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Safety Analysis:
Severe Accident Analysis

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I. Introduction

Introduction

- Definitions
  - **Severe Accident : [IAEA Safety Glossary, 2016 Revision]**
    - Accident more severe than those for a design basis accident and involving significant core degradation

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design extension conditions

What is severe accident?

- IAEA Safety Glossary
  - Accident more severe than those for a design basis accident and involving significant core degradation

Operational States

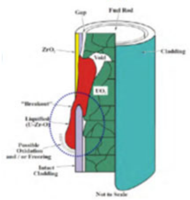
Accident conditions

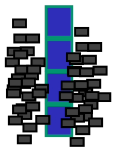
Plant Condition

Normal operation	**Anticipated Operation (AOO)**	**Design basis Accident (DBA)**	**Design extension Conditions (DEC)**

Transient

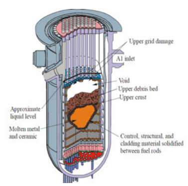
Fuel Degradation





Rupture at ~ 1200°C

Significant Core Degradation

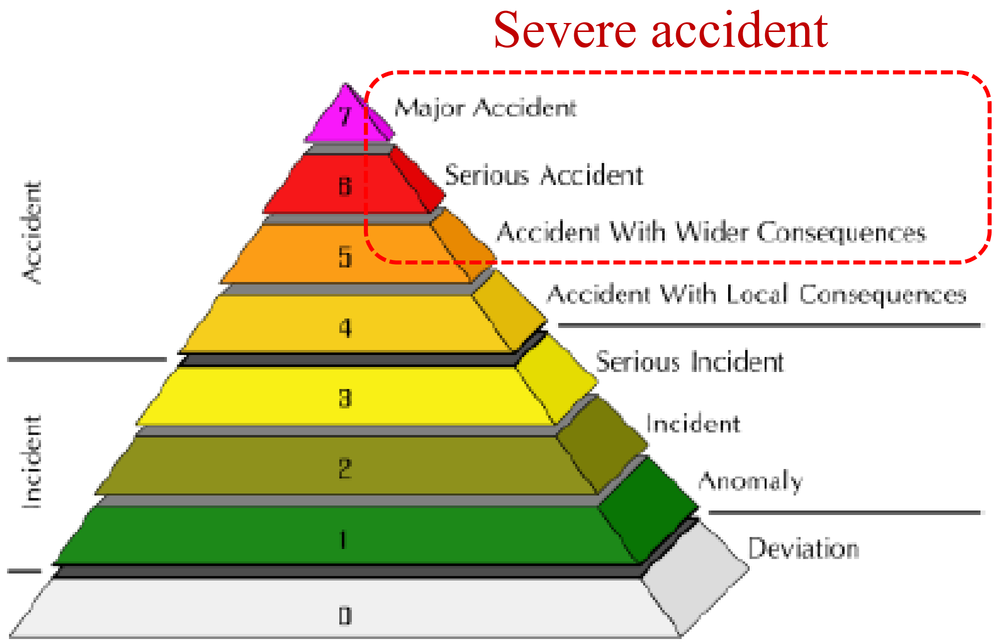


Introduction

- Plant States
  - **design extension conditions**
    - Postulated accident conditions that are not considered for design basis accidents, but that are considered in the design process of the facility in accordance with best estimate methodology, and for which releases of radioactive material are kept within acceptable limits.
    - Design extension conditions comprise conditions in events without significant fuel degradation and conditions in events with melting of the reactor core.
  - **beyond design basis accident**
    - Postulated accident with accident conditions more severe than those of a design basis accident. (superseded by design extension conditions)

Historical Records:
International Nuclear Event Scale (INES)

- The International Nuclear and Radiological Event Scale (INES) was introduced in 1990 by the International Atomic Energy Agency (IAEA)
  - to enable prompt communication of safety significant information in case of nuclear accidents.



A representation of the INES levels

Introduction

- Historical Experiences of Severe Accident (1)

	TMI-2	Chernobyl	Fukushima I
Date	1979. 3. 28	1986. 4. 26	2011. 3. 11
Reactor	PWR	RBMK	BWRs
Cause	Loss of feed water	Safety test! (RIA)	Earthquake/ Tsunami
Faults & Errors	- PORV failure - Faulty operator action	- Faulty reactor design - Operator violating procedure	- Limited access to Technical Support - Weak SAMG
Conse-quences	- Partial melting of core	- Disastrous hazard to public	- Multi-unit Damage: Core meltdown, H_2 explosion
			

Introduction

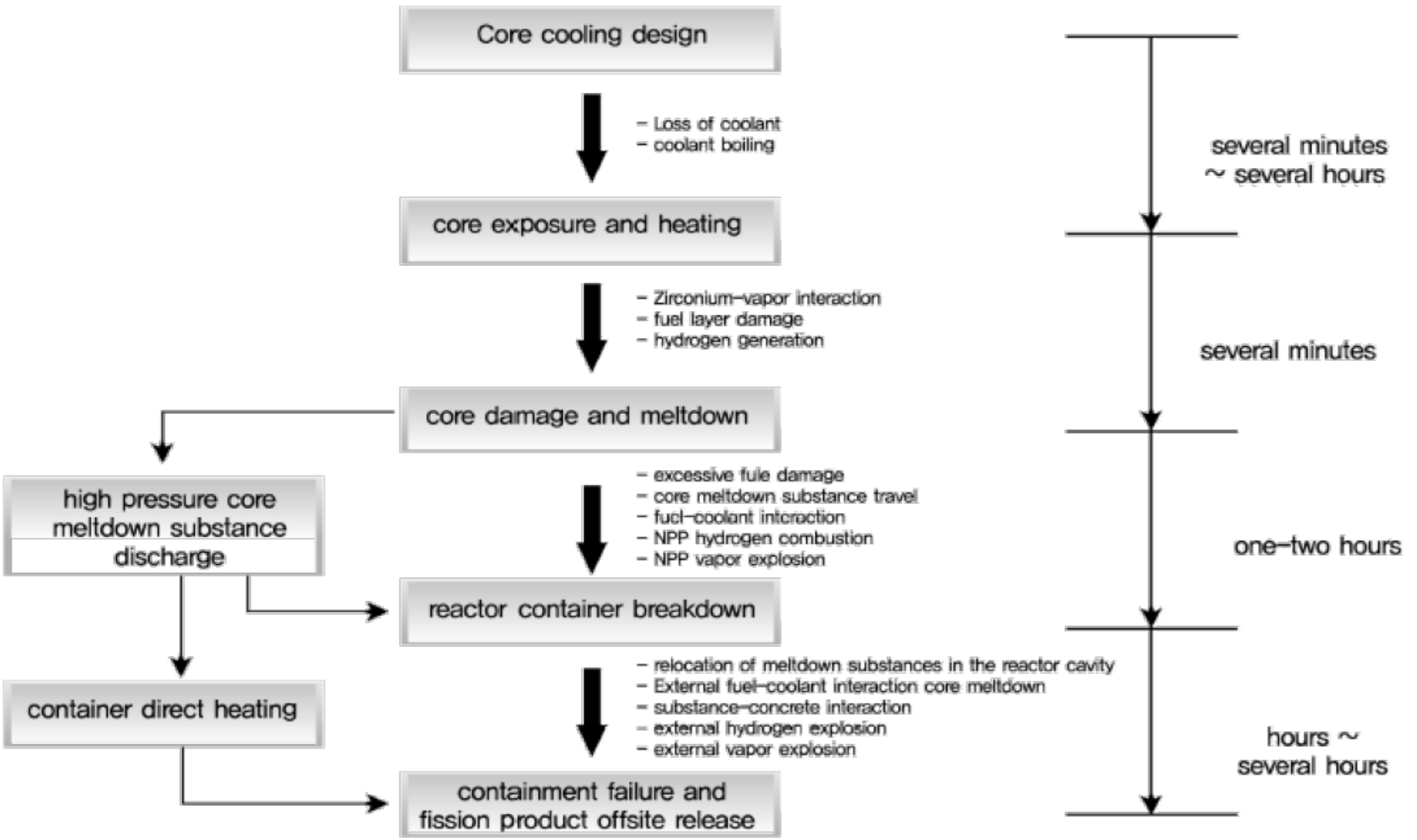
- Historical Experiences of Severe Accident (2)

Material	Radioactive releases compared (TBq)		
	TMI (1979)	Chernobyl (1988)	Fukushima (2011)
Iodine-131 equivalent	much less	5,200,000	770,000
Iodine-131	less than 1	1,800,000	160,000
Caesium-137	much less	85,000	20,500
Plutonium		6,100	

Ref.: World Nuclear Association Library

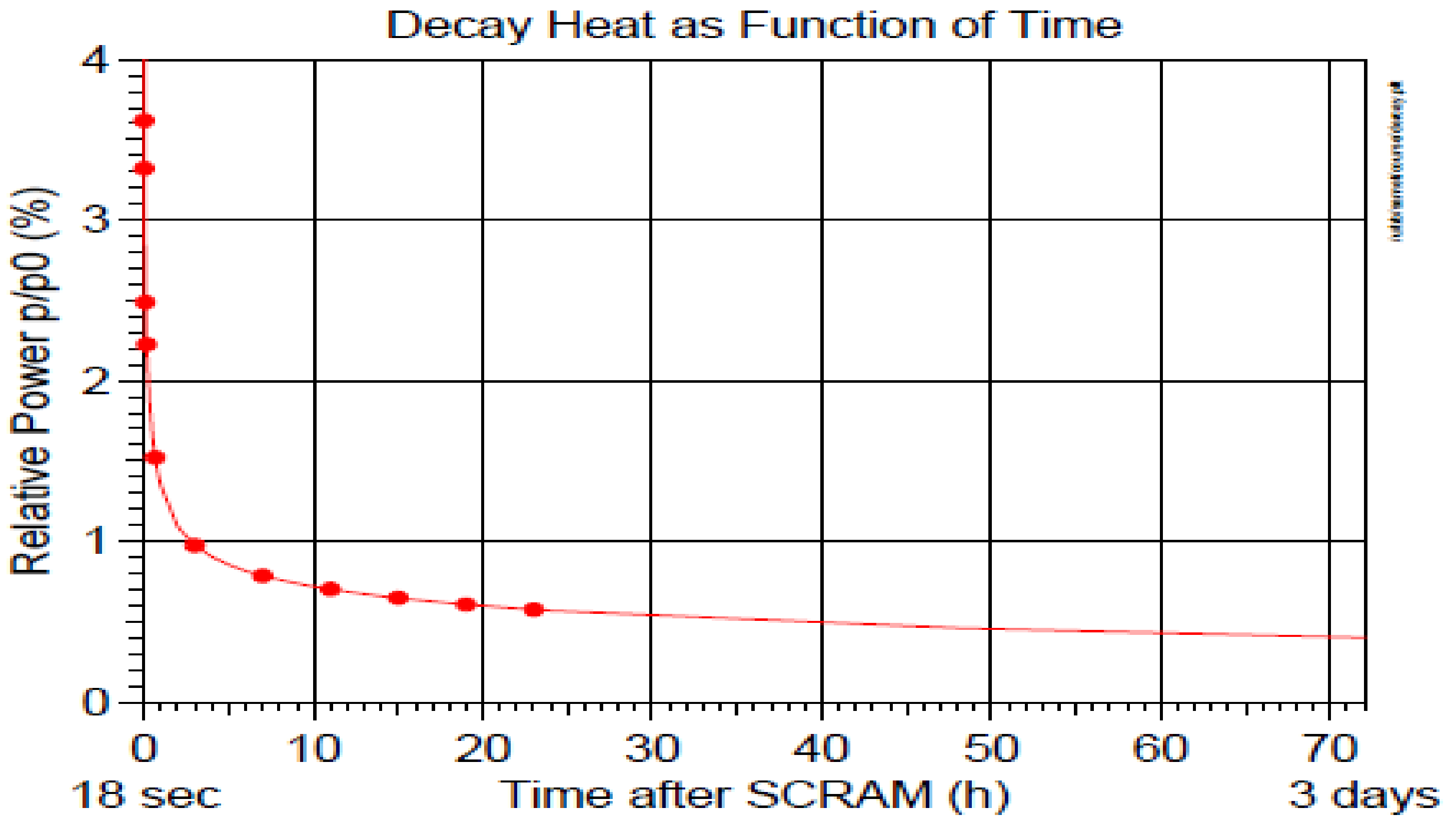
Introduction

- Progression of Severe Accident



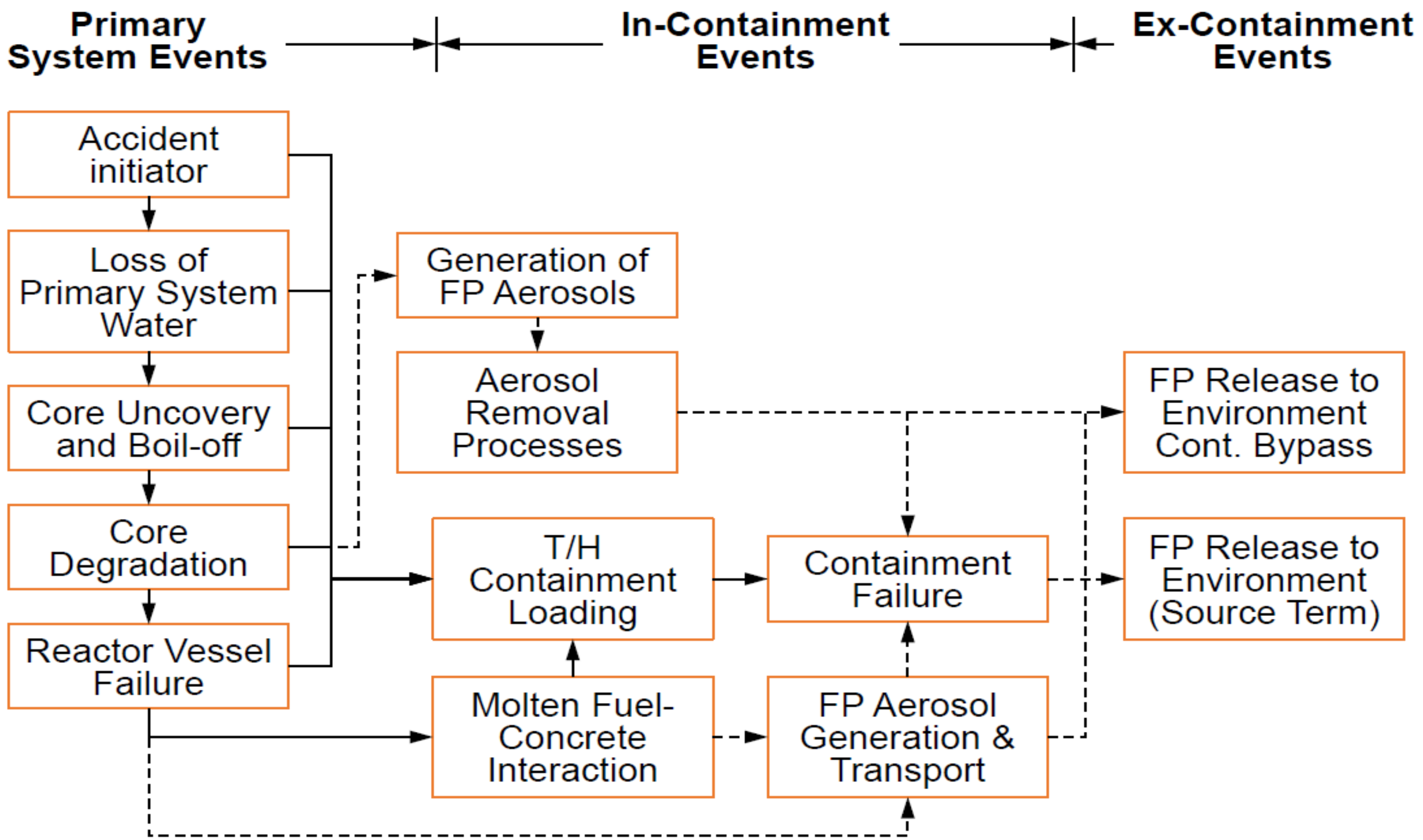
Introduction

- Decay Heat



Introduction

- Major Events during a Severe Accident

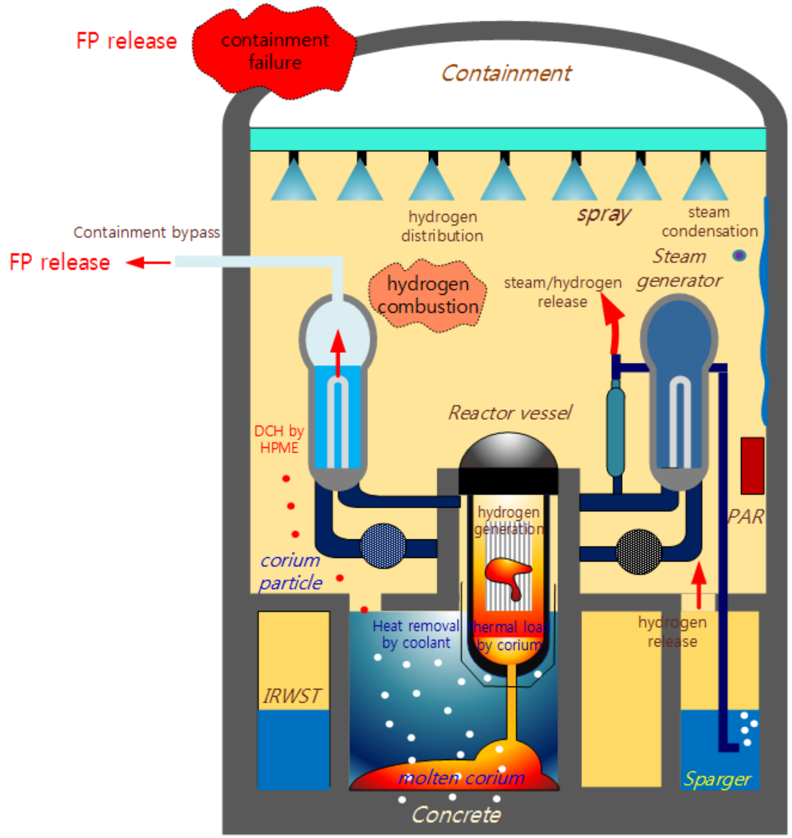


Introduction

- Challenges to Barriers during a Severe Accident
  - Cladding damage; excessive heat-up in combination with pressure difference acting on cladding leads to loss of cladding integrity with gap release
  - Fuel melting and core degradation; FPs accumulated in the fuel matrix are released
  - Fuel-coolant interaction in the reactor pressure vessel (RPV); steam explosion with potential generation of missiles and additional dynamic loading of the reactor coolant system (RCS)
  - High-pressure melt ejection (HPME) from the reactor vessel; with direct containment heating leading to rapid increase of containment temperature and pressure

Introduction

- Major Phenomena and Safety Issues
  - corium composition and mass
  - hydrogen generation
  - fuel coolant interaction
  - final corium configuration in RPV
  - thermal load on RPV
  - vessel failure mode
  - FP generation & transport
  - corium coolability



II. Severe Accident Phenomena

- In-Vessel Phenomena
- Ex-Vessel Phenomena

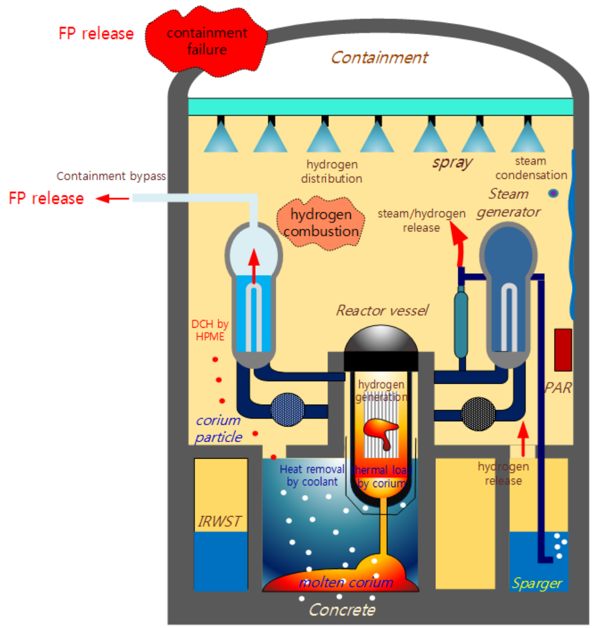
Severe Accident Phenomena

- In-Vessel Phenomena : Core degradation and meltdown
  - Core Uncovery and Heat-up
  - Cladding Oxidation
  - Melting, relocation and refreezing
  - Molten pool formation & collapse
  - Reactor vessel failure

Early Phase (up to loss of core geometry)

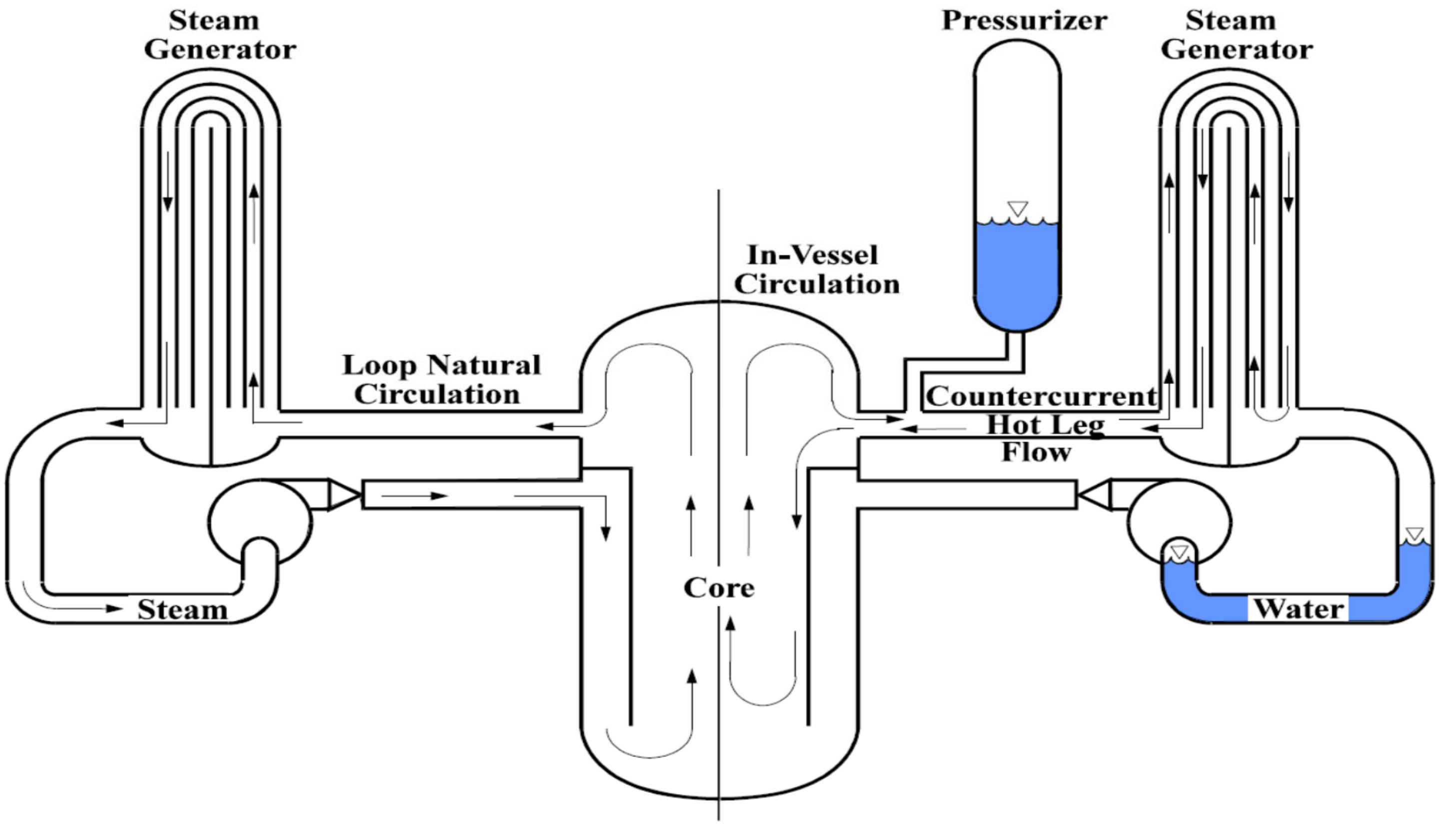
Late Phase

- Ex-Vessel Phenomena : Containment Behavior
  - Direct Containment Heating
  - Fuel Coolant Interaction (FCI)
  - Molten Core Concrete Interaction (MCCI)
  - Hydrogen Combustion



In-Vessel Phenomena

- Flow Pattern within Primary Side: Natural Circulation



- In-Vessel Natural Circulation (Steam)
- Full and half Loop Natural Circulation (Steam)

In-Vessel Phenomena

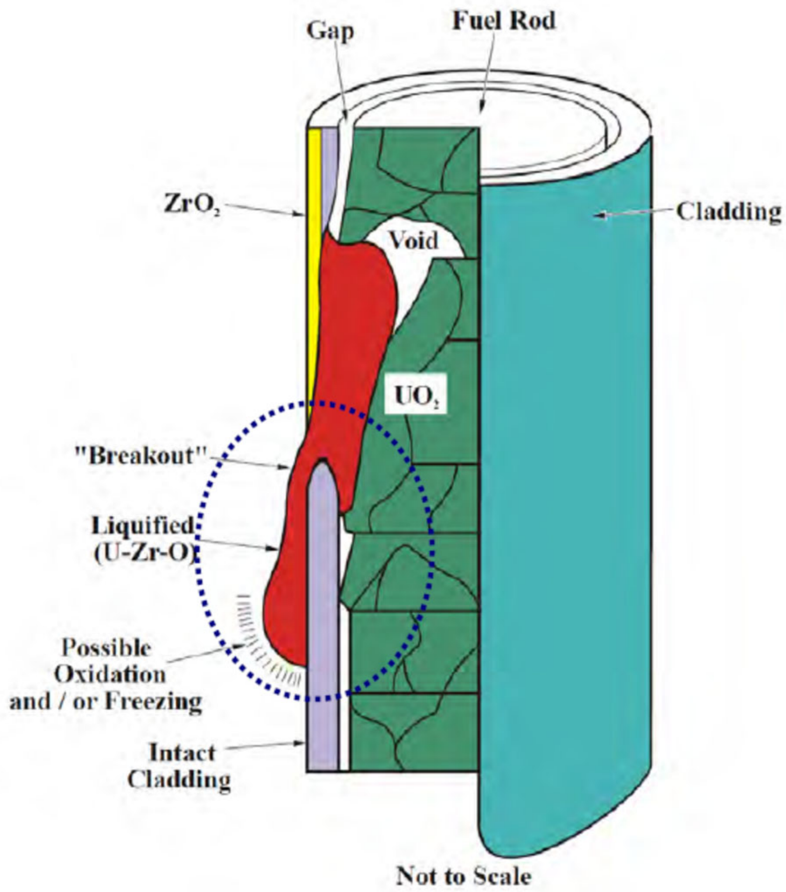
- Potential of Hydrogen Generation
  - At high temperature, Zr, stainless steel and B4C react with water to produce H_2

Chemical Reaction	Energy Release	Mol Weight
$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2$	$\Delta H = 64$ MJ/kg $_{zr}$	92 g/mol
$2Fe + 3H_2O \rightarrow Fe_2O_3 + 3H_2$	Not Significant	56 g/mol
$B_4C + 8H_2O \rightarrow 2B_2O_3 + CO_2 + 8H_2$	$\Delta H = 15$ MJ/kg $_{B4C}$	56 g/mol

  - Zr oxidation starts at ~ 1,270 K, escalating at ~1,850 K
  - The oxidation of Zr cladding by steam has the major effects on the accident progression: acceleration of the heat-up rate, embrittlement of the cladding, leading to fuel rod fracture and debris bed formation
  - **A typical PWR has about 20 tons of Zr in the cladding. What is the maximum mass of hydrogen from Zr-water reaction ? 1 mole of Zr (~92g/mole) reacts with 2 moles of steam, producing 2 moles of hydrogen ⇒ 20 tons/ 92 gr x 4 ≈ 870 kg**

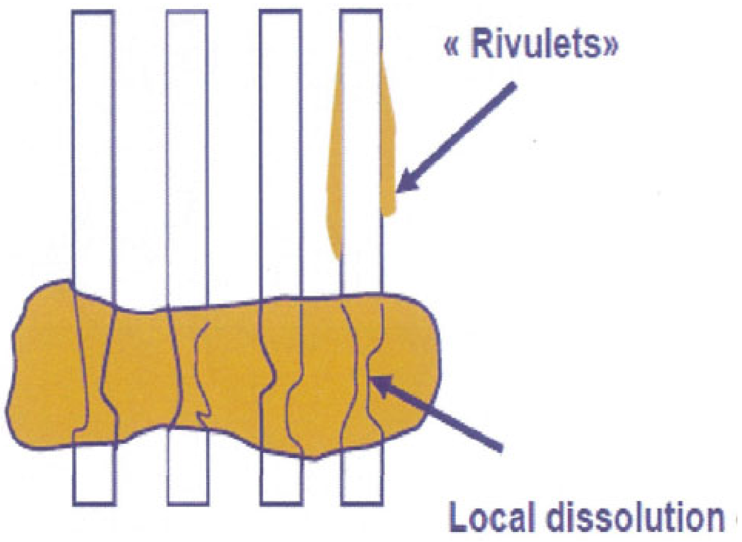
In-Vessel Phenomena

- Melting, Liquefaction, Holdup
  - **UO2 Melting**
    - UO2 melting occurs by molten Zr
    - UO2 liquefies far below its ceramic phase melting temperature
    - interaction mechanism is the oxygen diffusion between UO2 and molten Zr
    - onset of U-Zr-O corium formation
    - UO2 melting starts just after the Zr in the cladding melts and forms U-Zr-O
    - fuel liquefaction accelerates the release of fission products from the fuel



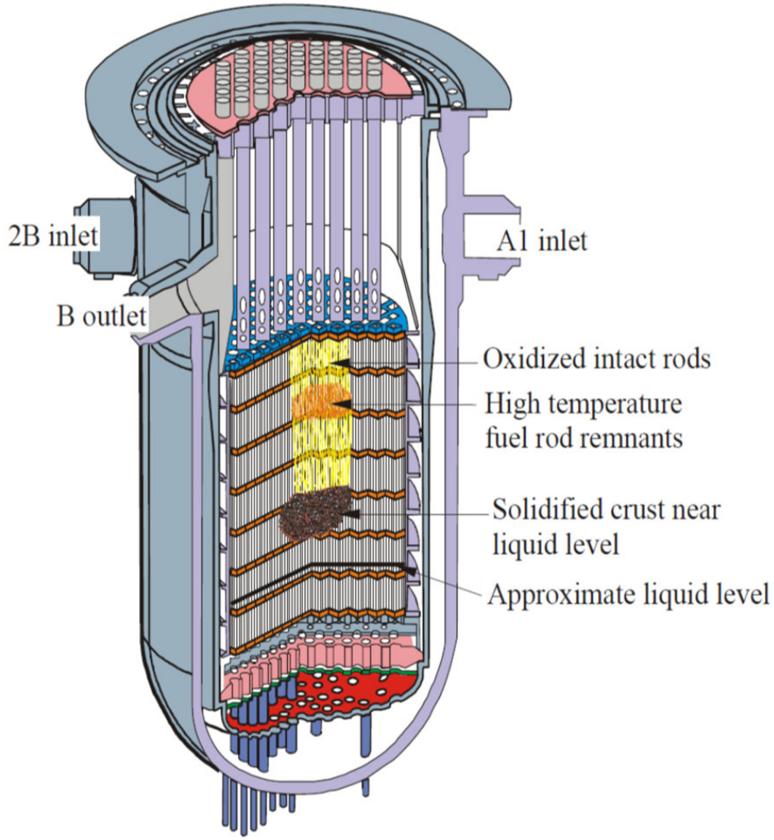
In-Vessel Phenomena

- Melting, Liquefaction, Holdup
  - Channel blockage
    - metallic melts relocation and blockage at 1,500 < T < 1,700 K
    - relocation and freezing in cold zones
      - near lower space grids or just above the water level
      - formation of egg-shaped crust
    - extensive core blockage (up to 90%)
    - relocation is a non-uniform process
    - frozen mixtures are mainly oxides (ZrO_2)



In-Vessel Phenomena

- Melting, Liquefaction, Holdup
  - **Eutectic Formation**
    - a mixture of chemical compounds or elements that has a single chemical composition
    - Grid – Clad : Ni-Zr eutectic (1200°C, 2192°F, 1473K,)
  - **Control Rod**
    - Ag-In-Cd control rod : (800°C, 472°F, 1073 K)
    - Stainless steel control rod cladding : (1450°C, 2642°F, 1723 K).
  - Melts holdup is near the lowest grid spacer which is just above water level in the core.
  - As reducing water level, melt pool relocate to the lower part of the core.

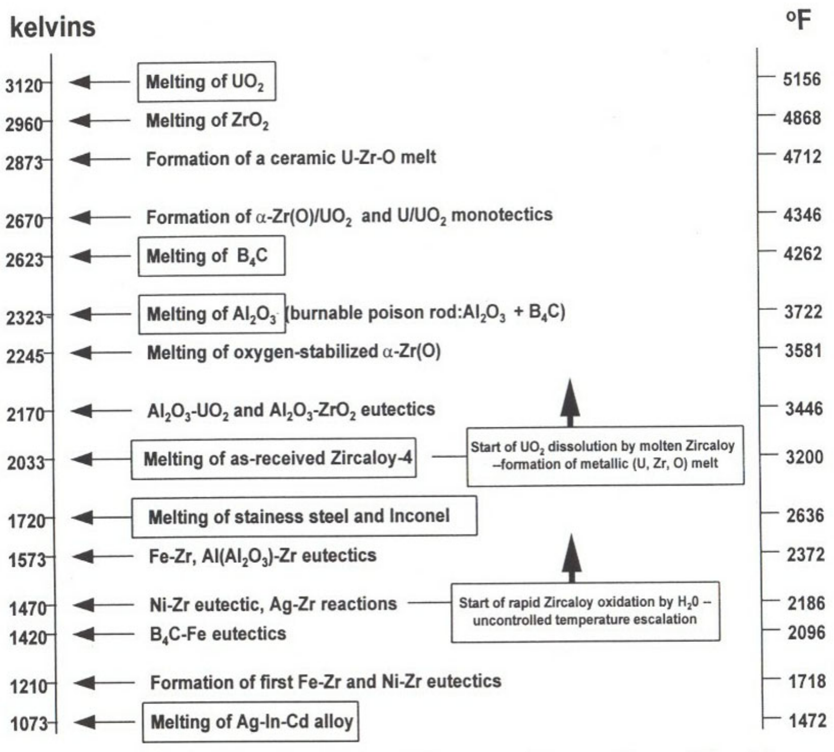


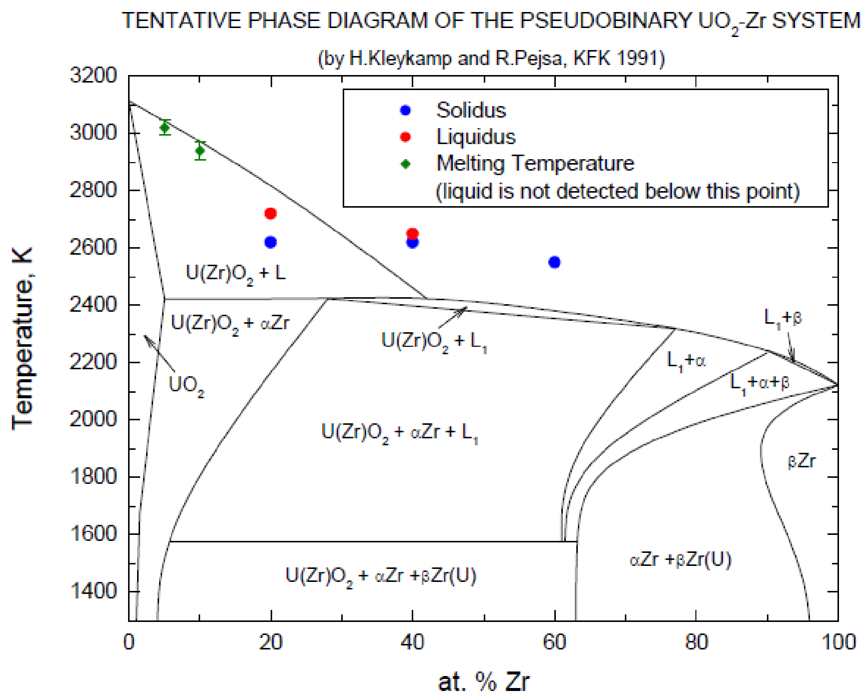
In-Vessel Phenomena

- Melting, Liquefaction, Holdup
  - **Eutectic Formation**
    - eutectic is a mixture of chemical compounds or elements that has a single chemical composition
    - it solidifies at a lower T than any other composition
    - This composition is the eutectic composition and the temperature is the eutectic
    - **This is responsible for large amounts of fuel liquefaction at temperature far below the UO2 melting temperature (~3100 K)**
  - **Single material melting temperature**
    - UO_2 (3123 K, 2850°C), ZrO_2 (2704°C), Zr (1760°C), Stainless Steel (1450°C)
  - **Eutectic Melting temperature**
    - Ni-Zr eutectic (1200°C), **Zr-based eutectics (1523K, 1250°C)**

In-Vessel Phenomena

- Composition of Core Melt
  - Oxide: UO2, ZrO2, Fe-Ni-Cr oxides, fission products
  - Metal: Zr, Fe-Ni-Cr-(O), Ag, In, Cd

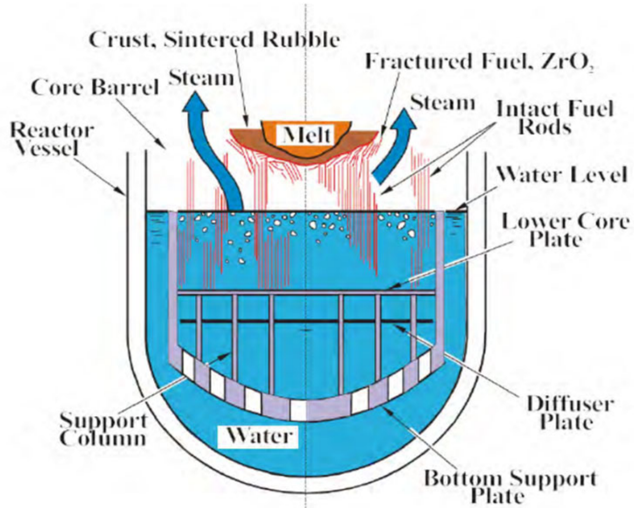




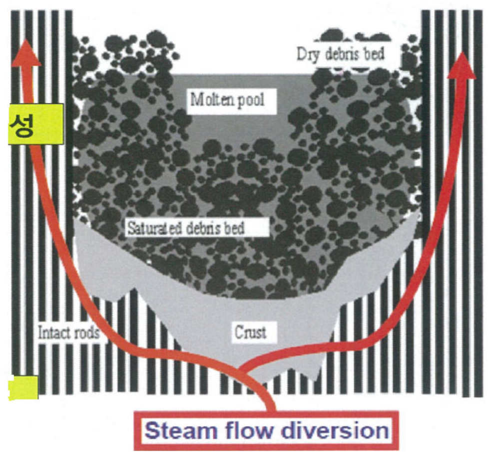
In-Vessel Phenomena

- Molten Pool Formation
  - channel blockage would redirect steam flow outward
  - diversion of steam flow makes the outer surface of the relocated melts to be cooled

    ⇒ crust formation
  - rapid transition from solid-liquid debris to a molten pool due to bad cooling by crust
  - molten pool grows if the peripheral heat transfer is smaller than the internal FP decay heat produced
  - molten pool supported by a lower bowl-shaped crust was observed in TMI-2

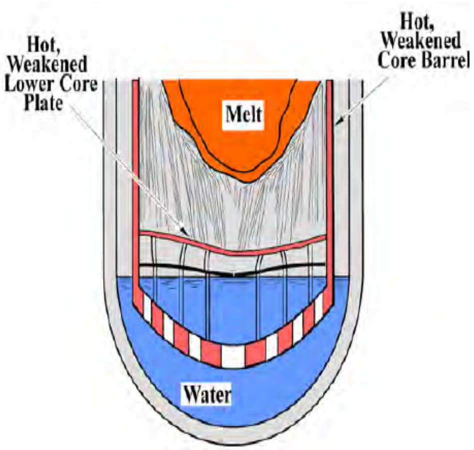


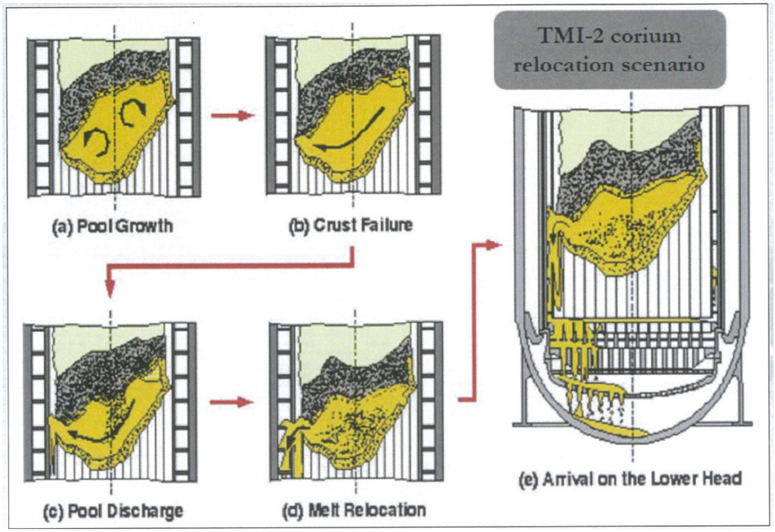
NUREG/CR-6042, Perspectives on Reactor Safety



In-Vessel Phenomena

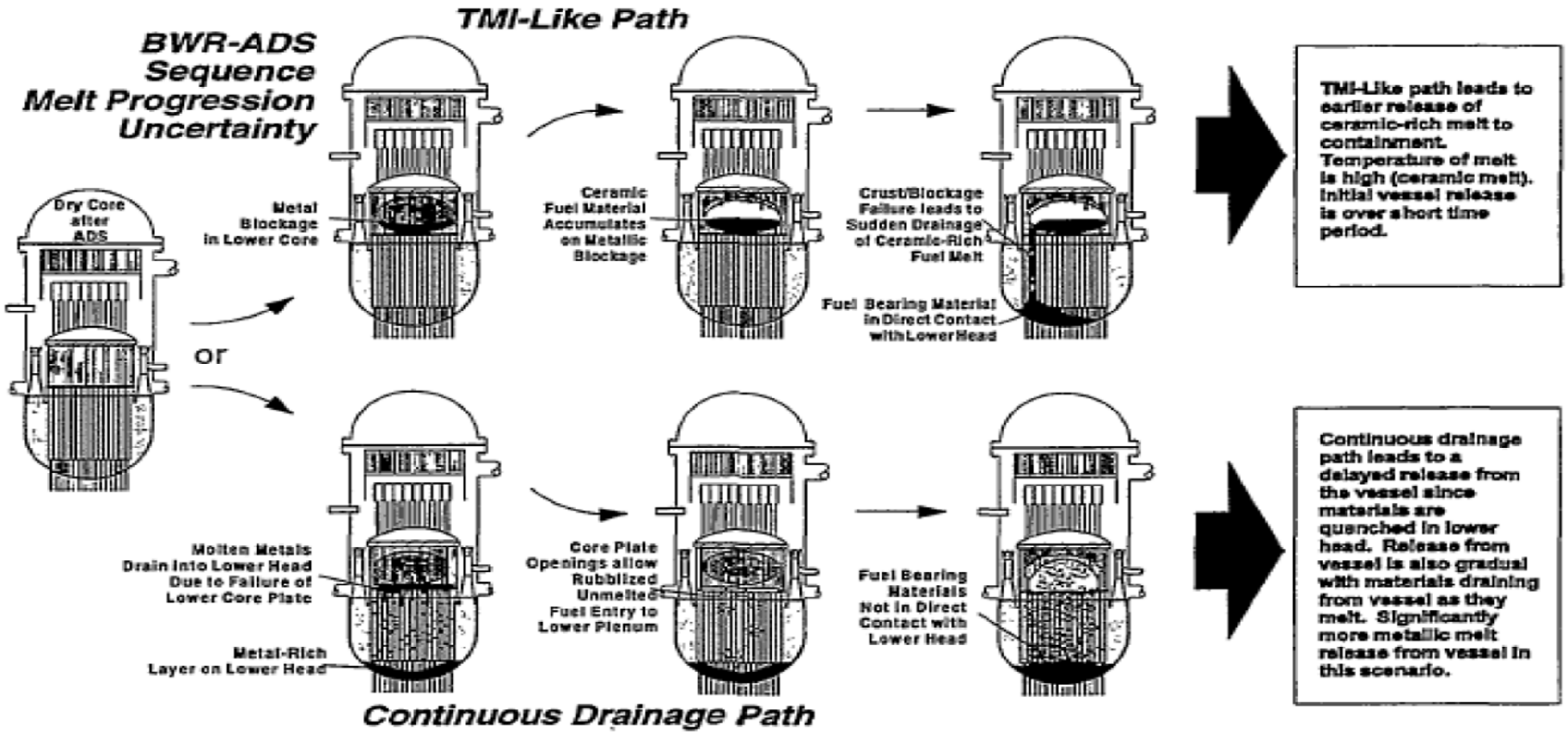
- Molten Pool Collapse
  - **Corium Discharge to Lower Head**
    - pool grows due to continued addition of decay heat
    - residual water level drops below the bottom of the active core, the structures supporting the crust and melts weakens
    - local crust failure results in a narrow continuous pour of corium to lower head





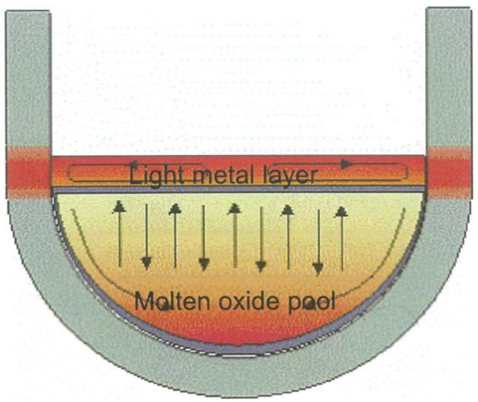
In-Vessel Phenomena

- Lower Head Relocation Alternatives
  - If there were little residual water present, a strong crust might not form in the core region. A narrow discontinuous stream or streams distributed over the duration of the core meltdown.

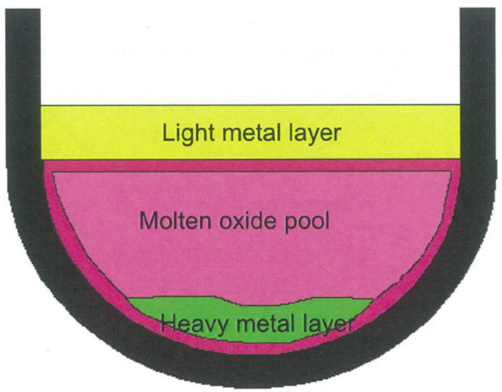


In-Vessel Phenomena

- Molten Pool Formation in the Lower Head
  - **Pool Configuration**
    - particle bed layer
    - Molten oxidic layer : UO2, ZrO2
    - light metallic layer : Zr, Fe
    - heavy metallic layer : U, Zr, Fe



2- layer

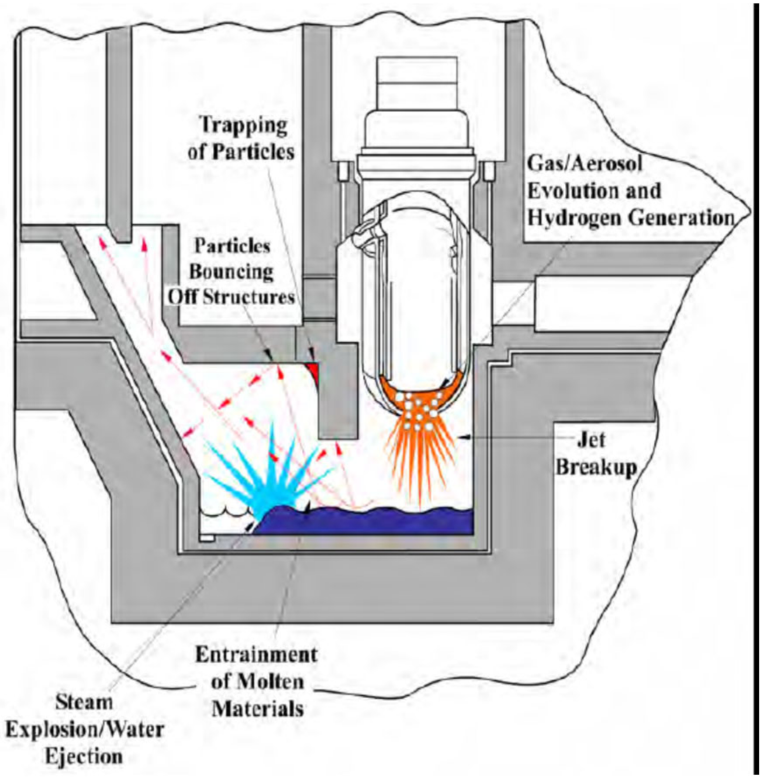


3-layer

In-Vessel Phenomena

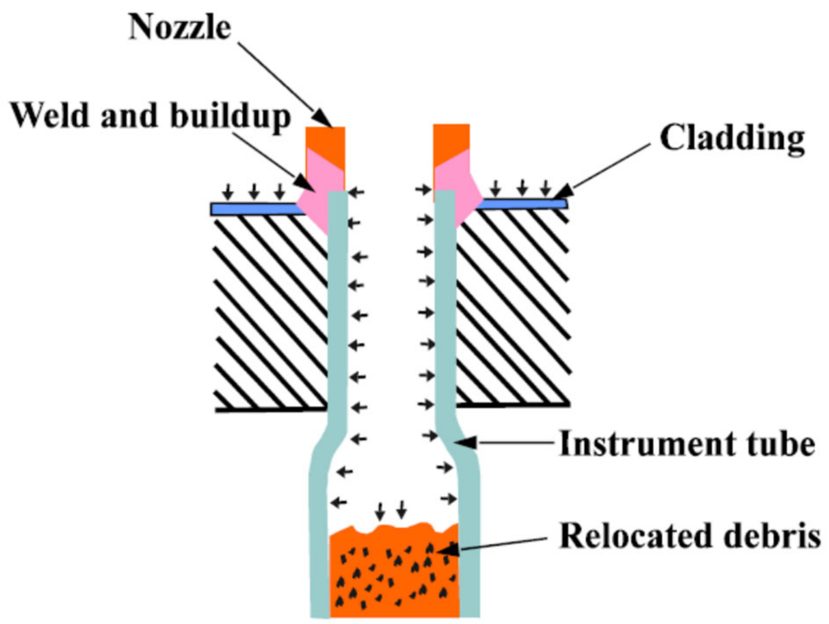
- Lower Head Failure Mechanism
  - Tube Rupture
  - Weld Failure, Tube Ejection
  - Global Failure by Uniform Heating
  - Local Failure by Peaked Heating

- Corium Pours into Cavity
  - **Ex-Vessel Phenomena Comes In!**



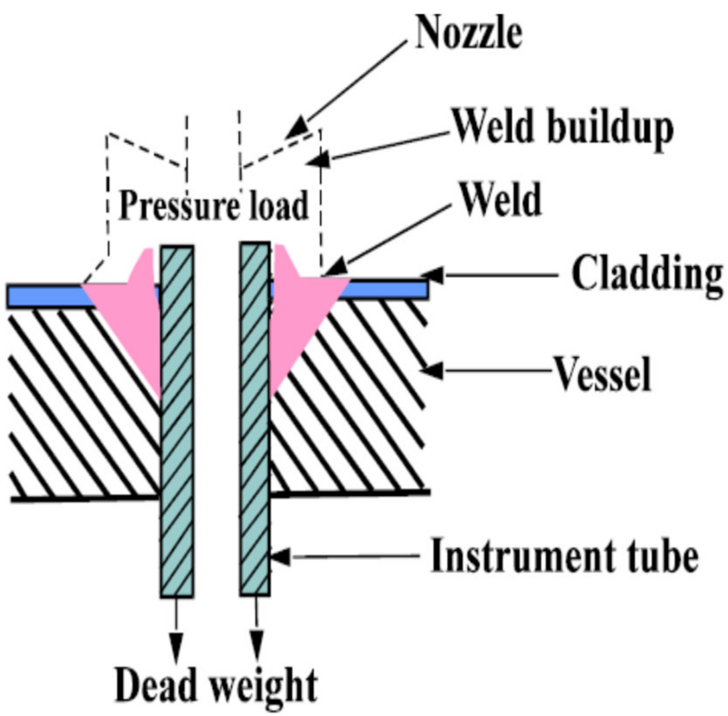
In-Vessel Phenomena

- Molten Pours onto the Lower Head - Lower Head Failure Mechanism
  - **Tube Rupture**
    - Result caused by penetration of hot debris through the tube to ex-vessel locations.
    - TMI-2 Data used to calibrate a melt-penetration model
      - Melt-penetration model predictions indicate that molten fuel did not penetrate through the instrument tubes to locations below the lower head.
      - Ex-vessel tube rupture was therefore not a significant threat at TMI-2.



In-Vessel Phenomena

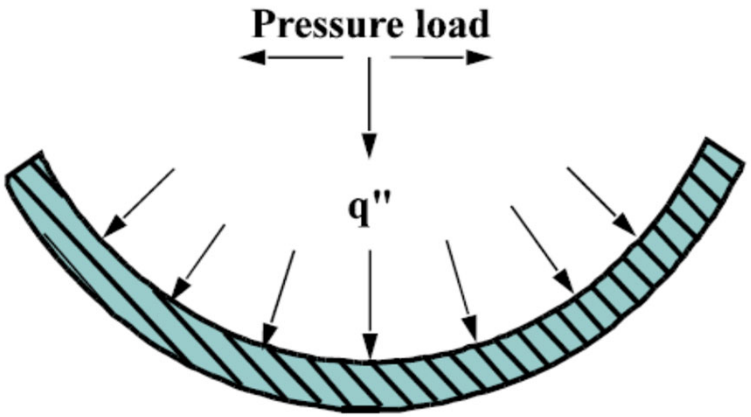
- Molten Pours onto the Lower Head - Lower Head Failure Mechanism
  - **Weld Failure, Tube Ejection**
    - Failure of a penetration tube weld (Figure)
      - sustained heating by debris surrounding a tube
      - high reactor coolant system pressure
    - At TMI-2
      - Metallurgical evidence indicates that the Inconel penetration welds did not melt.
    - Results of a subsequent lower head failure experiment
      - Deformation of the lower head can indeed cause penetration welds to fail first.



In-Vessel Phenomena

- Molten Pours onto the Lower Head - Lower Head Failure Mechanism

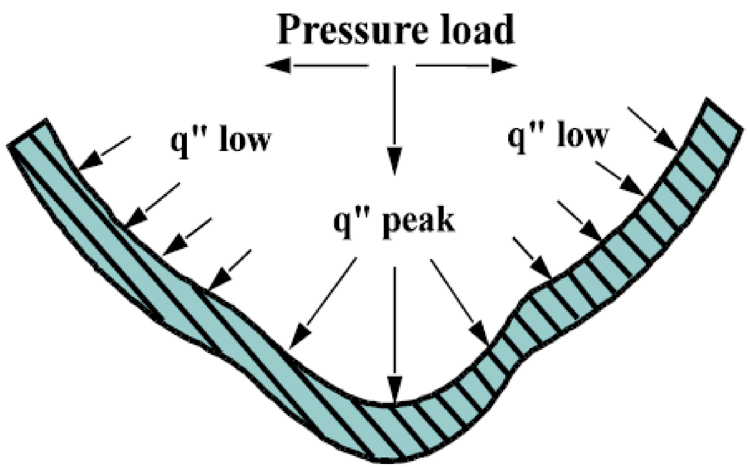
  - **Global Failure by Uniform Heating**
    - Based on the TMI-2 debris composition
      - Molten material temperatures greater than 2600°C(4712°F) in the central core region before relocation
      - Core debris in lower head : molten state.
      - Slow cooling.
    - Without cooling of the debris, global failure of the lower head was predicted to occur within 1.7 to 2.3 hours of the molten pour.



In-Vessel Phenomena

- Molten Pours onto the Lower Head - Lower Head Failure Mechanism

  - **Local Failure by Peaked Heating**
    - Failure due to the high temperatures in the hot spot
    - When the hot spot temperatures were imposed with a background temperature of only 327°C (621°F),the vessel was predicted to survive.
    - When the hot spot temperatures were imposed with a background temperature near the 727°C (1341°F) ferritic to austenitic steel transition temperature, lower head failure was predicted to occur 1.5 hours after the molten pour.

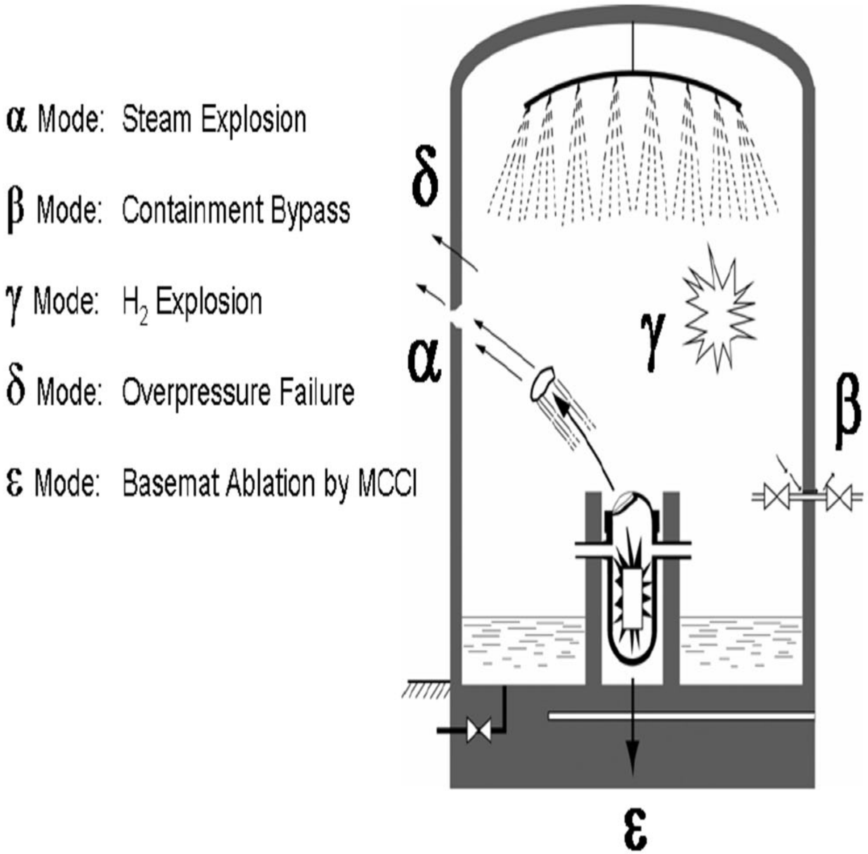


II. Severe Accident Phenomena

- In-Vessel Phenomena
- Ex-Vessel Phenomena

Ex-Vessel Phenomena

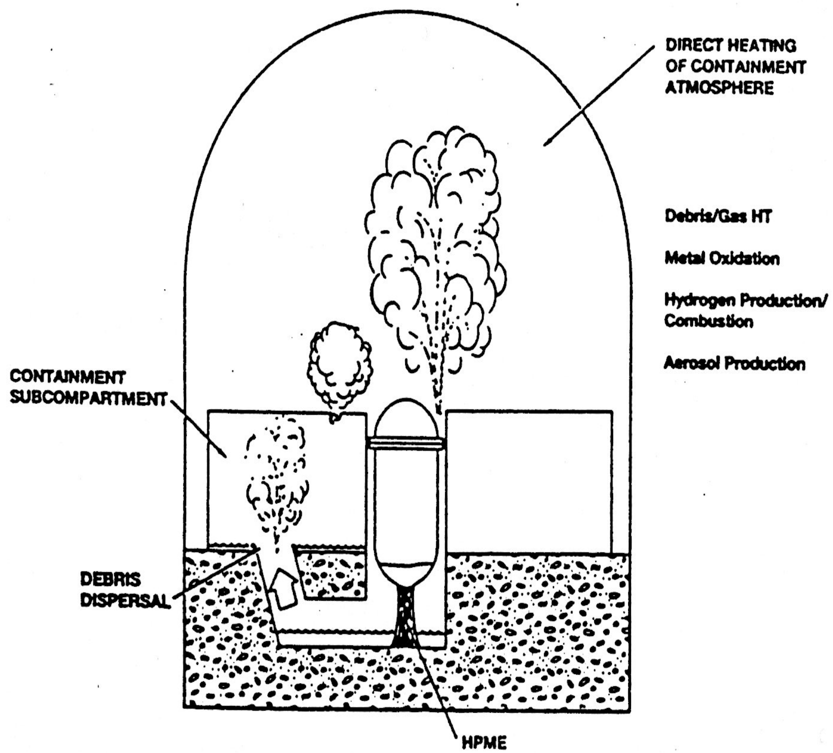
- Containment Failure Mode



Ex-Vessel Phenomena

- Direct Containment Heating (DCH)

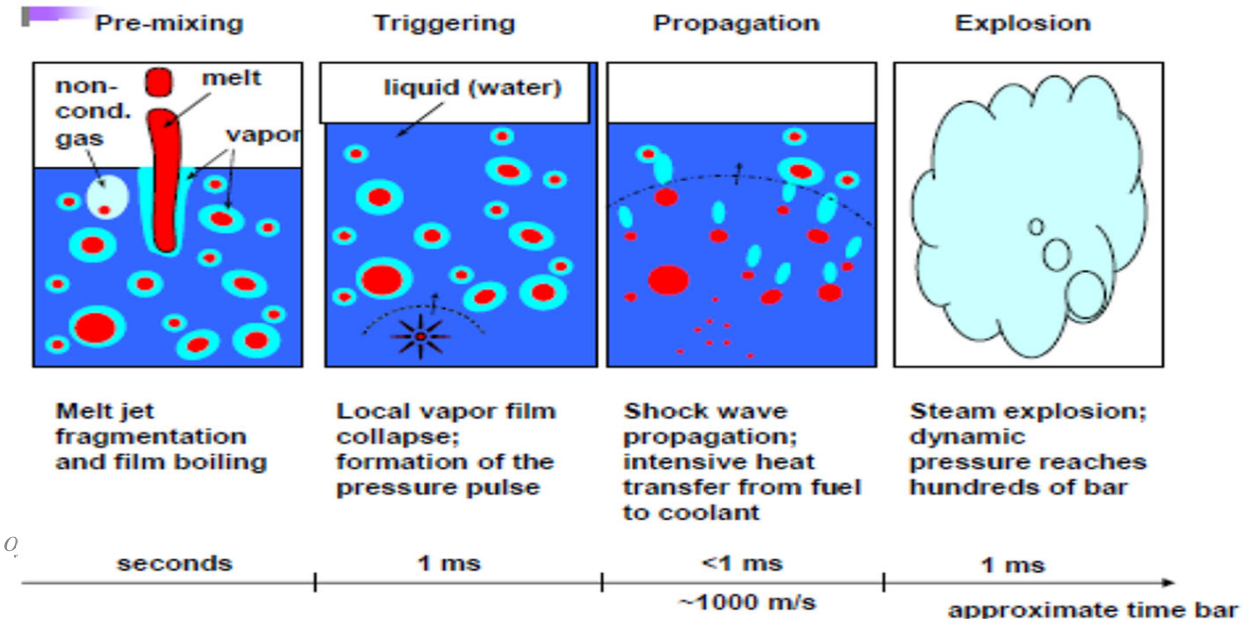
  - **High pressure of RCS can lead to Direct Containment Heating (DCH)**
    - When RPV fails at high pressure, molten material will be ejected into the upper containment.
    - Finely fragmented and dispersed core debris could cause containment heat up and high pressure spikes.



Ex-Vessel Phenomena

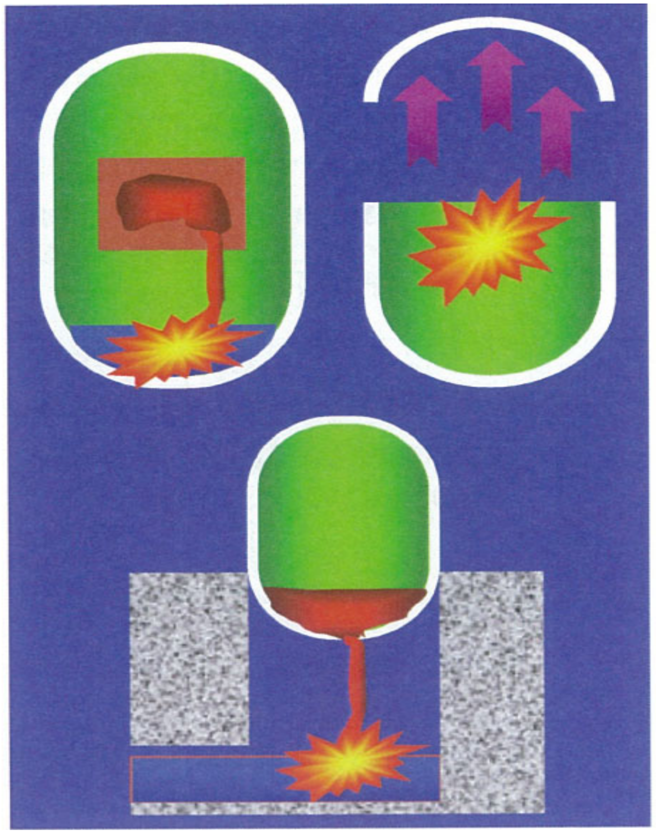
- Fuel Coolant Interaction (Steam Explosion Eutectic Formation)
  - **Explosion**
    - contact of high temperature melt and water makes an explosion
    - sudden generation of large amount of high pressure steam
    - interaction magnitude depends on melt mass, melt composition, melt entry velocity, water temperature, water pressure and water depth, etc.

- Fuel Coolant Interaction (Steam Explosion Eutectic Formation)
  - **Fundamental Physics**
    - fuel liquid breaks up into small particles
    - FC syrelatively small heat transfer between fuel liquid and surrounding coolant
    - stem remains in this non-explosive metastable state during a few mili-seconds up to a few seconds
    - Two possible mechanisms can be considered to produce rapid (explosive) vaporization resulting steam explosions by
      - large liquid superheating for homogeneous nucleation if the contact temperature is larger than the homogeneous nucleation temperature
      - further increase of jet/particle breakup to increase the heat transfer area



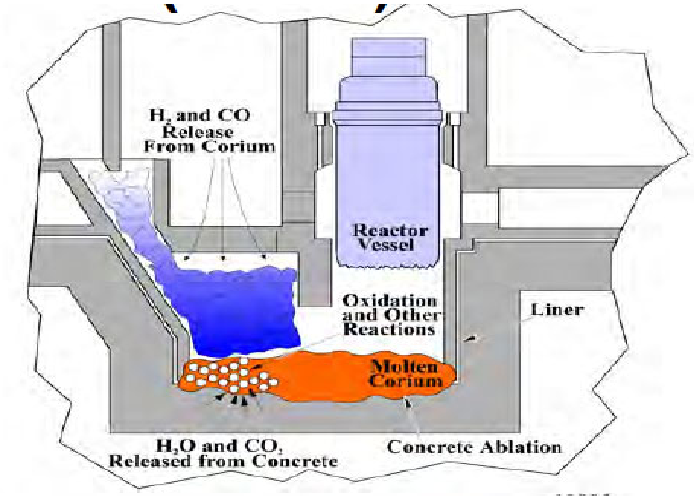
Ex-Vessel Phenomena

- Fuel Coolant Interaction (Steam Explosion)
  - **In-Vessel Steam Explosion**
    - alpha mode containment failure
      - large scale steam explosion makes missile of reactor head and attack the containment
      - probability is very low
    - not very likely due to
      - high pressure
      - nearly saturation temperature
  - **Ex-Vessel Steam Explosion**
    - more probable if the cavity is filled with water large scale steam explosion makes missile of reactor head and attack the containment
      - water is highly subcooled
      - pressure is atmospheric
      - large amount of corium poured into cavity

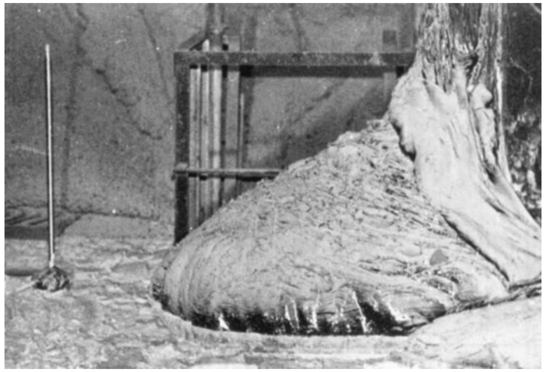


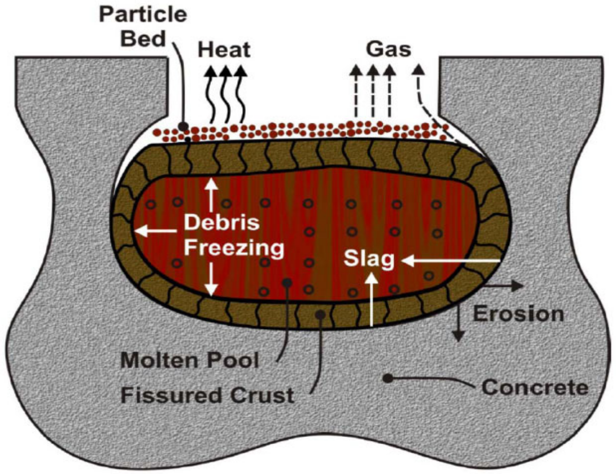
Ex-Vessel Phenomena

- Molten Corium Concrete Interaction (MCCI)
  - **Corium-Concrete Interactions (CCI)**
    - Progress Mechanism
      - RPV failaure
      - melt ejection
      - melt spreading
      - MCCI (floor erosion, gas generation, crust formation)
      - cooling upper part of the molten corium



※ Elephant's Foot at Chernobyl





Ex-Vessel Phenomena

- Molten Core Concrete Interaction (MCCI)
  - **Combustible Gas and Aerosol Generation**
    - Combustible Gas
      - Hydrogen
      - Carbon mono-oxide
      - Limited by metallic constituents in Corium
    - Non-condensible Gas
      - Carbon di-oxide
    - Aerosols
      - Fission Products : I+Br, Cs+Rb, Te+Sb, Sr, Mo, Ru, La(3), Nb, Ce+Np+Pu, Ba, etc.
      - Concrete : CaO, Al203, Na2O, K2O, SiO2, etc.
- **Open Issues**
  - Cooling Debris Bed in Cavity
  - Gradual Over-pressurization
  - Source Term resulted from MCCI

Ex-Vessel Phenomena

- Hydrogen Combustion
  - **Source of combustible gases**
    - oxidation of Zr metal with steam
    - ex-vessel reaction of metallic core debris with steam
    - molten corium concrete interaction
    - radiolysis of sump water Non-condensible Gas
  - **Combustion Flames**
    - $2H_2 + O_2 \Rightarrow 2H_2O + \Delta H_2$ exothermic
    - standing diffusion flame : flame stays at fixed location
    - deflagration : flame propagates at subsonic velocity
      - quasi-static (nearly steady state) loads on containment
    - detonation : flame propagates at supersonic velocity
      - transfer impulsive (dynamic) loads on containment
      - direct detonation is impossible because it needs a lot of ignition energy

Ex-Vessel Phenomena

- Hydrogen Combustion
  - **Flame Acceleration (FA) and Deflagration to Detonation Transition (DDT)**
    - detonation is induced by FA along channels, turbulent jets & fans
    - FA & DDT can be extremely destructive
    - FA criteria : $\sigma > \sigma critical$ where σ is the expansion ratio
  - **DDT onset criteria**
    - 7λ criterion : $L > 7\lambda$
    - L is the characteristic geometrical size of reacting mixture
    - λ is the detonation cell size of average mixture composition, measured experimentally and f (dry CH_2, Csteam, P,T)
  - **Hydrogen Mitigation**
    - PARs and/or igniters suitably distributed in the containment
    - inerting

Ex-Vessel Phenomena

- Containment Integrity
  - **Loss of containment integrity**
    - A late FP release may be much smaller than the early release
    - The containment integrity should be maintained for 24 hrs
    - Following this period the containment should provide a barrier against the uncontrolled release of FPs.
      - Avoid early failure due to hydrogen detonation, SE, DCH.
      - Avoid Late failure (after 24 hrs) due to longer-term gas producing MCCI
  - **Containment bypass**
    - A direct release of radioactive material outside the containment
      - Creep failure of steam generator tubes for some high pressure scenario
      - Interfacing systems loss of coolant accident (LOCA), etc.

III. Severe Accident Mitigation

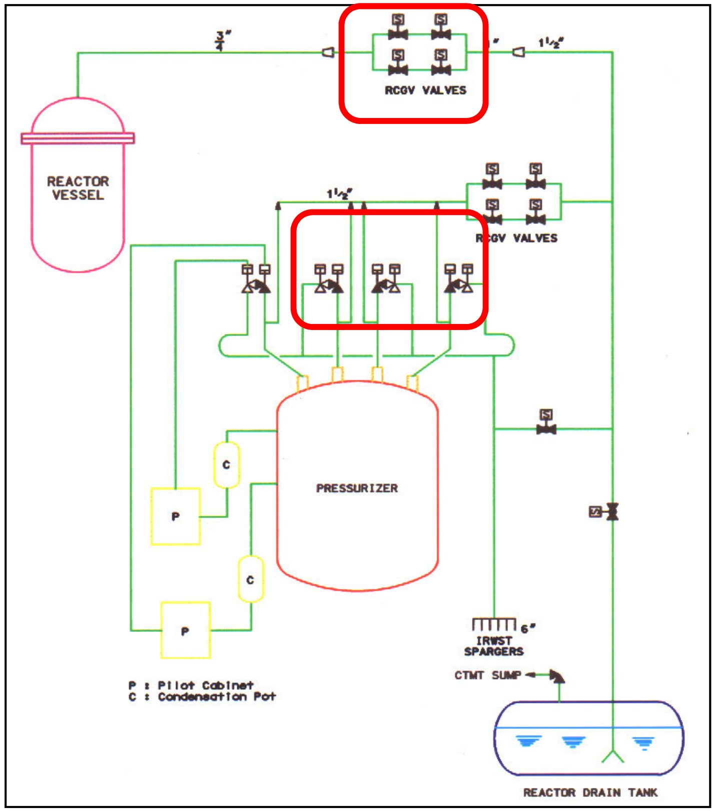
- DCH Mitigation
- IVR
- Ex-Vessel Core Catcher
- PAR
- CFVS

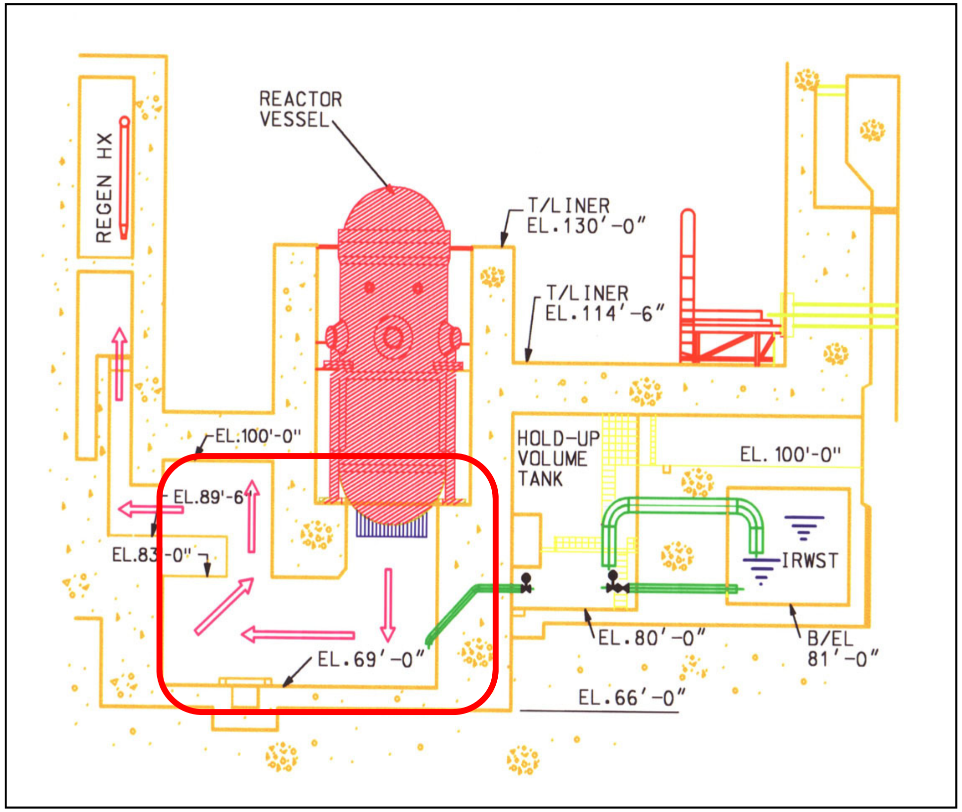
Severe Accident Mitigation

- Design Targets for Severe Accident Mitigation
  - **High pressure melt ejection (HPME)**
    - Reliable depressurization system to prevent HPME
    - Limit probability of corium ejection to upper area by designing limited flow paths
  - **Core melt/debris coolability**
    - In-Vessel Retention (IVR)
    - Reactor cavity floor space cooling (spreading room)
    - Protection from Molten Core Coolant Interaction (MCCI
  - **Hydrogen Control**
    - Hydrogen generation equivalent to 100% metal-water reaction of the fuel cladding
    - Limit containment H_2 concentration to no greater than 10%
  - **Containment performance**
    - Maintain leak tightness for 24 hours
    - Maintain fission product barrier for duration of event

Severe Accident Mitigation

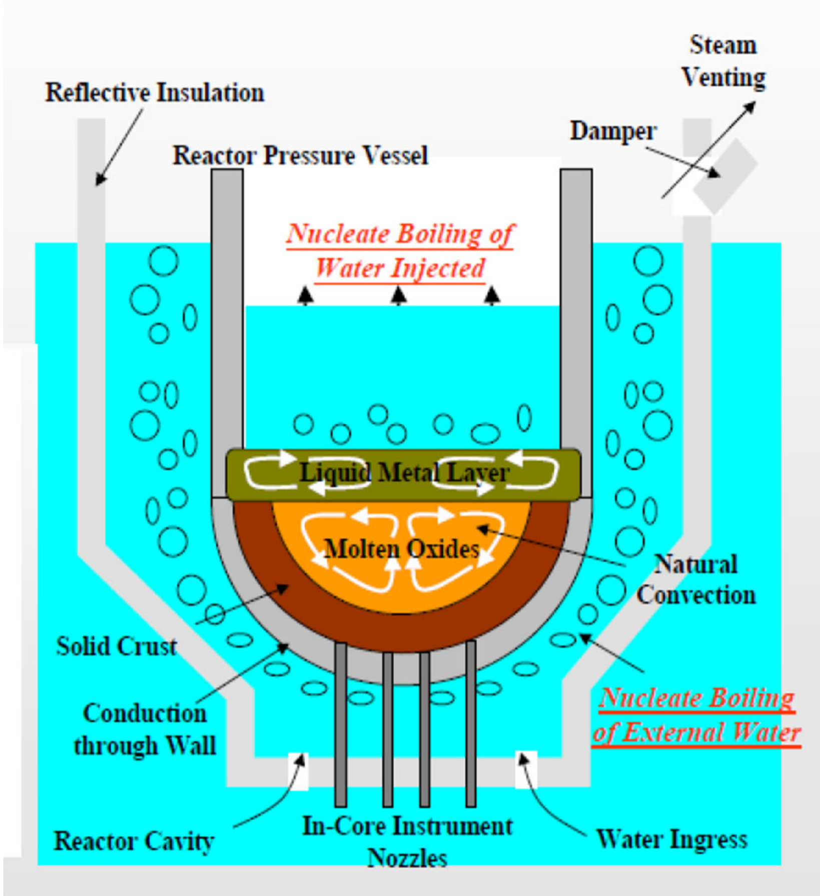
- Mitigation of DCH
  - **RCS depressurization**
  - **Cavity design to decrease the amount of ejected corium**





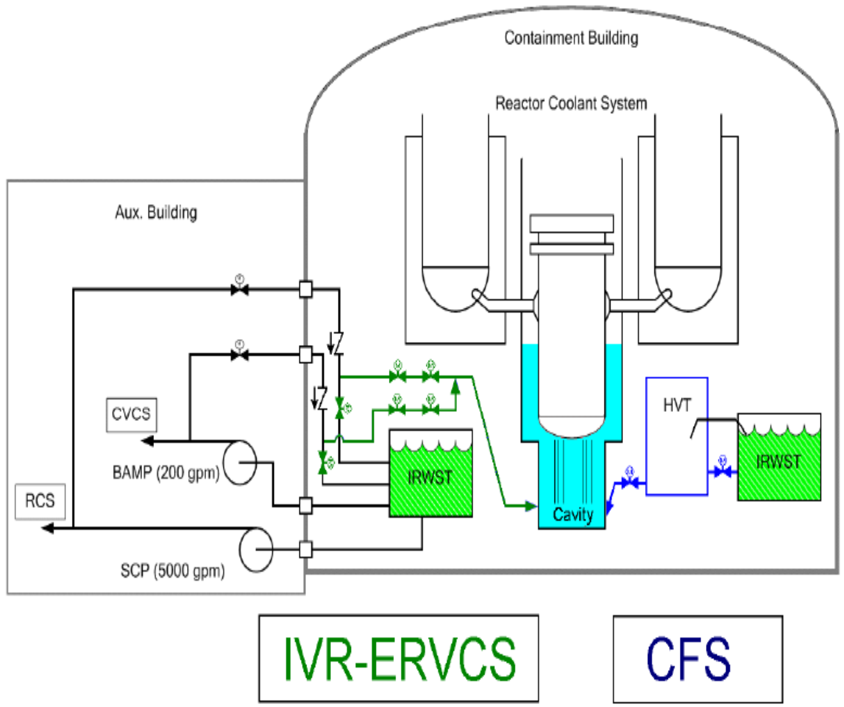
Severe Accident Mitigation

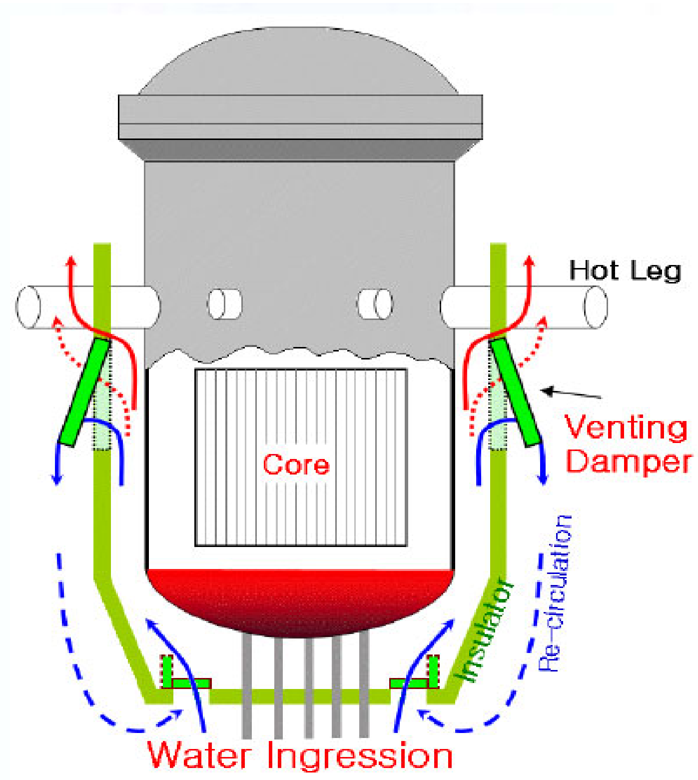
- Mitigation against Vessel Failure
  - **In-Vessel Retention (IVR)**
    - Retain molten core within vessel and maintain reactor vessel integrity
    - Cooing the reactor vessel outside (ERVC, External Reactor Vessel Cooling) is taken as a mean for IVR in some of the advanced LWRs (e.g. AP1400, AP600, AP1000, etc.)



Severe Accident Mitigation

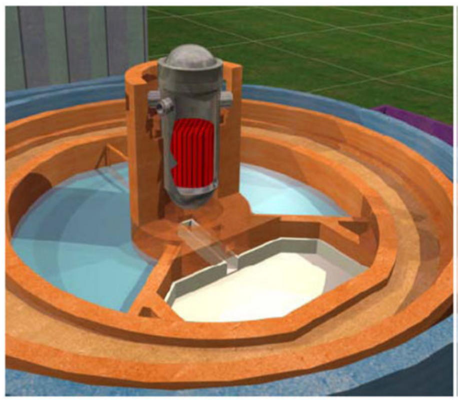
- IVR-ERVC System (APR1400)
  - Flood the reactor cavity up to the hot leg level using a shutdown cooling pump (SCP)
  - Evaporated coolant is replenished by a boric acid makeup pump (BAMP) or SCP



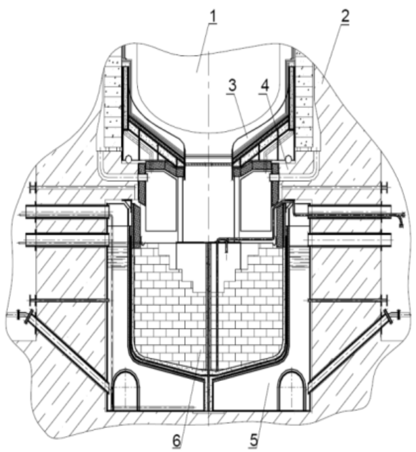


Severe Accident Mitigation

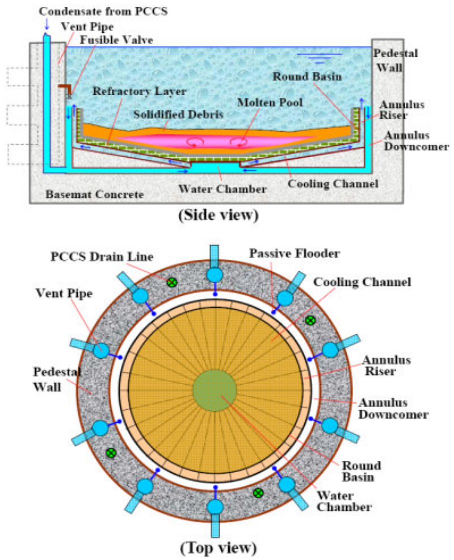
- Ex-vessel core catcher
  - **Primary goal**
    - To reliably accommodate and rapidly stabilize the corium, including the entire core inventory and reactor internals that is injected into the cavity following a postulated severe accident
  - **Design issues**
    - Analysis and enhancement of molten corium spreadability
    - Design of sacrificial and protective materials
    - Design of engineered cooling channel



EPR



VVER



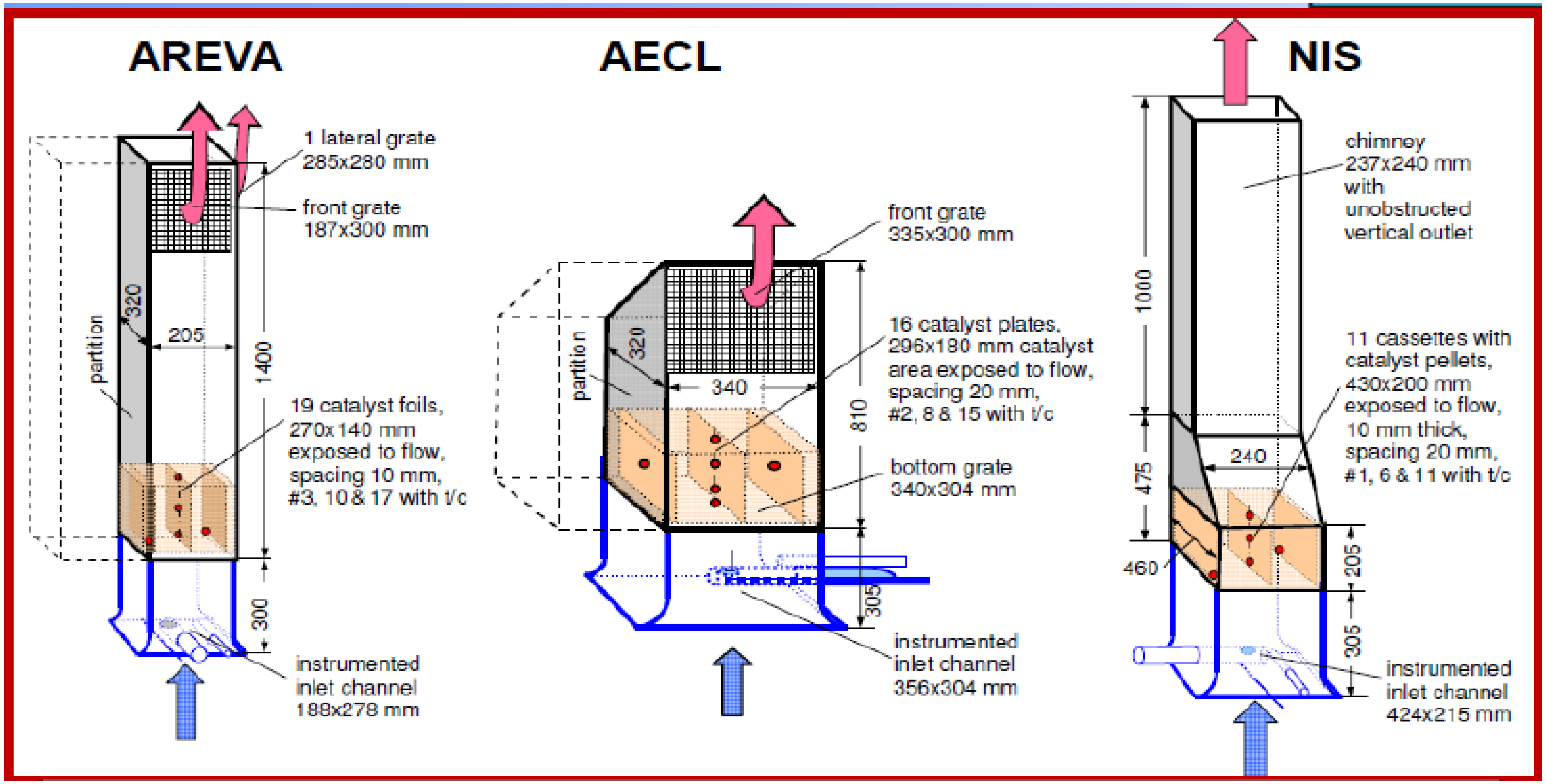
Toshiba

Severe Accident Mitigation

- Hydrogen mitigation (1)
  - **Passive Autocatalytic Recombiner (PAR)**
    - H_2 reacts with O_2 of air on catalytic surfaces
    - self-starting and feeding by natural convection
    - consumes H_2/O_2 passively
    - complex thermal-hydraulic problem (3D analysis necessary)
  - **Open Issues**
    - potential ignition source
    - effect of external convection flows
    - response to H_2 gradients

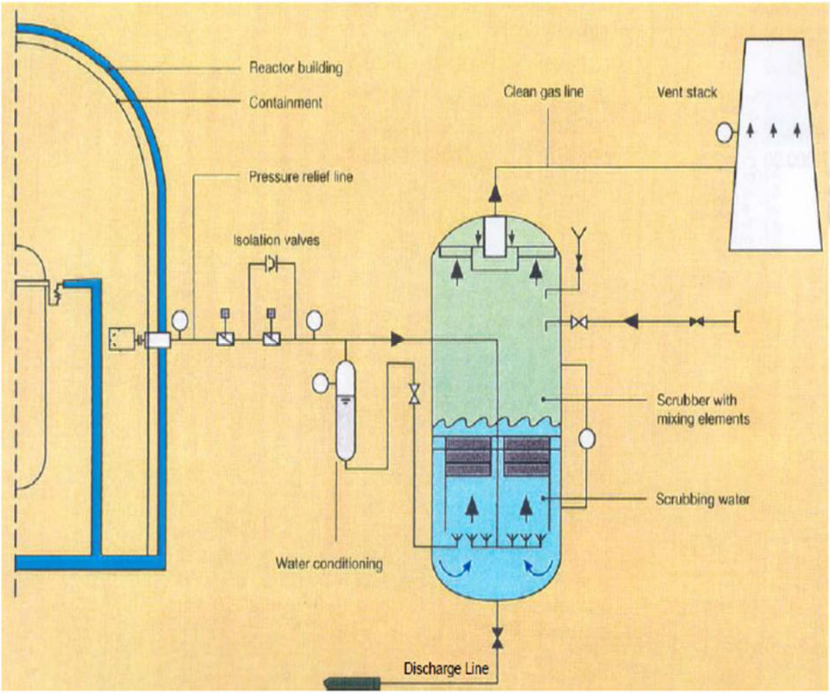
Severe Accident Mitigation

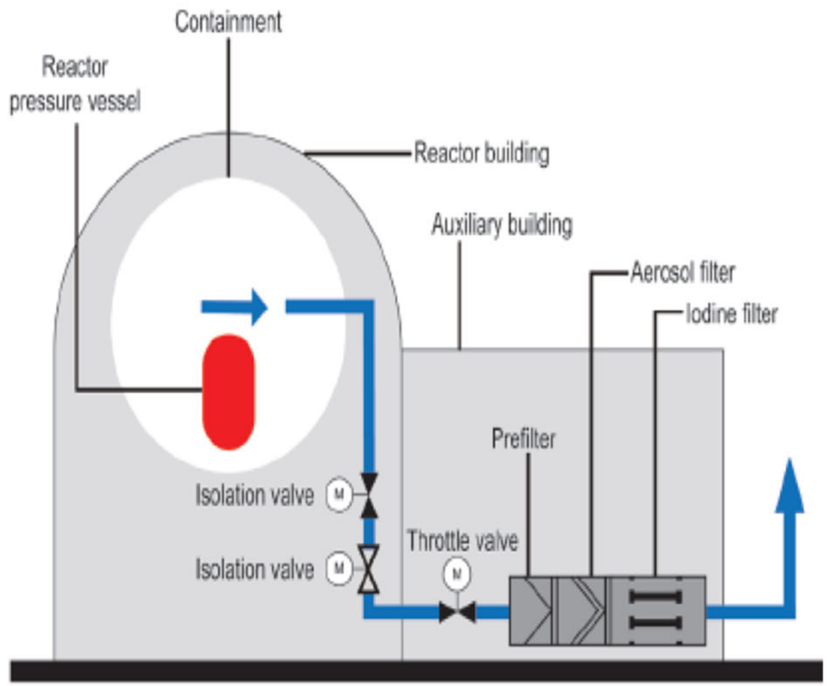
- Hydrogen mitigation (2)
  - PAR (Passive Autocatalytic Recombiner)



Severe Accident Mitigation

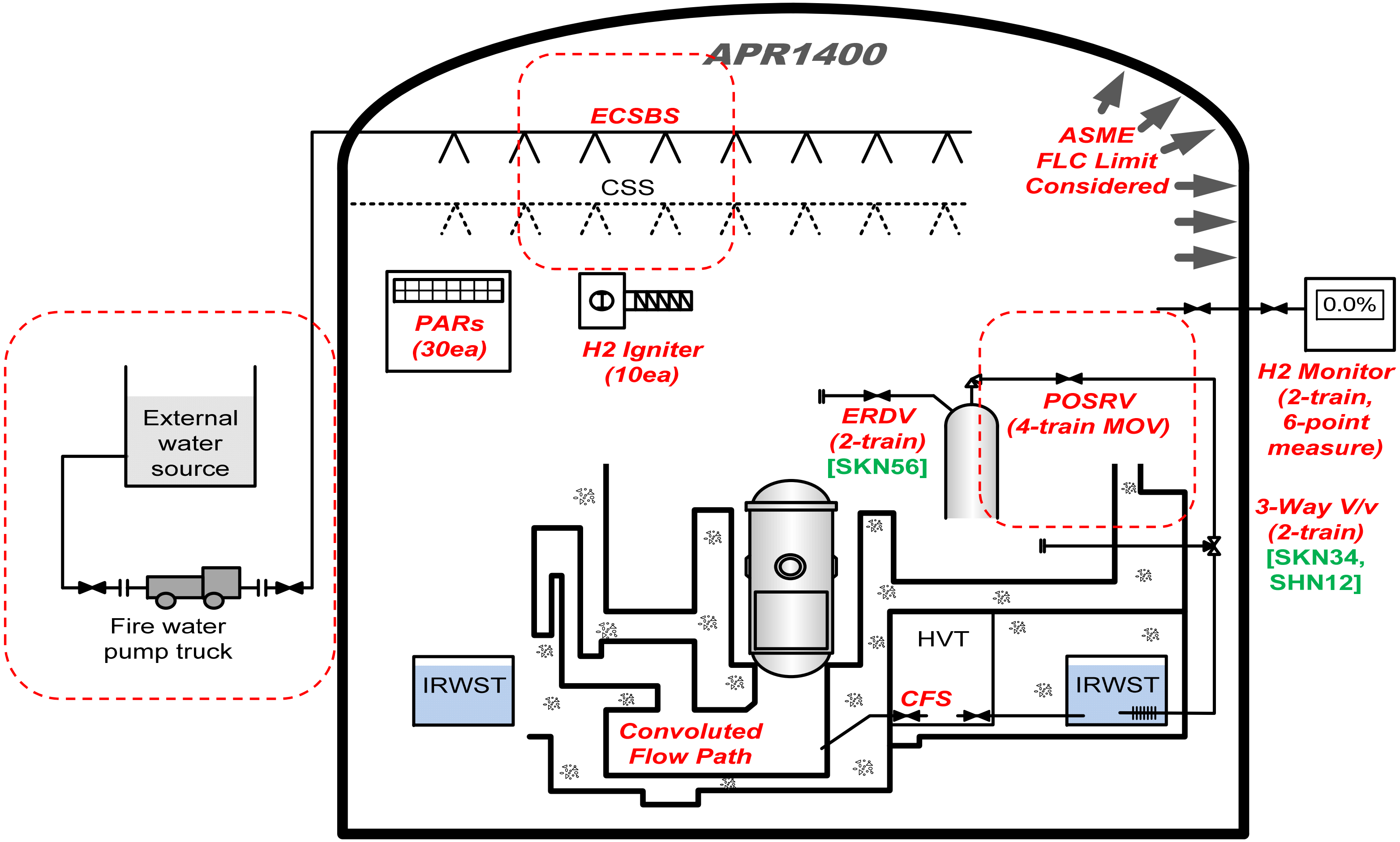
- Containment Filtered Venting System (CFVS)
  - Depressurization of containment
  - Filtration of radioactive materials





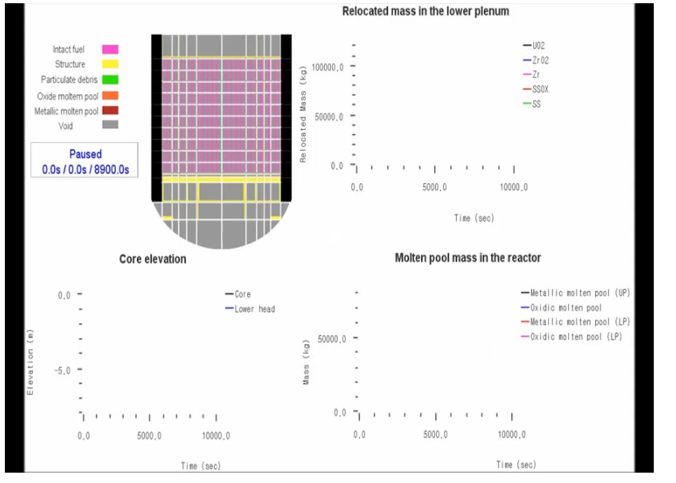
Severe Accident Mitigation

- Example of Severe Accident Mitigation Features for APR1400



CORE Behavior

- **LBLOCA+LOECC**
  - **IVR-Ex-vessel Cooling**
  - LBLOCA (Cold Leg DEGB)
    - Code : MELCOR2.1 + SNAP
    - IC and BC
      - 100% FP
      - LOECC
      - SIT (Safety Injection Tank) only available

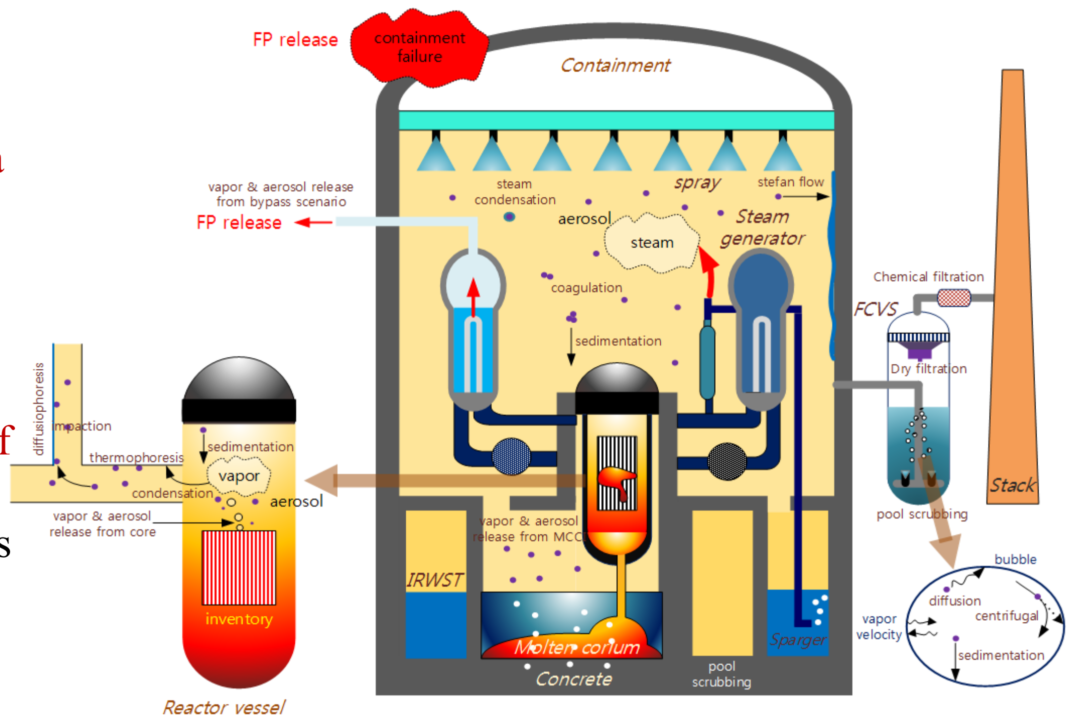


IV. Severe Accident Source Term

- Fission Product Behavior
- Reference Source Terms

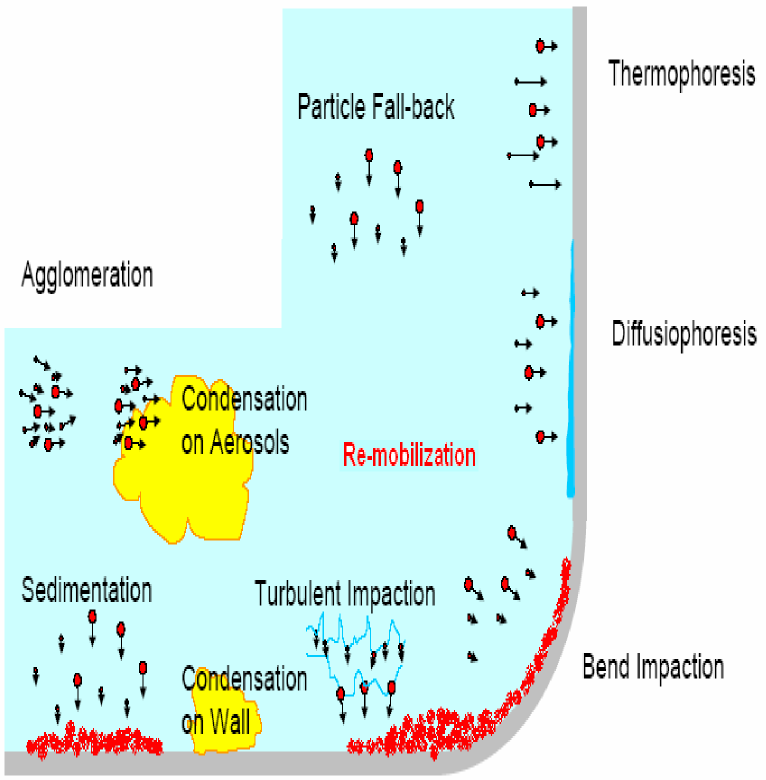
Severe Accident Source Term

- Definition of fission product (FP) source term
  - the quantity, timing, chemical species and physical forms of radioactive material released from a degrading reactor core into the environment
- Attenuators of FP in severe accidents
  - The primary circuit modifies the physicochemical form and timing of the radioactive release.
  - The containment building attenuates the gas borne debris, mainly by aerosol agglomeration and sedimentation.
- Revaporization / Resuspension of deposits
  - Revaporization due to heating
  - Resuspension due to external forces.



Severe Accident Source Term

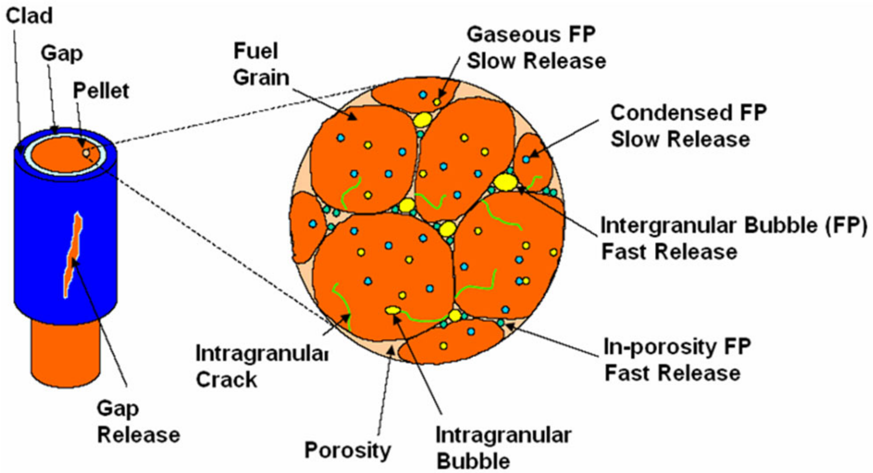
- Aerosol Behaviour
  - **Agglomeration /Coagulation**
    - Gravitational
    - Brownian
    - Turbulent
  - **Aerosol growth by steam condensation**
    - Kelvin effect including latent heat effect
  - **Aerosol removal**
    - Gravitational settling
    - Deposition by diffusion
    - Thermophoresis
    - Diffusiophoresis
    - Inertial and turbulent motions



Short Course on Severe Accident Phenomenology, London (UK), 15th-19th April 2013

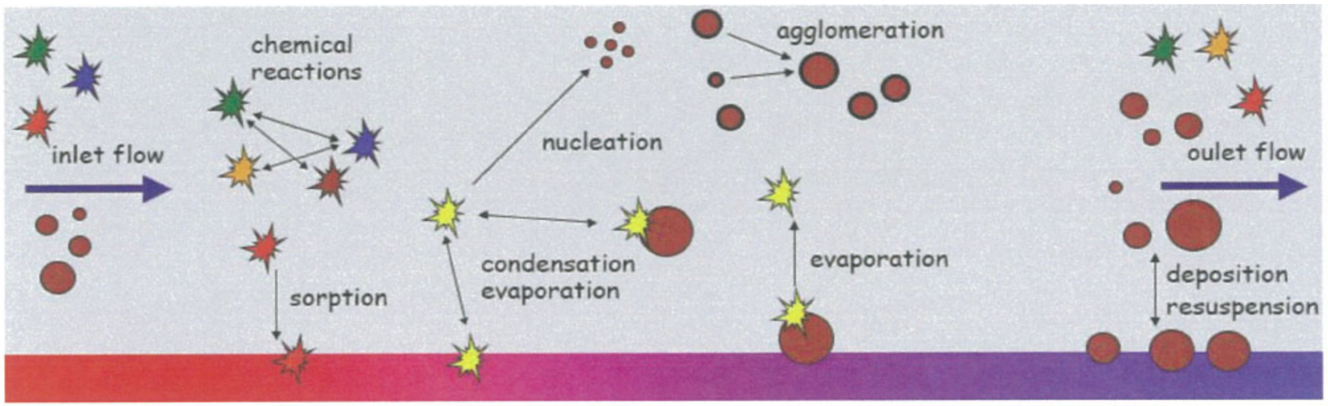
Severe Accident Source Term

- Release from Fuel
  - Agglomeration /Coagulation
    - At high temperature (≥ 2,000°C), release of volatile elements depends on the temperature and the time
    - The surrounding atmosphere, oxidizing or reducing, is important to the chemical form
    - Noble gases, iodine, cesium, tellurium and strontium are volatile and completely released from the fuel
    - Low volatile elements exhibit a more complex behavior, but are not radiologically significant in general



Severe Accident Source Term

- FP Behavior in the Primary System
  - The primary circuit modifies the physiochemical form and timing of the radioactive release
  - The influencing parameters on FP transport by gas or liquid are T/H, release path, traps and obstacles in the primary system
  - High retention factors for aerosols (50~70%) are expected in the primary circuit
  - Retention mechanisms are principally diffusiophoresis, thermophoresis and gravitational settling
  - Noble gas and the gas form of other elements are not retained at all.



after F. Cousin, Idealized transport phen. of FPs and structural materials, ANE 61 (2013) 135–142

Severe Accident Source Term

- FP Behavior in the Containment
  - **Agglomeration /Coagulation**
    - The "in-containment source term" is a function of time
    - FPs released into the containment and removed by ESF and natural processes
    - FP aerosols agglomerate and deposit on the walls and floor within 4 hrs, and are transported to the sump when spray is activated
    - Deposition is the main phenomenon that lowers the radioactivity contained in the gas through
      - agglomeration and sedimentation

        - thermophoresis,
        - diffusiophoresis,
        - impaction
        – hygroscopicity

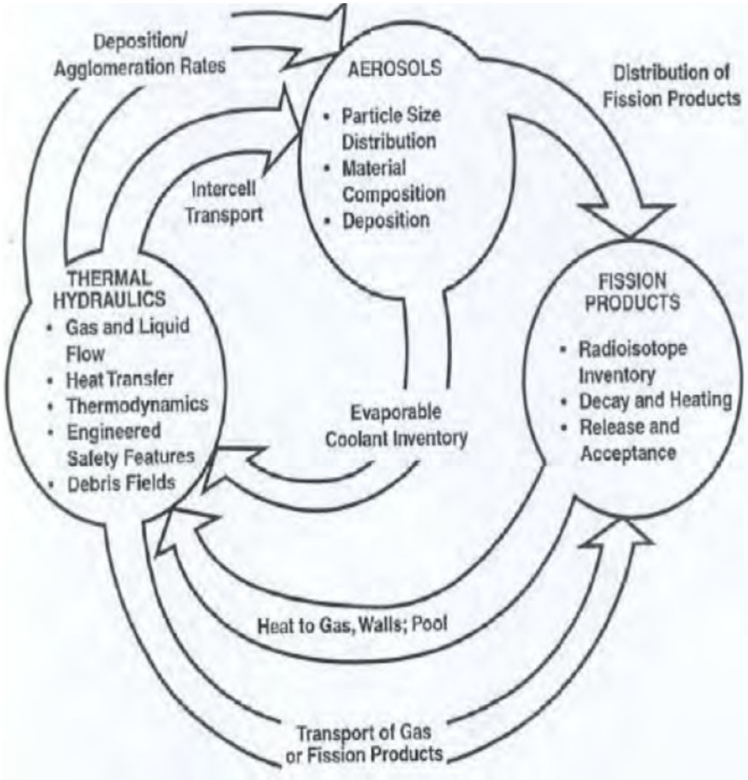
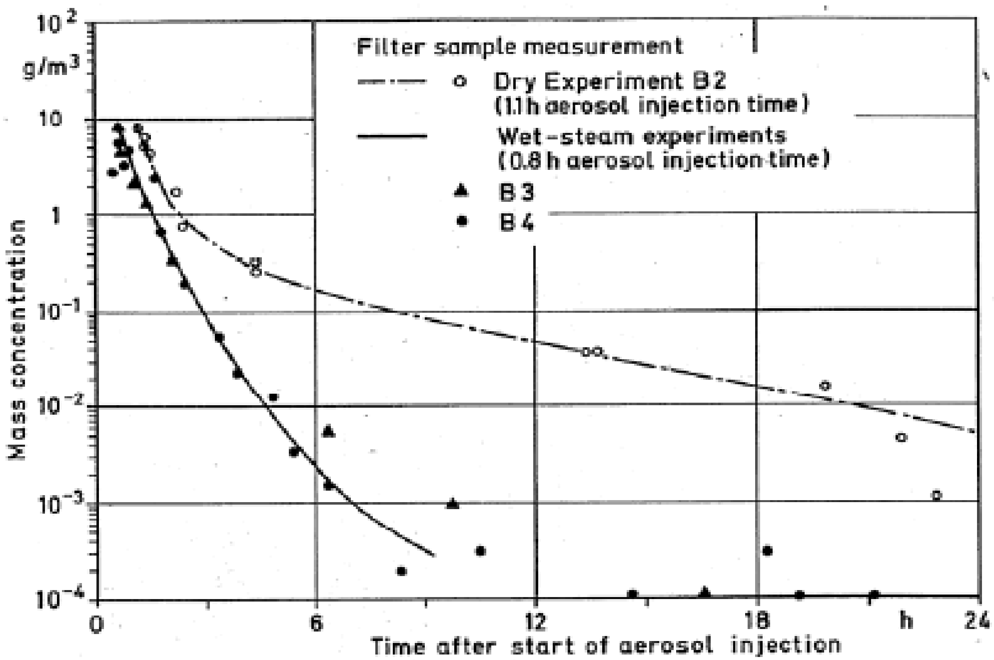


Illustration of feedback mechanisms

Severe Accident Source Term

- FP transport/retention in the containment
  - **FP aerosols agglomerate and deposit** on the walls and floor within 4 hours, and are transported to the sump when spray is activated.



Aerosol depletion measured in DEMONA tests under dry and wet conditions

Severe Accident Source Term

- Reference Source Terms
  - For DBAs, this should be done by means of a conservative analysis of the expected behavior of the core and of safety systems
  - Consideration should be given to the most pessimistic initial conditions for the relevant parameters
    - inventory of radionuclides in systems
    - allowable leak rates
    - physicochemical forms of the radionuclide in the containment
  - TID-14844 (1962) assumptions
    - 100% of the core inventory of Noble Gases
    - 50% of the Iodine (half of which deposit very rapidly) and 1% solid
      - the source term within containment is instantaneously available for release iodine chemical form is predominantly (91%) in elemental form, with 5% particulate iodine and 4% in organic form

Severe Accident Source Term

- Reference Source Terms
  - **Comparison of Two Source Terms**

Factor	Old methodology (TID-14844, R.G 1.4)	New methodology (NUREG-1465, R.G 1.183)
Release timing	Instantaneous	Phased over 1.8 hrs
Noble gases	100%	100%
Other FPs	50% Iodine, 1% Solids	40% I, 30% Cs, 5% Te, 2% Ba
Iodine form	91% I_2, 4% organic, 5% aerosol	4.85% inorganic vapor, 0.15% organic vapor, 95% aerosol
Solids	Normally ignored for dose calculation	Treated as aerosol
Natural deposition	50% plateout of I_2	Choice of models
Dose timing	First two hours for EAB	Worst two hours for EAB
Dose metric	Thyroid, Whole Body	Total Effective Dose Equivalent (TEDE)

Severe Accident Source Term

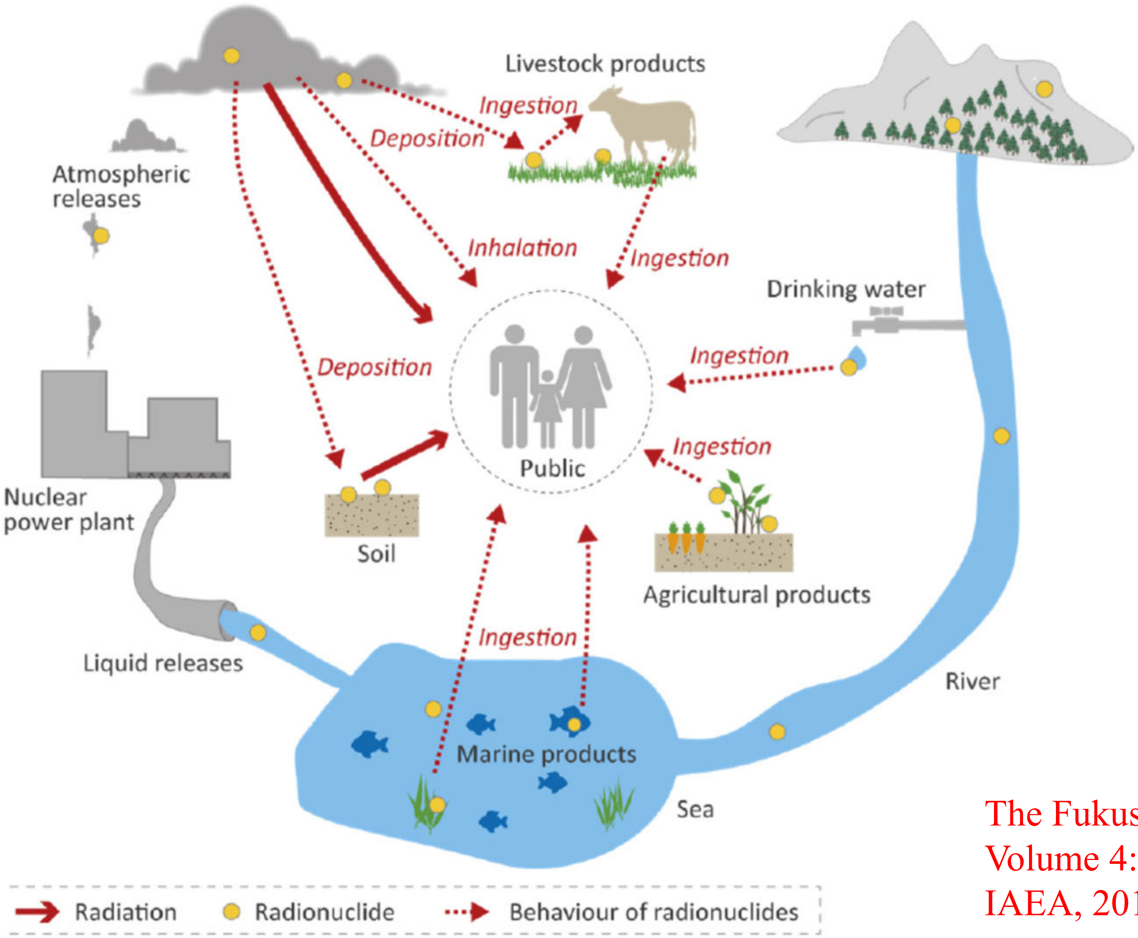
- Reference Source Terms
  - **Alternative Radiological Source Terms (NUREG-1465)**

	Gap Release*	Early In-Vessel	Ex-Vessel	Late In-Vessel
Duration(hrs)	0.5	1.3	2.0	10.0
Noble Gases	0.05	0.95	0	0
Halogens	0.05	0.35	0.25	0.1
Alkali Metals	0.05	0.25	0.35	0.1
Te group	0	0.05	0.25	0.005
Ba, Sr	0	0.02	0.1	0
Noble Metals	0	0.0025	0.0025	0
Cerium group	0	0.0005	0.005	0
Lanthanides	0	0.0002	0.005	0

* Iodine entering containment is composed of at least 95% CsI, with no more than 5% I+HI.

Severe Accident Source Term

- Release Path to the Environment



The Fukushima Daiichi Accident, Technical Volume 4: Radiological Consequences, IAEA, 2015

V. Computer Codes for Severe Accident Analysis

Computer Codes for Severe Accident Analysis

- Objectives of severe accident analysis
  - evaluation of ability of design (in particular containment) to withstand severe accidents and to identify particular vulnerabilities
  - demonstration of capability of equipment including instrumentation to be used in accident management
  - verification of compliance with the plant radioactive release targets
  - assessment of doses to the control room operators and in all other locations where operator activities may be required
  - identification of accident management measures that could be carried out to mitigate the effects
  - specification of inputs for off-site emergency planning

Computer Codes for Severe Accident Analysis

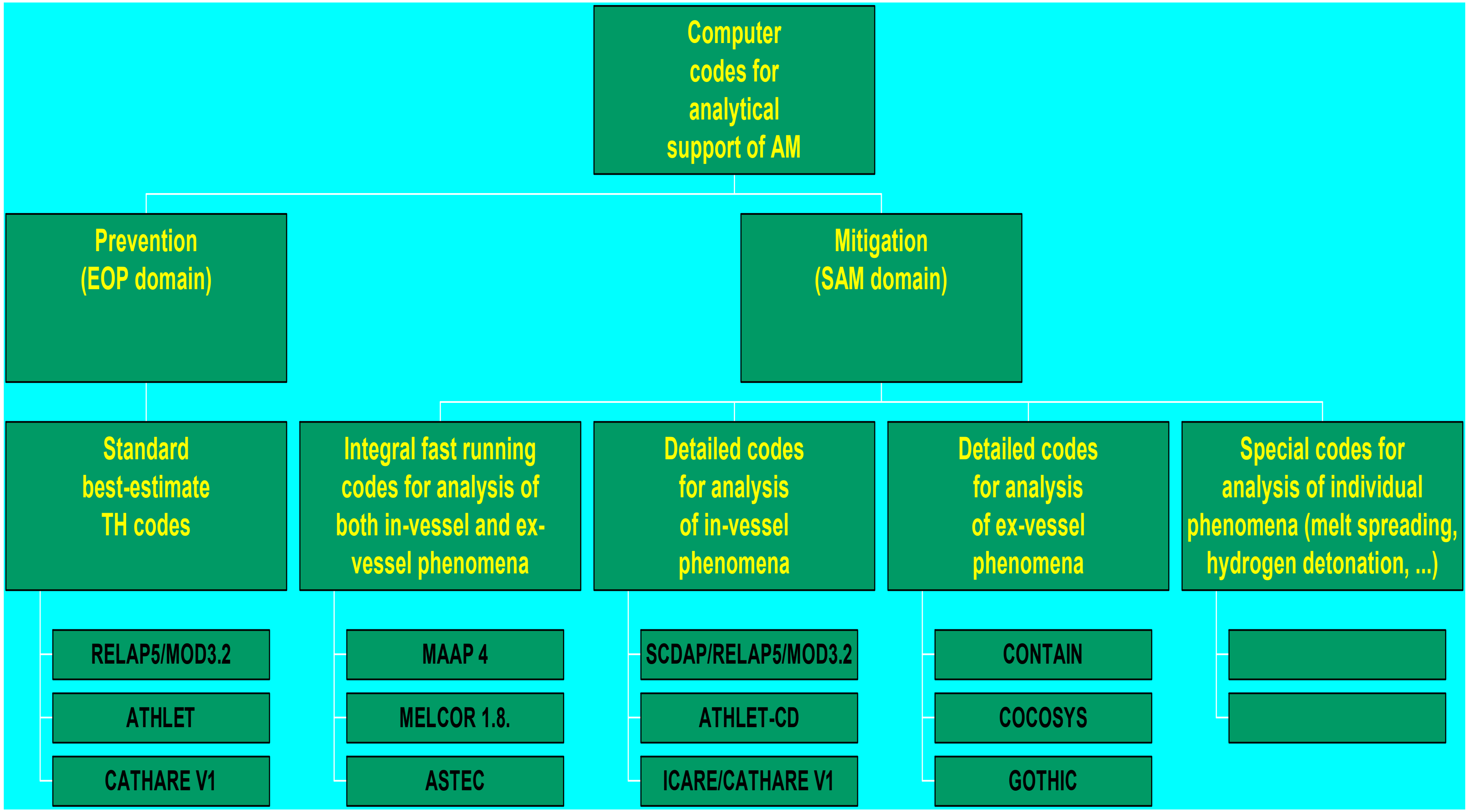
- Characteristics of Severe Accident Analysis Code
  - **Wide range of processes to be covered (thermal-hydraulics, chemistry, metallurgy, FP transport)**
  - **Phenomena to be modelled**
    - Core degradation and fuel melting, vessel melt through
    - In-vessel and ex-vessel cooling of core melt
    - In-vessel melt retention
    - Fuel-coolant interaction, steam explosions
    - Distribution of heat inside the RCS
    - High-pressure melt ejection/direct containment heating
    - Hydrogen generation, distribution and combustion
    - Failure or by-pass of the containment
    - Release and transport of fission products
    - Core-concrete interaction, basemat melt through
  - **Knowledge of phenomena and validation of codes limited (large uncertainties in calculations to be considered)**

Computer Codes for Severe Accident Analysis

- Categorization of computer codes for severe accident analysis
  - **Fast running integral codes**
    - Well balanced combination of detailed and simplified models for analysis of all phenomena in whole NPP
    - Computational time< min (real time; 12 hours)
    - ~50 PSA calculations per month
  - **Detailed codes**
    - Based on mechanistic models, typically either for analysis of in-vessel or ex-vessel phenomena
    - Computational time less than 10-times real time
  - **Special (dedicated) codes**
    - For analysis of individual phenomena (melt dispersal, lower head melt retention, steam explosion, hydrogen deflagration/detonation, melt spreading)
    - Both simple, fast running codes as well as complex codes with large computational times

Computer Codes for Severe Accident Analysis

- Example of Computer Code used for Severe Accident Analysis



Summary

Summary (Recapping)

- Introduction
- Severe Accident Phenomena
- Severe Accident Mitigation
- Severe Accident Source Term
- Computer Codes for Severe Accident Analysis

References

- International Atomic Energy Agency, Design of Reactor Containment Systems for Nuclear Power Plants, Safety Guide NS-G-1.10, 2004.
- B. R. Sehgal, Nuclear Safety in Light Water Reactors –Severe Accident Phenomenology, ISBN:978-0-12-388446-6, Elsevier, 2012.
- Sandia National Laboratory and Univ. of New Mexico, Perspectives on Reactor Safety, USNRC NUREG/CR-6042, 1994.
- Didier Jacquemain, Nuclear Power Reactor Core Melt Accidents, ISBN: 978-2-7598-1835-8, IRSN, 2015.
- L. Soffer et al., Accident Source Terms for Light-Water Nuclear Power Plants (final Report), USNRC NUREG-1465, 1995.

Appendix

- Terminology
  - **Heat-up :** Temperature rises when core becomes uncovered
    - zircaloy steam reaction produces hydrogen and heat
    - cladding fails
    - release of volatile fission products (FP) which partially deposit in the primary
    - circuit and/or escape to the containment with steam/H2
  - **Core Uncovery :** water mixture level in the reactor vessel falls below the top of the active fuel
  - **Core Damage :** fuel assemblies are deformed by mechanical fracturing, or by liquefaction due to material interactions or by melting
  - **Early Phase :** refers to the initial stages of core damage, including oxidation of cladding, melting and relocation of mainly metallic materials of fuel bundles
  - **Core Melt :** the reactor core overheats and this leads to significant melting or liquefaction of the core materials

Appendix

- Terminology
  - **Degraded Core :** an advanced state of core damage in which the original fuel bundle geometry has been substantially lost, due to molten material relocation
  - **Late Phase :** refers to the stages of core degradation involving substantial melting and relocation of fuel materials including ceramics, comprising the displacement of materials to the vessel lower plenum and the containment, if the vessel failure occurs
  - **Core Melt/Slump :** bulk of core is uncovered; melt core begins to fall into water pool in vessel bottom
    - fission product migration through primary circuit and to the containment can be significant for volatile fission products
    - **Core Melt/Slump :** bulk of core is uncovered; melt core begins to fall into water pool in vessel bottom
  - **Melt through :** pressure vessel fails as molten core debris melts the bottom head and drops into reactor cavity

Thank you – Questions?