-concrete interaction
  - CFS consists of the HVT(Holdup Volume Tank), four MOVs and associated pipes





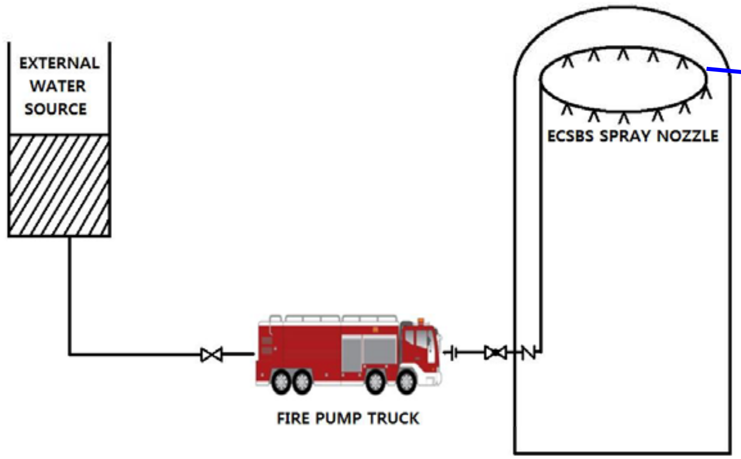
Severe Accident Mitigation Features

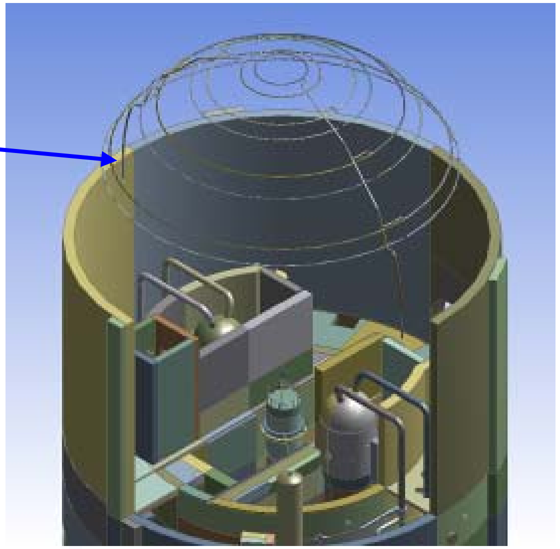
- **Reactor Cavity Structure Design**
  - Reactor cavity structure design minimizes challenges posed by DCH, MCCI and FCI
  - Robust reinforced reactor cavity structure with large cavity volume
  - Convoluted flow path and core debris chamber room to decrease the amount of ejected core debris that may reach the upper containment
  - Sufficient cavity floor area (>0.02m^2/MW_t) for corium debris spreading and cooling
  - Minimum reinforced concrete thickness of 3 feet on the top of the containment embedded steel liner



Severe Accident Mitigation Features

- **Emergency Containment Spray Backup System (ECSBS)**
  - Alternate means of providing a containment spray in the event of a beyond design basis accident in which both CS and SC pumps, and/or the IRWST are unavailable
  - Piping connection to the dedicated ECSBS header line with 50 spray nozzles
  - An effective means to prevent a catastrophic failure of the containment during severe accident
  - Multiple external water sources (reactor makeup water tank, demineralized water storage tank, fresh water tank, and raw water tank)





Severe Accident Analysis Methodology

Severe Accident Analysis Methodology

- **General Approaches**
  - Employ MAAP 4.0.8 for severe accident progression analysis
  - Employ separate effects codes for specific phenomena (MELTSPREAD, CORQUENCH and TEXAS-V)
  - Use existing severe accident experimental databases and employ existing analytical models
  - Review recent experimental and analytical results for their applicability to the APR1400
    - Farmer M.T. et. al., “Corium Coolability under Ex-Vessel Accident Conditions for LWRs,” NET, Vol. 41, June 2009

Severe Accident Analysis Methodology

- **General Approaches (Cont'd)**
  - latest MAAP4 Version 4.0.8
    - Enhancements from Version 4.0.7
    - EPRI Released on 16th of April, 2012
    - Additional improvements
      - Hydrogen diffusion flame model
      - Additional PAR model
      - A capability to impose 100% active fuel clad metal-water reaction

Severe Accident Analysis Methodology

- **General Approaches (Cont'd)**
  - Six severe accident issues are addressed for the APR1400:
    1. Hydrogen Mixing and Combustion
    2. Core Debris Coolability and Molten Core Concrete Interaction
    3. High Pressure Melt Ejection and Direct Containment Heating
    4. Steam Explosion
    5. Containment Performance
    6. Equipment Survivability

Hydrogen Mixing and Combustion

- **Objective**
  - Accommodate hydrogen generation equivalent to a 100% Metal Water Reaction of the fuel cladding
  - Limit containment hydrogen concentration to no greater than 10 volume %
  - Ensure a well-mixed containment and provide containment-wide hydrogen control
  - Ensure that no detonable conditions exist anywhere in containment
  - Ensure that the containment integrity is maintained against AICC (Adiabatic Isochoric Complete Combustion) pressure resulting from combustion of 100% MWR-generated hydrogen

Hydrogen Mixing and Combustion

- **Mitigation Features**

  - Robust large dry pre-stressed cylindrical concrete Containment.
  - Large, well ventilated containment good for hydrogen mixing
  - Highly reliable Hydrogen Mitigation System (HMS)
    - 30 PARs (Passive Autocatalytic Recombiners)
    - 8 igniters

Hydrogen Mixing and Combustion

- **Method of Analysis**
  - Hydrogen Generation, Distribution and Control Analysis using MAAP 4.0.8
    - MAAP 4.0.8 model with 36 nodes, 87 junctions, 188 heat sinks, which MAAP benchmarks with large scale tests have shown to be sufficient.
  - Selection of Severe Accident Sequences
    - Representative scenarios based on the PRA and bounding sequences such as LOCA (LB, MB, SB), TLOFW, SBO

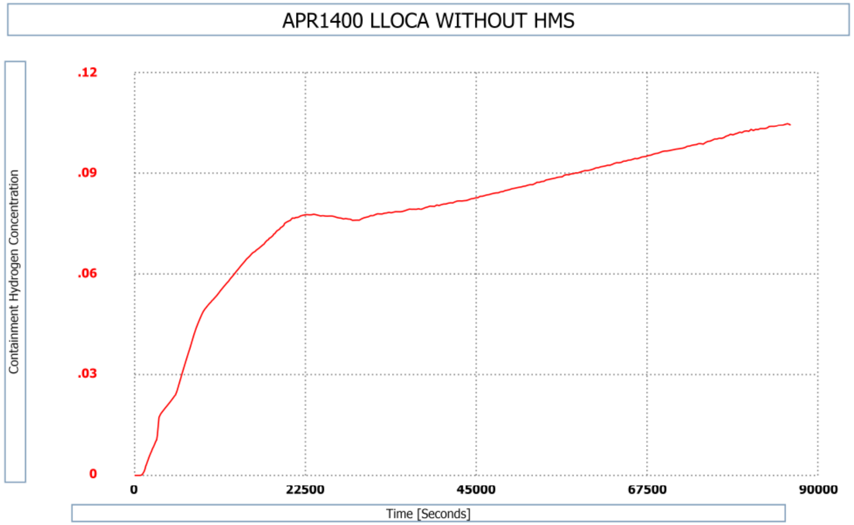
Hydrogen Mixing and Combustion

- **Method of Analysis (Cont'd)**
  - Deflagration to Detonation Transition (DDT)
    - The possibility of DDT is evaluated for every sequence, in every node, at every MAAP time step.
    - The evaluation is dependent on the gas temperature, pressure, gas concentrations, node geometry.
    - Detonation cell width is calculated and compared to node geometry to determine possibility of DDT.
  - Maximum AICC Hydrogen Combustion Pressure Loads
    - Calculated by 100% MWR equivalent hydrogen and containment volume
    - Flammable Condition by Flammability Limit Curve

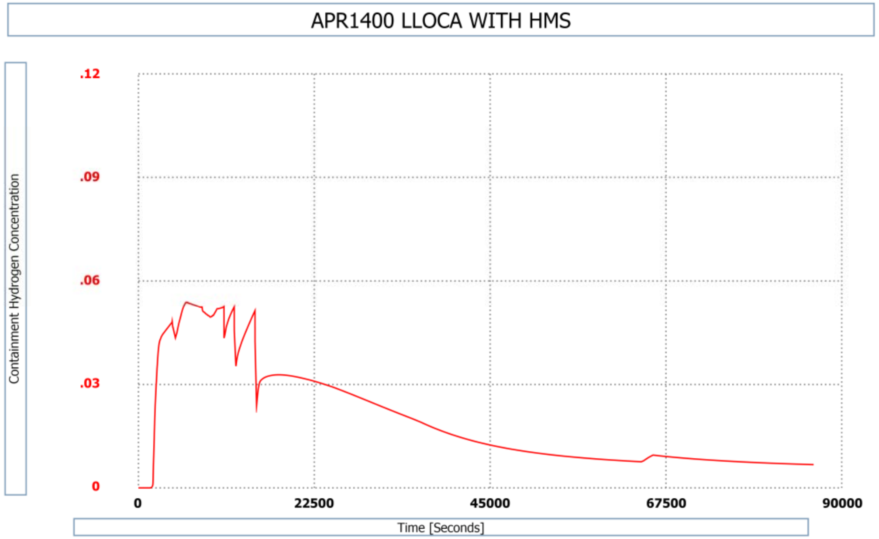
Hydrogen Mixing and Combustion

- **Analysis results**
  - The analysis results of global effect showed that the hydrogen concentration in the containment can be maintained well below 10 volume % with HMS
  - DDT evaluation is ongoing
  - Evaluated P_{AICC} (99 psia) < FLC Design Pressure (123.7 psia)
  - Engineering judgment complemented by hydrogen analysis results is used for the locations for PARs and igniters

Hydrogen Mixing and Combustion



H_2 Conc. w/o HMS



H_2 Conc. with HMS

Core Debris Coolability and Core Concrete Interaction

- **Objective**
  - Provide reactor cavity floor space to enhance debris spreading
  - Provide a means to flood the reactor cavity to assist debris cooling
  - Protect the containment liner
  - Ensure that pressure and temperature resulting from core-concrete interactions do not exceed Factored Load Category for 24 hours
- **Design Mitigation Features**
  - Large reactor cavity floor area for corium spreading and cooling
  - Gravity-driven cavity flooding system to flood the reactor cavity

Core Debris Coolability and Core Concrete Interaction

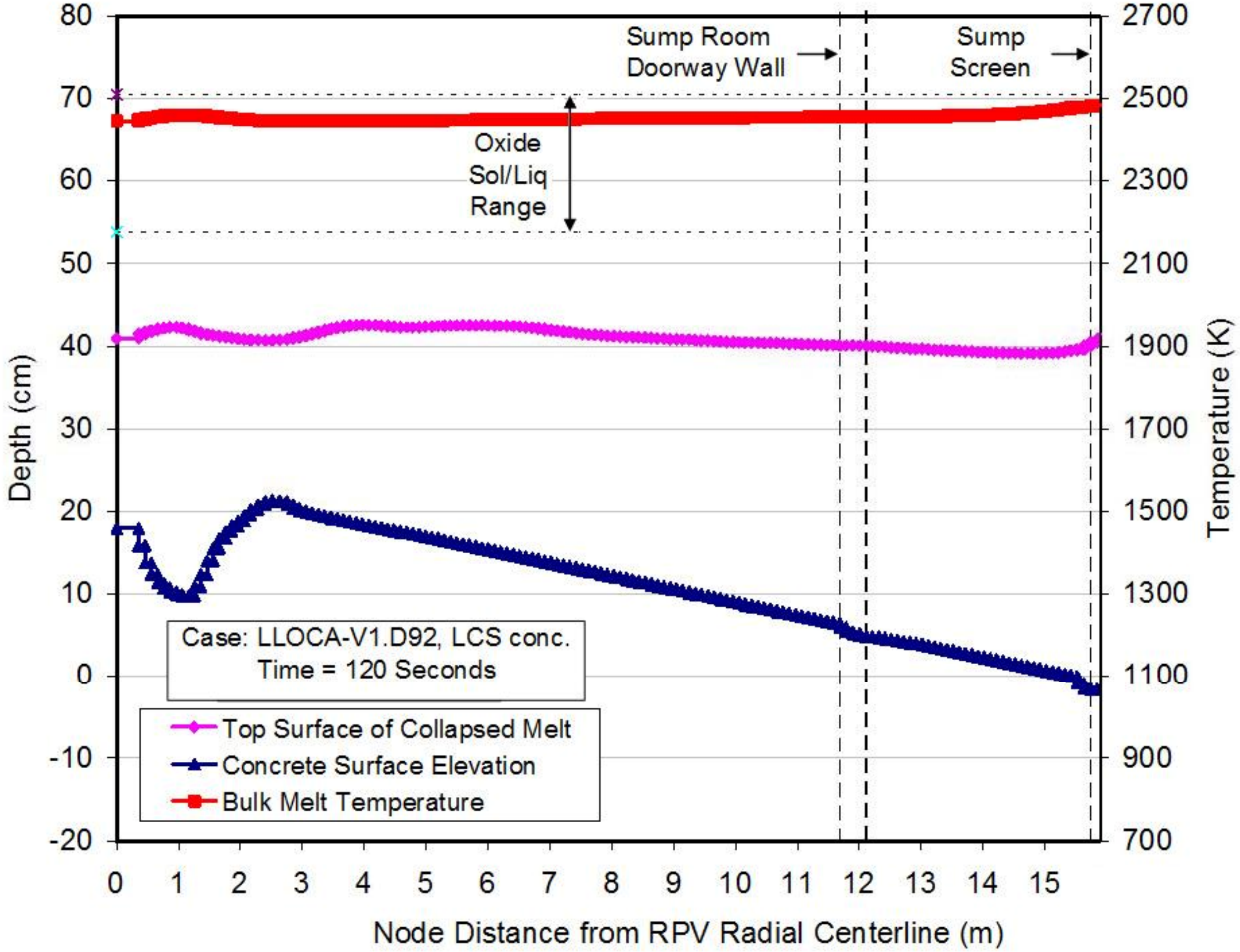
- **Method of Analysis**
  - MAAP 4.0.8
    - Calculation of an initial inventory and corium composition
    - Melt pour conditions based on MAAP 4.0.8 analyses for a Large Break LOCA sequence
  - Sequence analysis using MELTSPREAD and CORQUENCH
  - Adjustment of MAAP 4.0.8 model parameter FCHF based on the CORQUENCH results
    - Modeling of the corium-to-water heat transfer enhancement due to water ingression and melt eruption.
  - Evaluation of various scenarios such as LOCA (LB, MB, SB), TLOFW, and SBO using MAAP 4.0.8

Core Debris Coolability and Core Concrete Interaction

- **Application of Recent Research Results**
  - Assessment of MELTSPREAD and CORQUENCH codes against the extensive experimental database including the recent CCI experiments
  - MELTSPREAD
    - Evaluation of the extent of core melt spreading in the containment under wet cavity conditions
  - CORQUENCH
    - Evaluation of the subsequent long-term core concrete interaction behavior with overlying coolant using state-of-the art heat transfer models

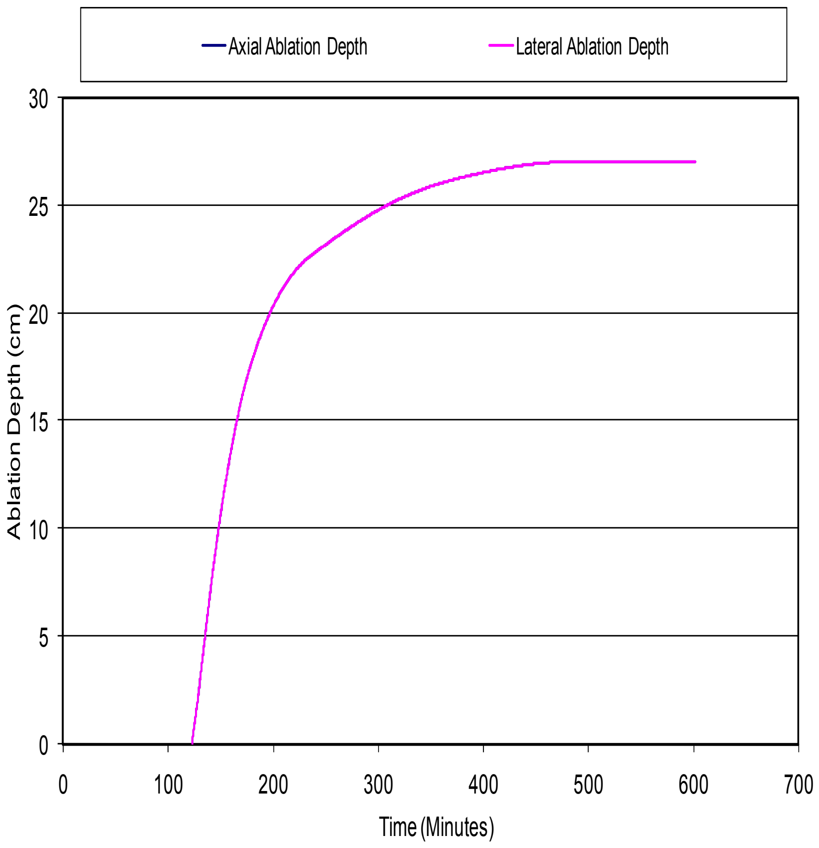
Core Debris Coolability and Core Concrete Interaction

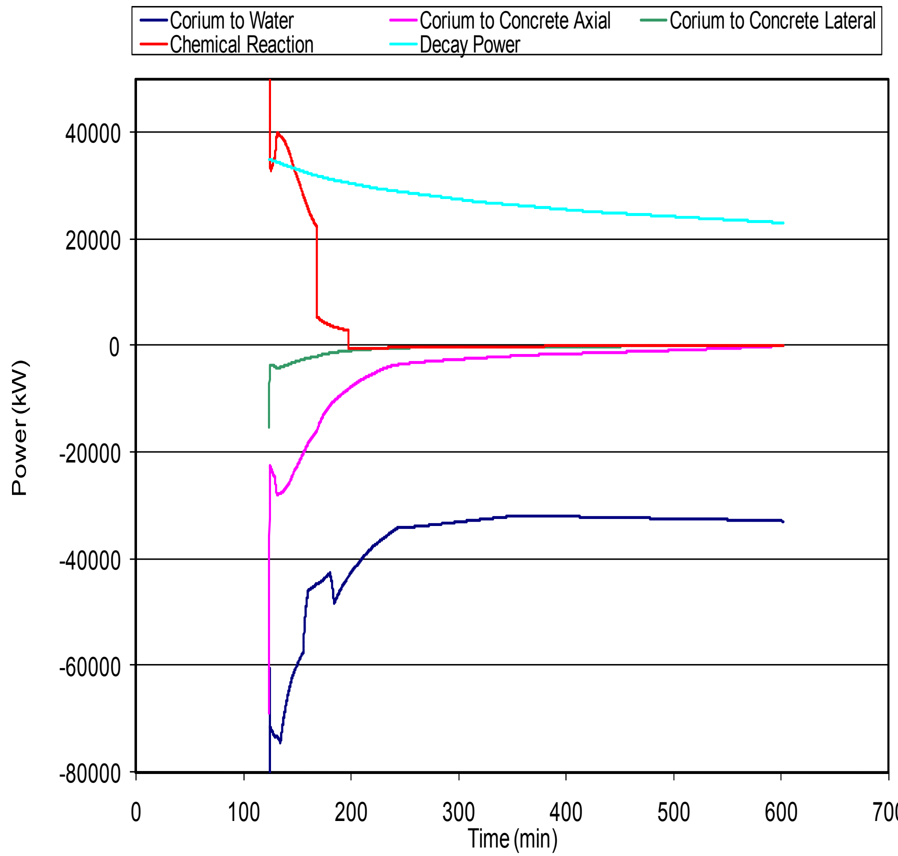
- **MELTSPREAD Results: Melt Distribution at 120 seconds**



Core Debris Coolability and Core Concrete Interaction

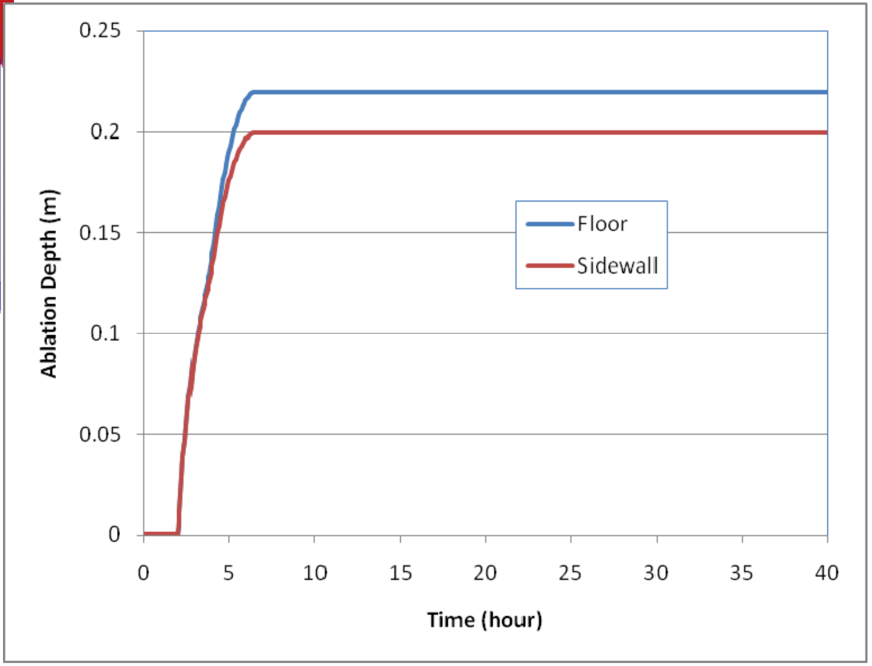
- **COREQUENCH Results for LCS (Limestone / Common Sand) Concrete**



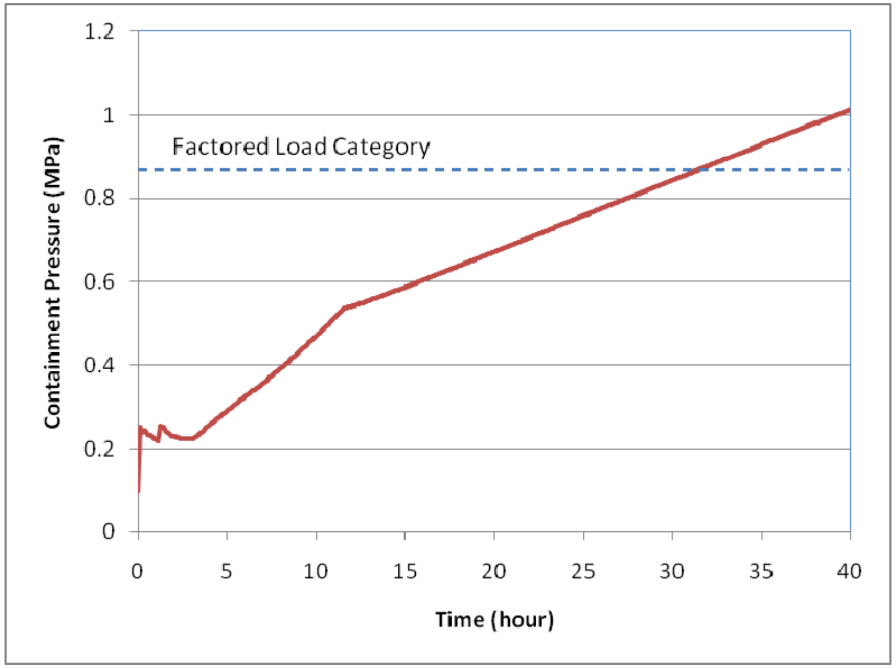


Core Debris Coolability and Core Concrete Interaction

- **MAAP Results**



Erosion Depth
(LBLOCA w/ FCHF = 0.0245)



Containment Pressure
(LBLOCA w/ FCHF = 0.0245)

High Pressure Melt Ejection and Direct Containment Heating

- **Objective**
  - Provide a reliable RCS depressurization system
  - Provide convoluted flow path to decrease the amount of ejected core debris that could reach the upper containment
- **Design Mitigation Features**
  - Safety Depressurization and Vent System (SDVS)
    - Depressurize RCS so that HPME will not occur
  - Reactor cavity and lower compartment designs
    - Reactor cavity and lower compartment configurations would lead to retention of most of core debris in lower compartment

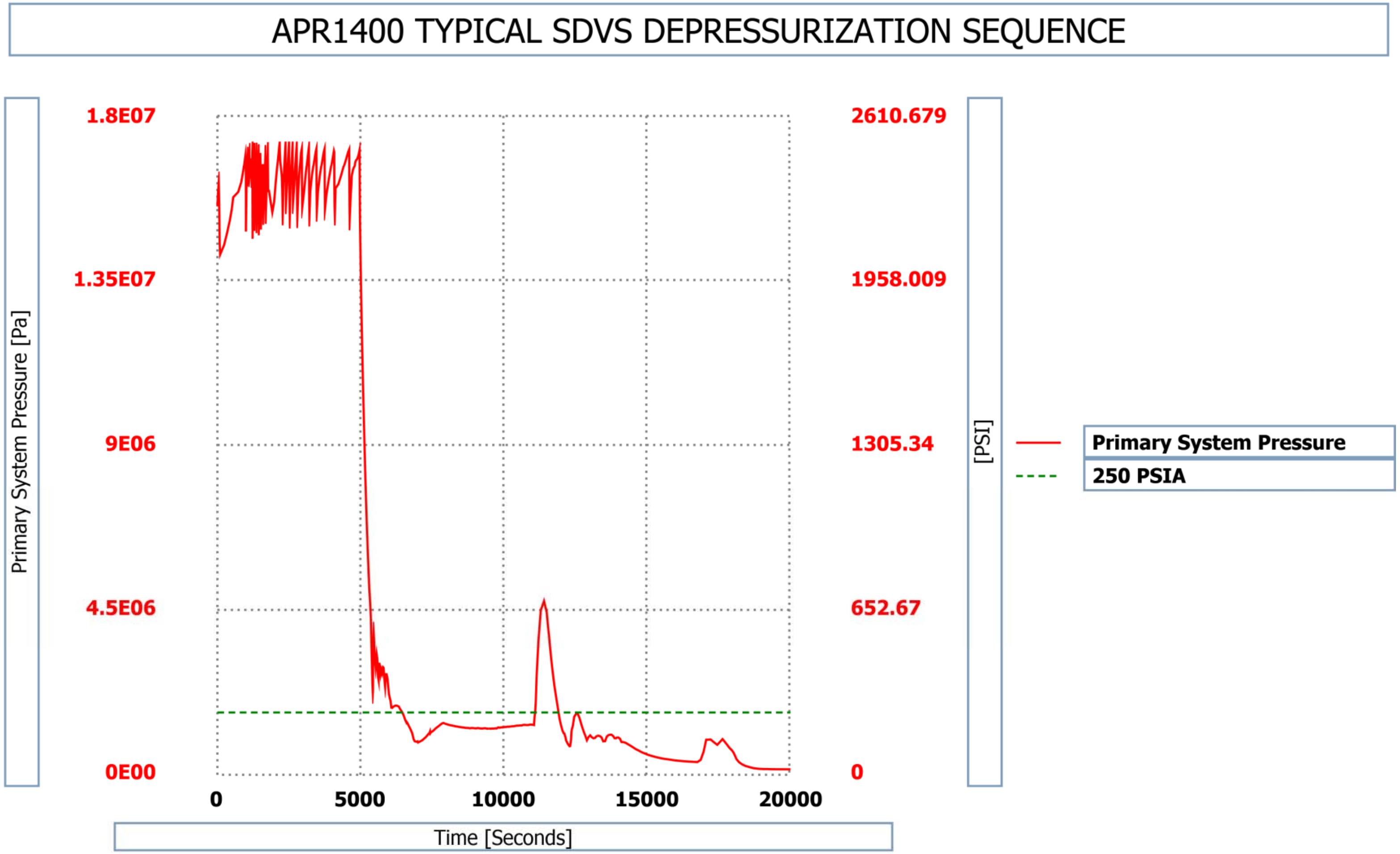
High Pressure Melt Ejection and Direct Containment Heating

- **Method of Analysis for RCS depressurization**

  - Use the MAAP 4.0.8 code to examine the spectrum of accident sequences including top ranking PRA sequences to evaluate the Safety Depressurization and Vent System and ensure that the design provides desired depressurization

High Pressure Melt Ejection and Direct Containment Heating

- **Analysis results**



High Pressure Melt Ejection and Direct Containment Heating

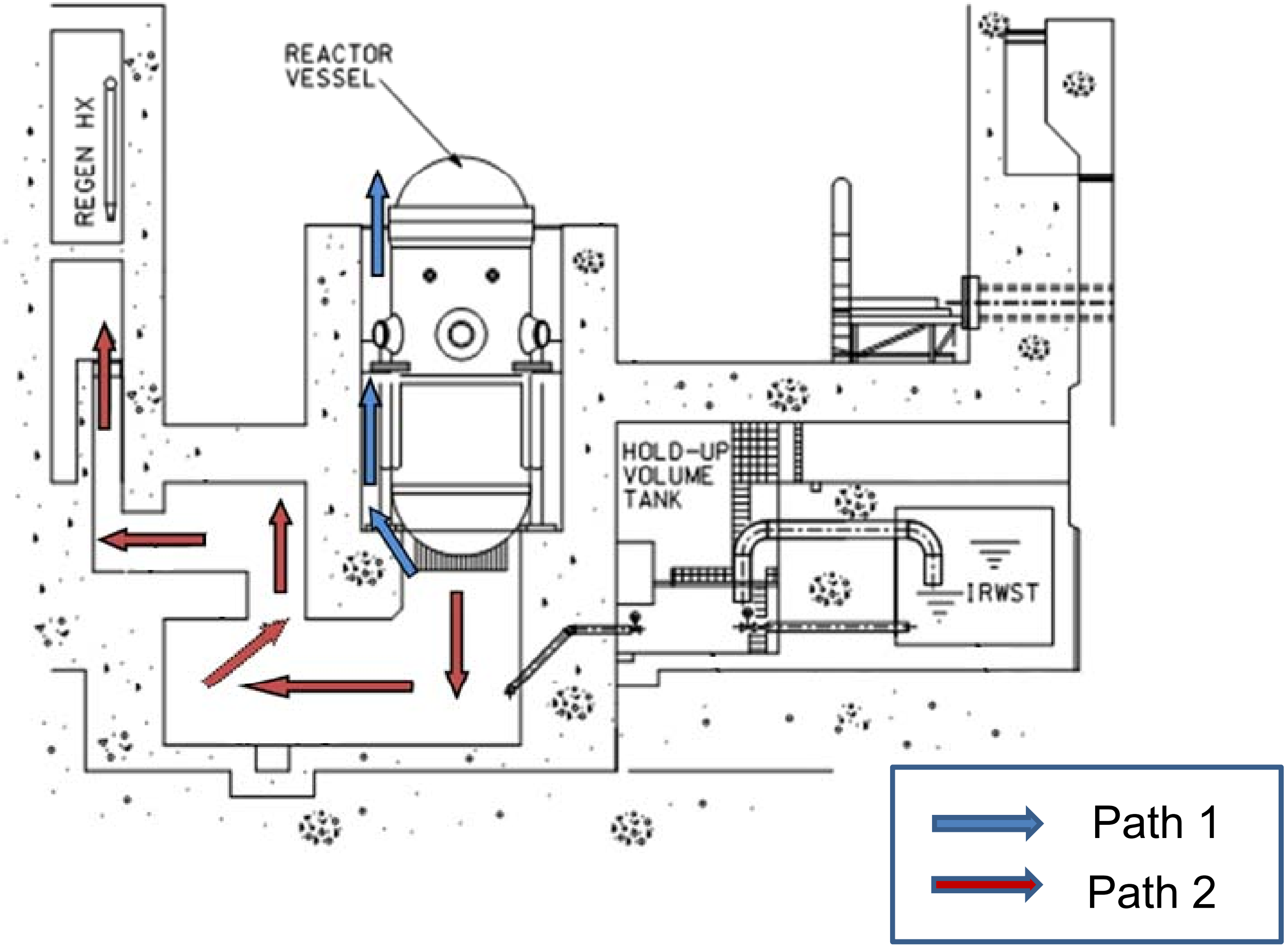
Method of Analysis for HPME

- Small LOCA scenarios leading to HPME are considered

Scenario	Description	RCS Pressure
V	SBLOCA with Re-pressurization of RCS by Operator Intervention without Containment Spray	17 Mpa
Va	SBLOCA with Re-pressurization of RCS by Operator Intervention with Containment Spray	17 Mpa
VI	SBLOCA under Wet Core Condition	9 Mpa

- Two possible paths of gas and corium flows during HPME are examined
  - Path 1: from cavity to sub-compartment directly
  - Path 2: from cavity to upper compartment directly

High Pressure Melt Ejection and Direct Containment Heating

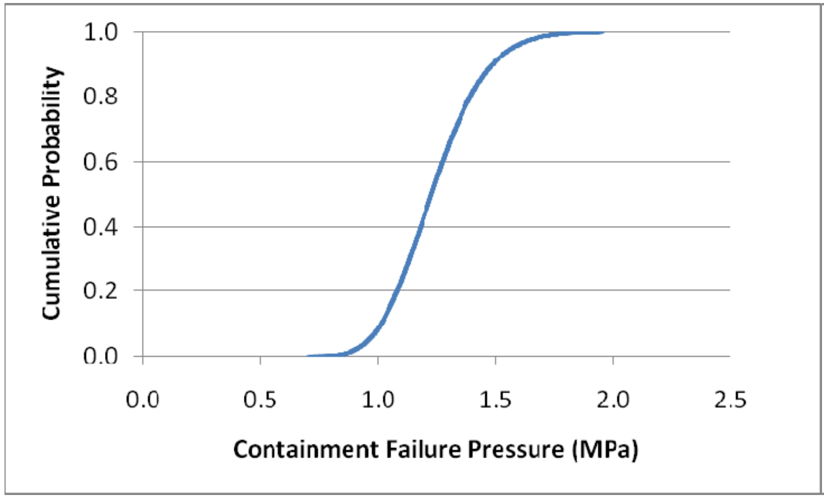


High Pressure Melt Ejection and Direct Containment Heating

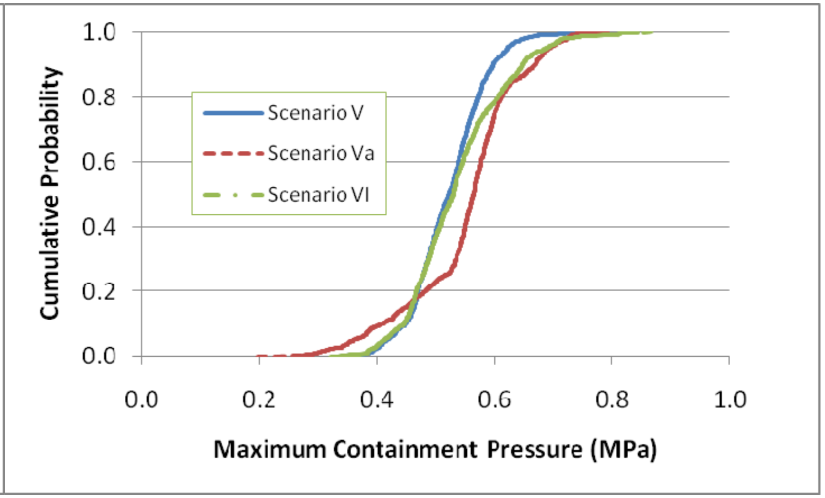
- **Method of Analysis for HPME (Cont'd)**
  - Uncertainties of key input parameters are examined with LHS (Latin Hypercube Sampling) method
    - Mass of molten UO_2 in the lower plenum
    - Fraction of Zr oxidation
    - Containment failure pressure (fragility curve)
    - Coherence ratio of gas and corium
  - The maximum containment pressure and temperature are evaluated using two cell equilibrium (TCE) Model
    - Evaluate conditional containment failure probability (CCFP) based on the number of cases with a failed containment

High Pressure Melt Ejection and Direct Containment Heating

- **Analysis results**
  - Scenarios V, Va, and VI (SBLOCA) were selected with representative RCS and containment pressures
  - CCFPs (Conditional Containment Failure Probability) for the three scenarios are all less than 0.1%



Containment Failure Pressure Distribution



Maximum Containment Pressure Distributions

Steam Explosion

- **Objective**
  - To confirm the low risk of the in-vessel steam explosion (IVSE) in the APR1400
  - To ensure that the energetic of the ex-vessel steam explosion (EVSE) does not threaten the integrity of cavity structure in the APR1400

- **Design Mitigation Features**
  - Reactor pressure vessel
  - Reactor cavity design
  - Pre-stressed concrete containment with a steel liner plate

Steam Explosion

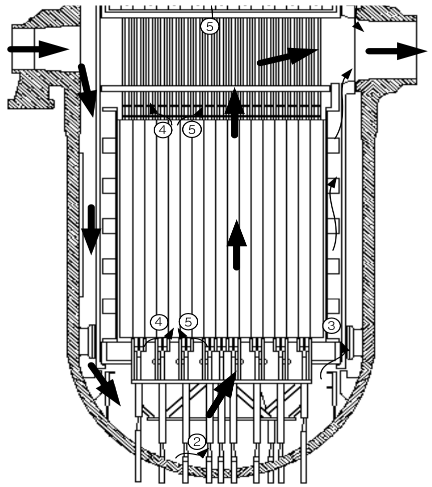
● Method of Analysis

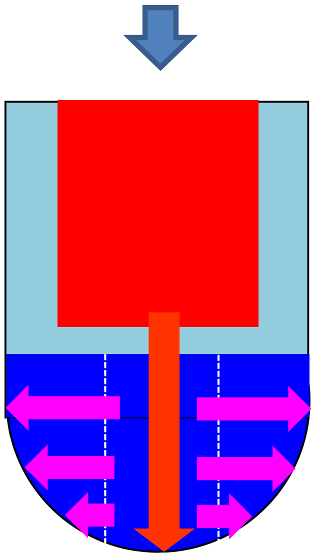
- Initial and Boundary Conditions
  - Initial and boundary conditions with the parameter ranges for the sensitivity analyses for IVSE and EVSE by MAAP 4.0.8
- Steam Explosion Loads
  - Evaluation of the energetics of IVSE and EVSE with TEXAS-V
- Structure Integrity
  - Calculations of the RPV structure integrity against the estimated IVSE loads with ABAQUS
  - Calculations of the cavity structure integrity against the estimated EVSE loads with ABAQUS
- Sensitivity Analysis
  - Sensitivity analysis of the initial and boundary conditions of key parameters affecting to the steam explosion loads against the surrounding structures

In-Vessel Steam Explosion (1/4)

Method of IVSE Analysis

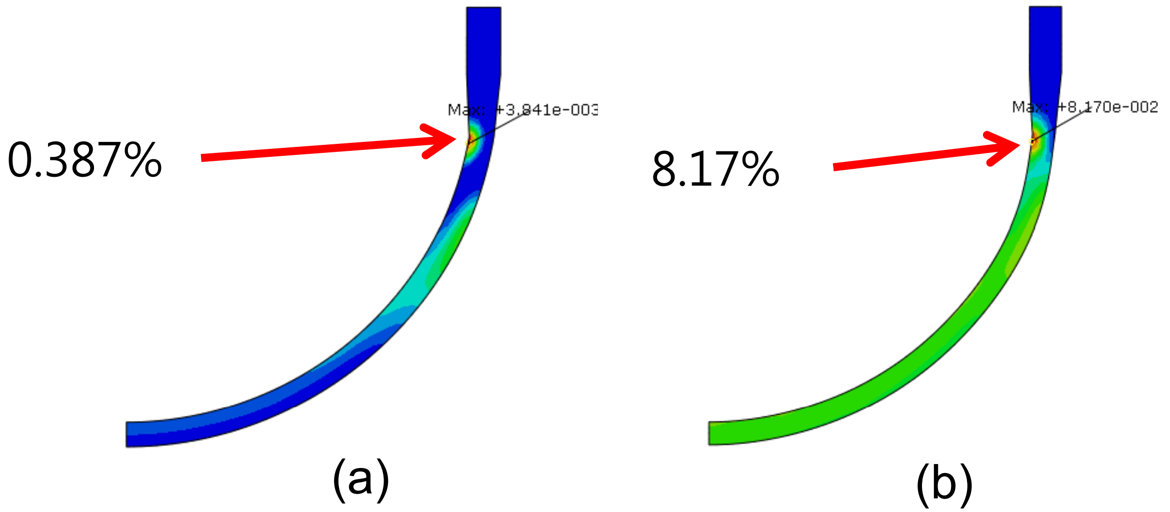
- RPV Internal Structures
  - Simplified internal structure
- IVSE Loads Analysis
  - 1-D TEXAS-V analysis at the center of the RPV
  - IVSE triggering due to the bottom contact of corium jet
- RPV Structure Analysis
  - Direct application of the maximum IVSE load on to the RPV inner wall





In-Vessel Steam Explosion (2/4)

- **Results of IVSE Analysis**
  - Preliminary analysis for the APR1400 RPV
    - ABAQUS 6.10 with two-dimensional Axi-symmetric Model
    - The maximum equivalent plastic strain is well below the failure criteria (11%) suggested by Shockey et. al [J. of Pressure Vessel Tech., 1980].



Distributions of Equivalent Plastic Strain for Maximum IVSE Pressures of (a) 50.5 MPa (146.04 kPa-s) and (b) 150 MPa (452.0 kPa-s)

In-Vessel Steam Explosion (3/4)

- **Application of Recent Research Results of IVSE**
  - WASH-1400 (1975) [NUREG-75/0114]
    - ALPHA mode of containment failure due to IVSE induced "missile" generation
  - SERG-1 (1985) [NUREG-1116] & SERG-2 (1995) [NUREG-1529]
    - Deterministic and probabilistic analysis with expert opinions concluded that the conditional probability of containment failure is less than 10^{-3} or negligible. The issue of alpha mode of containment failure is resolved from risk perspective (10 out of 11 experts)
    - Lower head vessel failure due to IVSE remains as a safety issue

In-Vessel Steam Explosion (4/4)

- **Application of Recent Research Results of IVSE (Cont'd)**
  - OECD/CSNI FCI Specialist Meeting (1997) [NEA/CSNI/R(97)30]
    - Reconfirm the conclusions of SERG-1 and 2
  - SERENA-I (2007) [NEA/CSNI/R(2007)11]
    - Predicted peak pressure ranged from ~10 to ~120 MPa (from some 10 to 200 kPa-s)
    - The loads are far below the capacity of the defined-model intact vessel, confirming sufficient safety margin
  - SERENA-II (2012) [Final Draft Report]
    - No exercise

Ex-Vessel Steam Explosion (1/2)

- **Method of EVSE Analysis**
  - Ex-Vessel Reactor Cavity
    - EVSE with flooded cavity (partial flooding)
  - EVSE Load Analysis
    - Initial and boundary conditions for EVSE load evaluation
      - Initial conditions based on MAAP 4.0.8 analysis results
      - Corium release by ICI tube failure
    - TEXAS-V analysis for the evaluation of EVSE load
      - 1-D Approaches + Underwater shock propagation
  - Ex-Vessel Reactor Cavity Structure Analysis
    - Structure analysis to evaluate structure integrity of containment due to EVSE load

Ex-Vessel Steam Explosion (2/2)

- **Application of Recent Research Results of EVSE**
  - SERENA-I (2007) [NEA/CSNI/R(2007)11]
    - Validation of mechanistic FCI models with the high energetic simulant test data was in progress
    - Increase in the question of quantifying the containment safety margin for EVSE due to the scatter of the results
  - SERENA-II (2012)
    - Limited number of EVSE tests in well-designed facilities (TROI and KROTOS)
    - Validation of limited number of mechanistic models with the lower energetic corium test data is in progress
      - Role of melt properties and void fraction in mixing
      - Solidification model
    - Reactor calculations for PWR and BWR EVSE with the models are in progress

Containment Performance

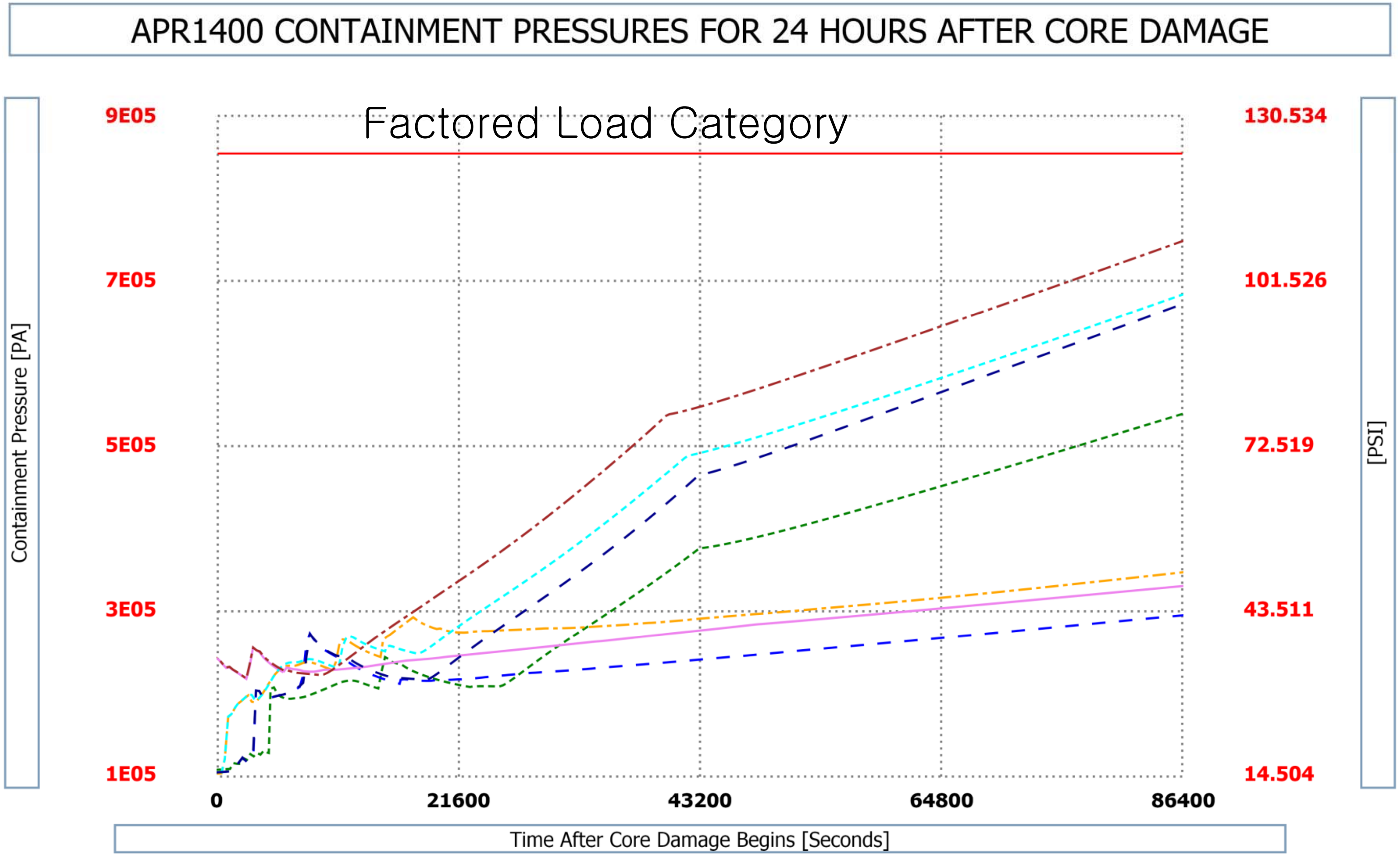
- **Objective**
  - To maintain its role as a reliable, leak-tight barrier by ensuring that containment stresses do not exceed FLC for a minimum period of 24 hours following the onset of core damage
  - To provide a barrier against the uncontrolled release of fission products following this period
- **Design Mitigation Feature**
  - Large dry pre-stressed cylindrical concrete containment with a steel liner plate

Containment Performance

- **Method of Analysis**
  - MAAP 4.0.8 is used to calculate the containment pressure transients for various accident scenarios
    - Selection of representative severe accident sequences based on the PRA and bounding sequences
  - Containment performance analysis considering the steam from cooling of core debris and non-condensable gases from CCI
    - Pressurization by steam and non-condensable gases
    - Evaluation of fission product release
    - Primary/ secondary system and containment response
  - To demonstrate long-term containment overpressure does not exceed the FLC for concrete containment for 24 hours following the onset of core damage

Containment Performance

- **Analysis Results**



Equipment Survivability

- **Objective**
  - Reasonable assurance that mitigation features will operate in the severe accident environment for which they are intended and over the time span for which they are needed
  - To confirm safety related equipment and components will survive the harsh environmental conditions of severe accident and perform their intended function for 24 hours following the onset of core damage

Equipment Survivability

- **Method of Analysis –** Identification of target equipment and components
  - Identify safety related equipment and components that need to be evaluated for survivability
  - Identified equipment and components are divided into two groups
    - Equipment and components needed before vessel failure
    - Equipment and components needed after vessel failure

Equipment Survivability

- **Method of Analysis – Determination of Severe Accident Environmental Conditions**
  - Analysis for the various accident scenarios using the MAAP 4.0.8 code to determine the environmental conditions (pressure, temperature and radiation) expected in each containment node
    - Environmental conditions before vessel failure
    - Environmental conditions after vessel failure
  - MAAP4-DOSE is used to determine the radiation exposure of the equipment

Equipment Survivability

- **Method of Analysis – Assessment of individual target equipment and components for the severe accident environmental conditions**
  - Comparison of the severe accident environmental condition with test data from the equipment vendor
  - Results of severe accident environmental testing
    - Sandia/INEL Severe Accident Seals and Gaskets Test Program
    - Sandia/CBI Personnel Airlock Testing
    - EPRI Large-Scale Hydrogen Experiments

Equipment Survivability

- **Method of Analysis – Assessment of individual target equipment and components for the severe accident environmental condition (cont'd)**
  - Thermal-lag calculation to show that the local temperature of the limiting component (typically non-metallic) is less severe than the environmental conditions produced by hydrogen burns
  - Alternate approach such as protecting the equipment with a fire wrap or through redundancy

Summary

Summary

An overview of the APR1400 severe accident analysis has been presented, including:

- the strategy and approach to comply with the NRC requirements
- the severe accident mitigation features of the APR1400
- the severe accident analysis methodology for the APR1400