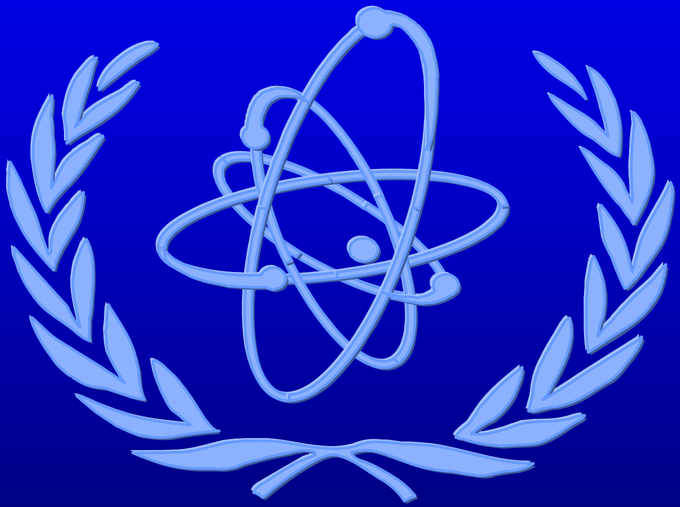
MODULE 2:

Severe Accident Phenomena
-- an overview --



Outline of Discussion

- Overview of major severe accident phenomena
  - Chronology of core damage
  - Major changes in core configuration & plant state

- Provide some references for additional study

A Simple View of Severe Accident Progression – 3 Phases

- Phase 1: Initial Fuel Damage
  - Fuel rod heating to ~1400C
  - Oxidation of fuel cladding (acceleration in heatup)
  - Control rod melting
- Phase 2: Core Melting & Relocation
  - Clad failure and material interactions cause partial liquefaction of fuel and formation of particulate debris
  - Melt / debris relocates downward
  - Debris accumulates on lower core support structures and in the lower head
- Phase 3: Reactor Vessel Lower Head Fails
  - Discharge of core debris into containment
  - Core debris interactions with containment structures

The Accident at Three Mile Island 2 Passed through Phases 1 and 2

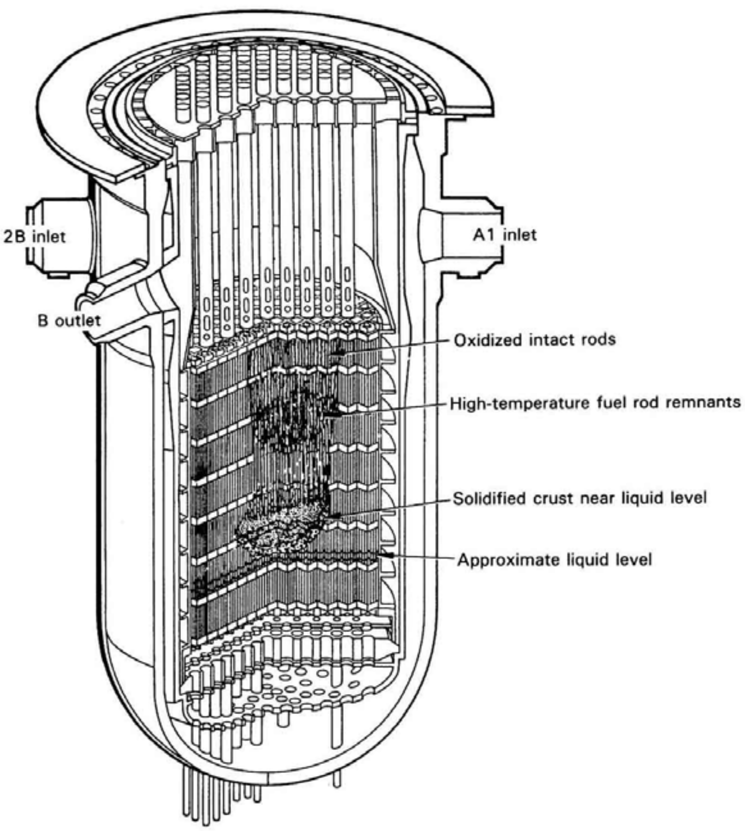
- The sequence of major events:
  - [0:00] Feedwater pumps and turbine trip
  - [0:00+] PORV opens at 15.55 MPa followed by reactor trip
  - [0.00++] PORV fails to reclose at 15.20 MPa (start of LOCA)
  - [0.01-] Operators manually start one makeup pump
  - [0:01] Pressurizer water level reaches lowest level then rises
  - [0:02] High-pressure injection (HPI) initiated and RV pressure decreased below 11 MPa
  - [0:03] Pressurizer high-level alarm
  - [0:04] Operator throttled HPI isolation valves and stopped one makeup pump
  - [0:12] Pressurizer level comes back on-scale and drops rapidly.

TMI-2 Sequence of Events (2)

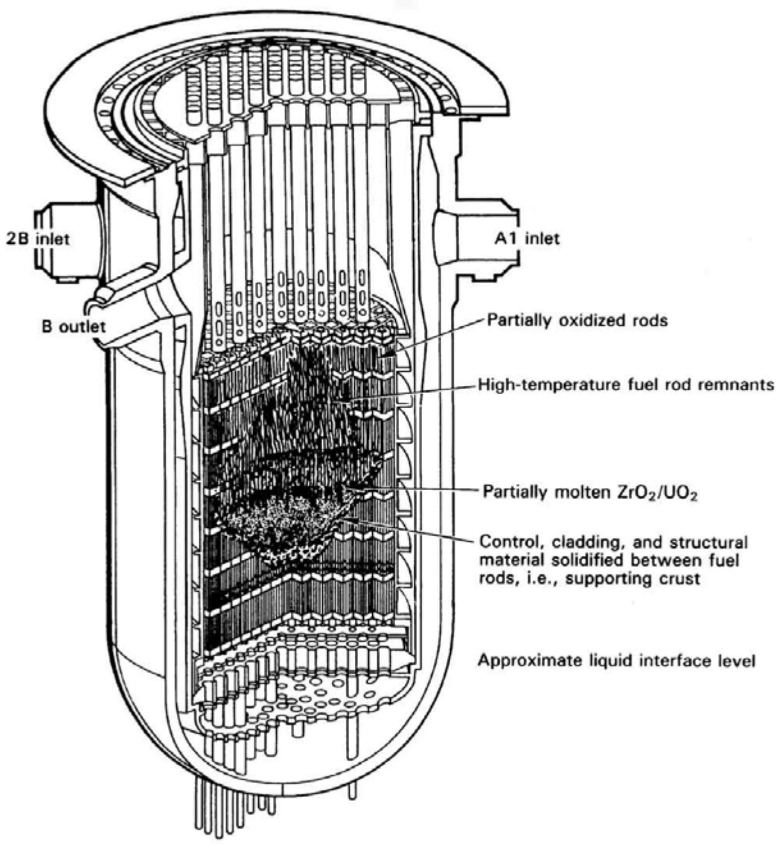
  - [0:15] Reactor coolant drain tank rupture disk blows
  - [1:51] Loop A & B hotleg temperatures increase (offscale), cold leg temperatures decreasing
  - [2:19] PORV block valve closed (loss of coolant halted)
- Subsequent (unobserved) events:
  - [2:20] Water level dropped to approx. mid-core
  - [2:50] Start of melting, downward fuel relocation
  - [2:54] Reactor coolant pump started and run for 17 min
  - [3:44] Molten pour into lower head
- Termination :
  - [4:22] Makeup pump started, RV begins to refill

TMI-2: A Chronology of Core Damage

[Broughton, et al., Nucl Tech. Vol. 87, 1989]



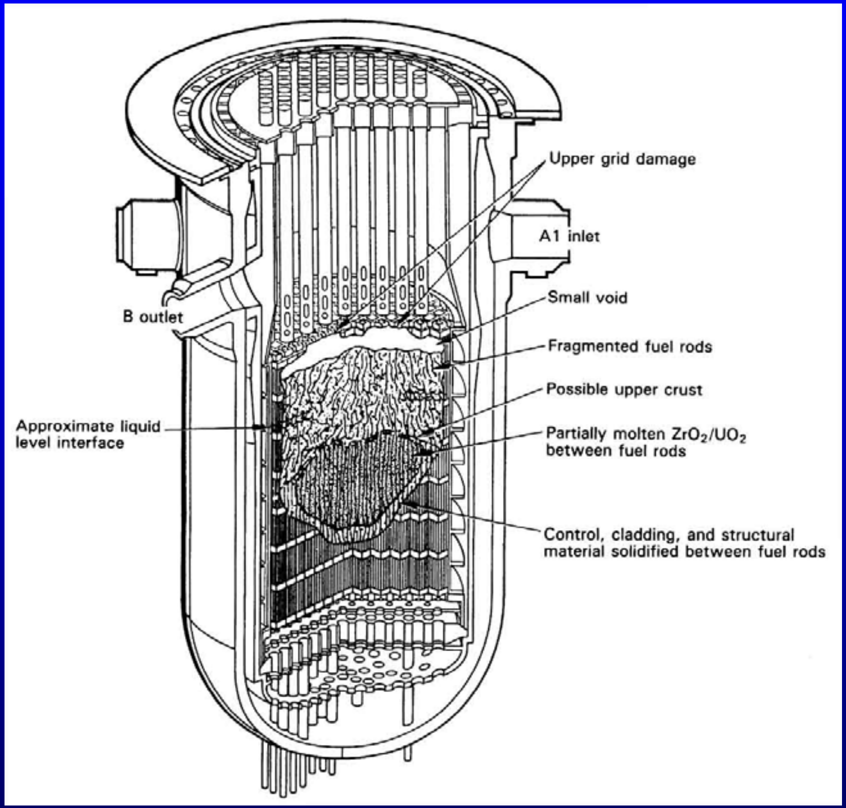
Core Condition – approx. [2:30]



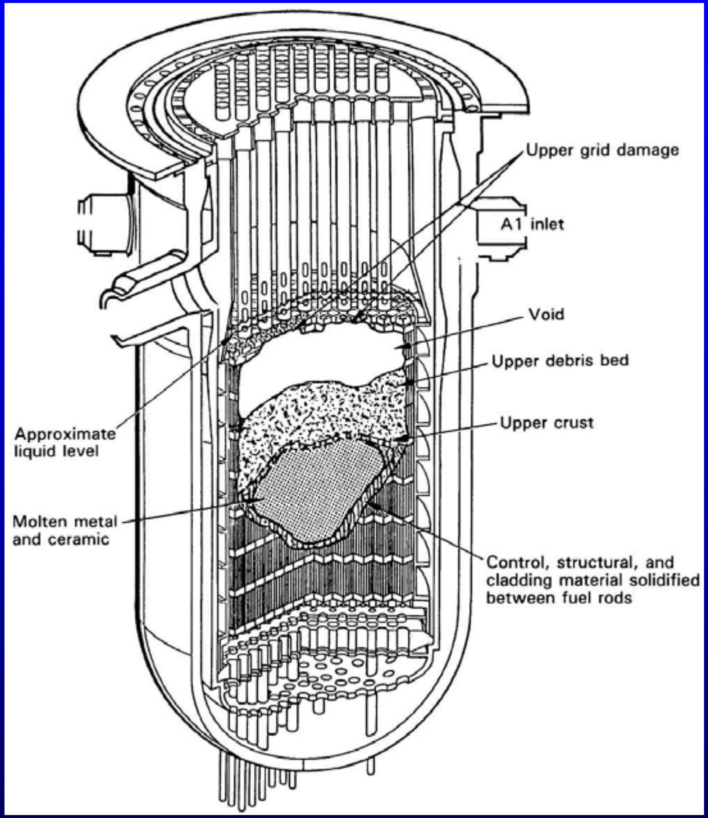
Core Condition approx. [2:53]

TMI-2: A Chronology of Core Damage

[Broughton, et al., Nucl Tech. Vol. 87, 1989]



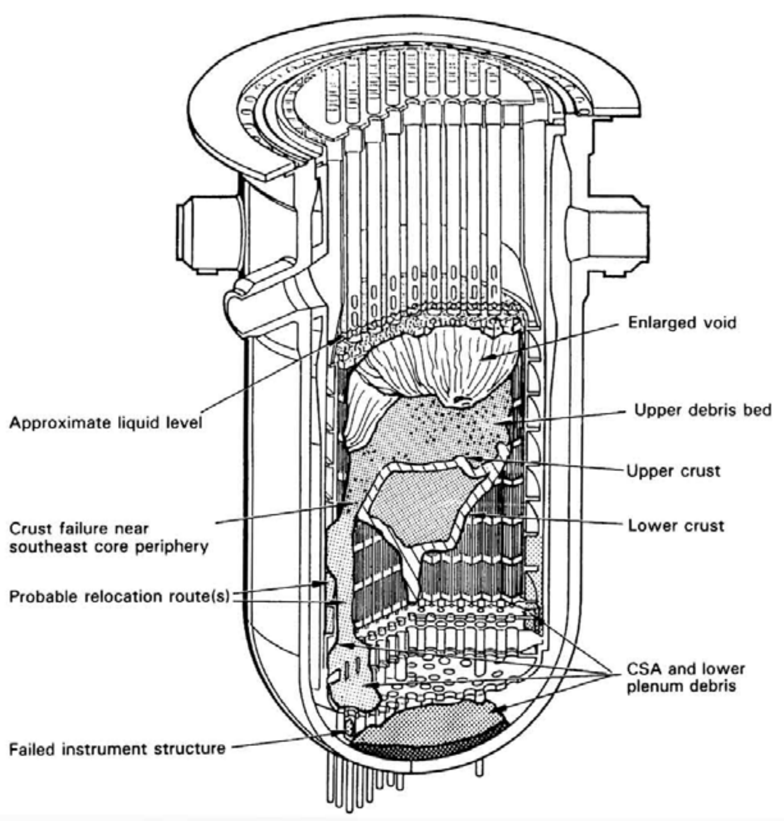
Core Condition – approx. [3:00]



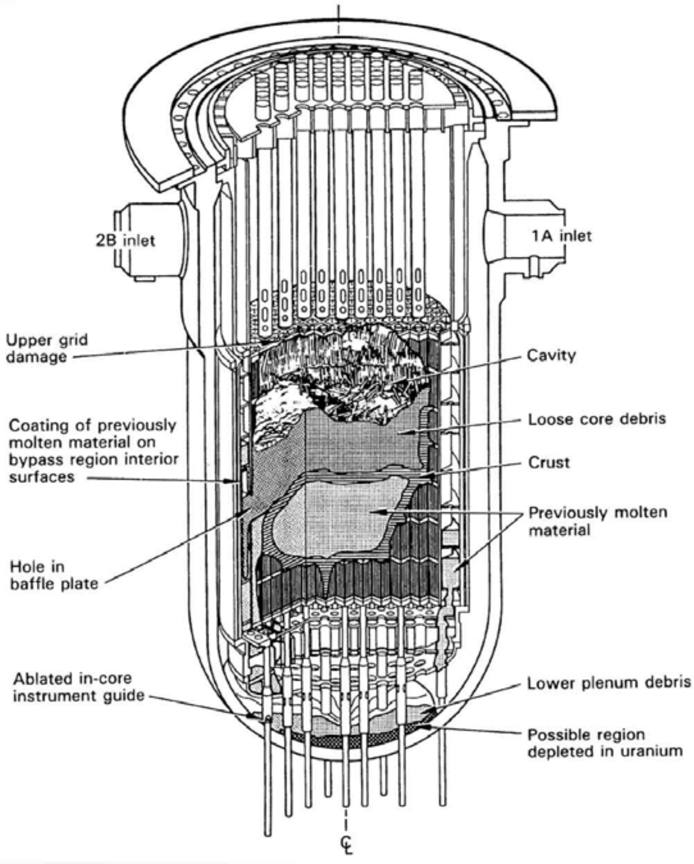
Core Condition approx. [3:43]

TMI-2: A Chronology of Core Damage

[Broughton, et al., Nucl Tech. Vol. 87, 1989]



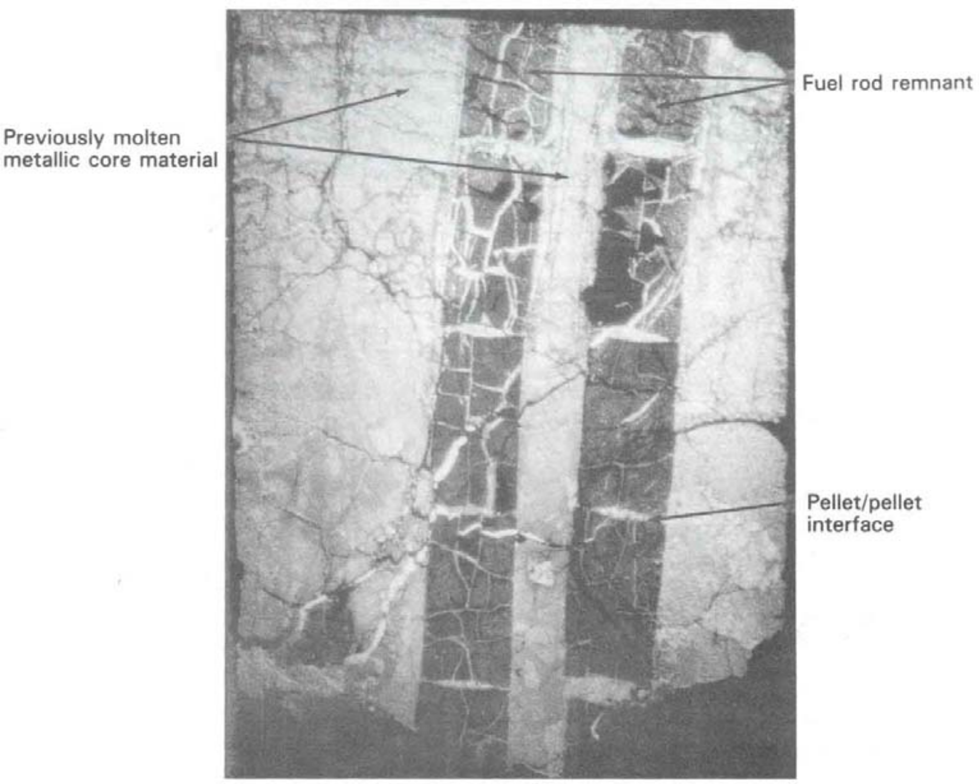
Hypothesized core configuration
during melt relocation



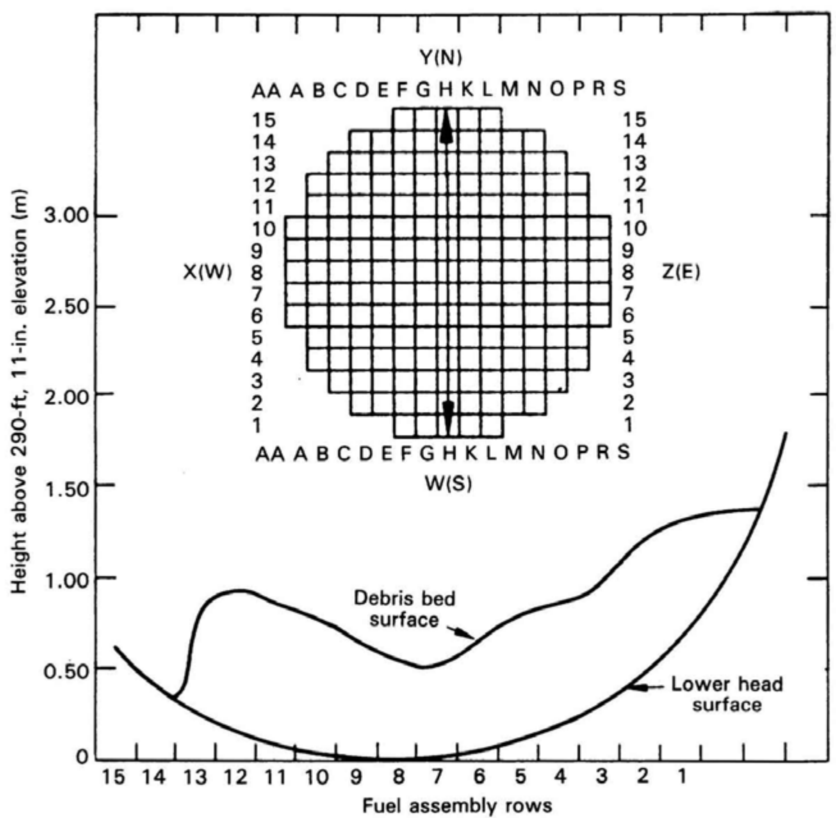
Core end state configuration

TMI-2: Post-accident examination

[Broughton, et al., Nucl Tech. Vol. 87, 1989]



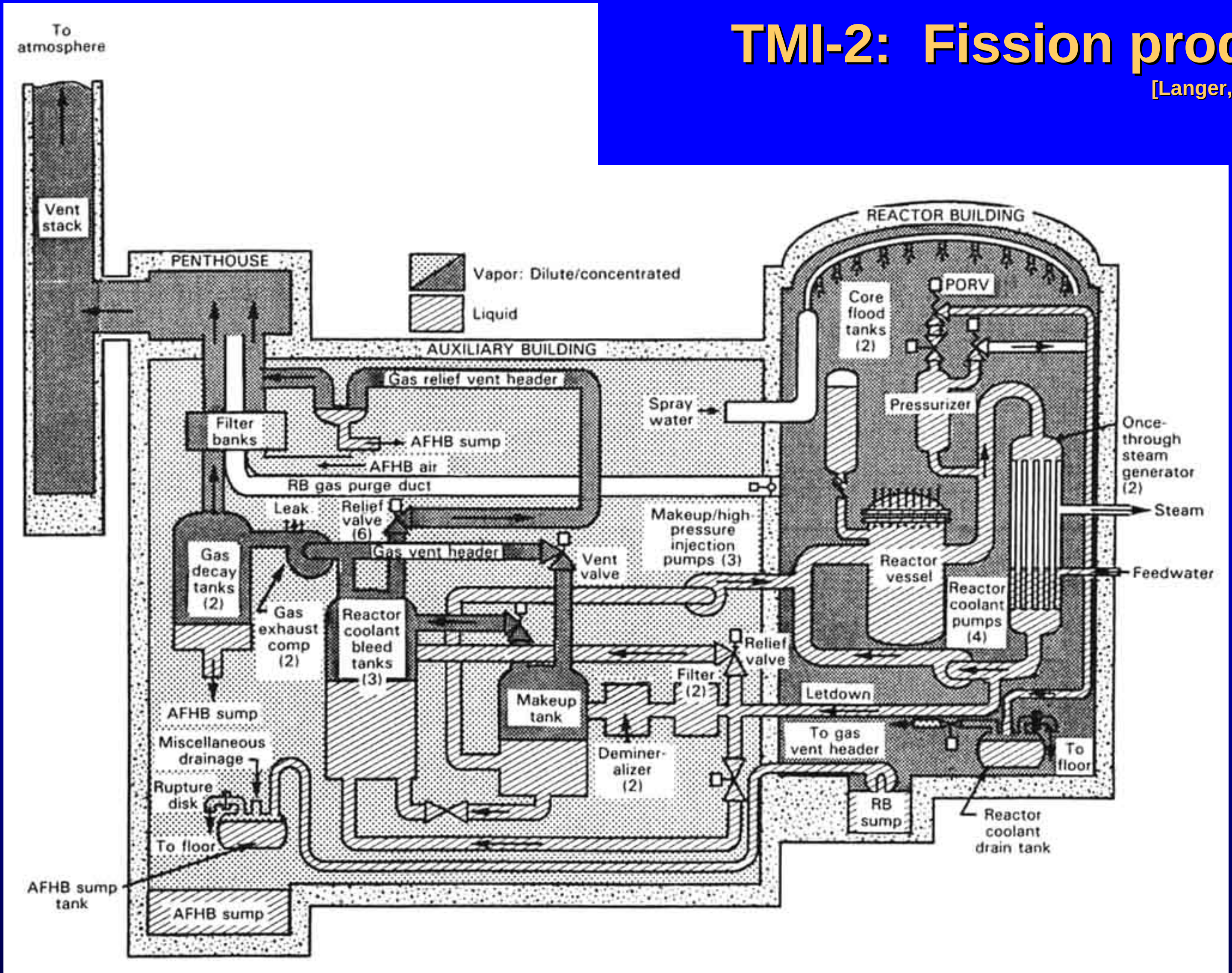
Sample of material from lower crust near the RV centerline



Frozen debris bed on lower head

TMI-2: Fission product release

[Langer, et al., Nucl Tech. Vol. 87, 1989]



Fractional release to environment

^{88}Kr	0.009
^{133}Xe	0.010
^{133m}Xe	0.047
^{135}Xe	0.006
^{131}I	2.3E-7

Accident Progression - Phase 1

- **Major features: Initiation of clad oxidation & control rod melting**
  - **Oxidation: Reaction of exposed metallic surfaces (Zirconium clad) to steam**
    - **"Run-away" exothermic oxidation at temperatures greater than ~1200C**
  - **Control rod melting**
    - **Ag-In-Cd alloy melting temperature ~ 800C**

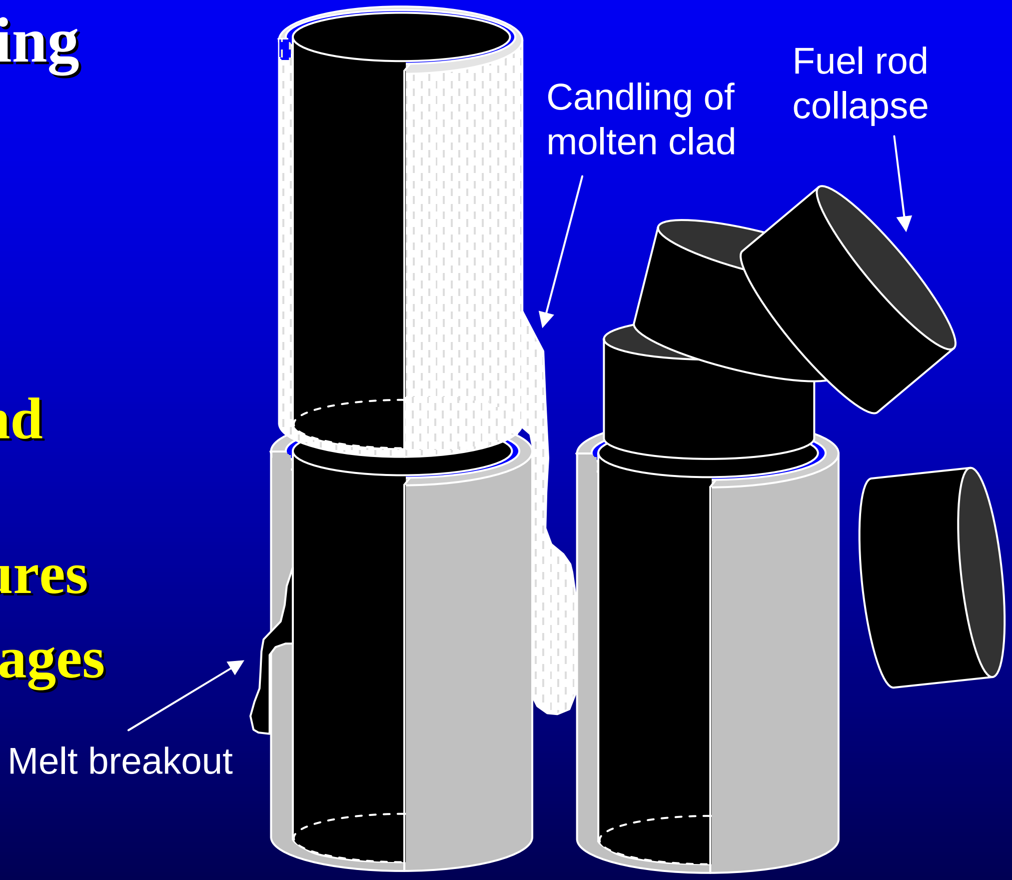
Effects of Phase 1 Features on Accident Progression

- **Heat of reaction causes significant increase in fuel assembly heat up rate**
- **Potential melting a downward “candling” of molten control rod & clad material**
    - **Refreezes at lower elevation, reducing coolant flow area**
- **Major source of hydrogen to containment**

$$Zr + 2H_2O \rightarrow 2H_2 + ZrO_2$$

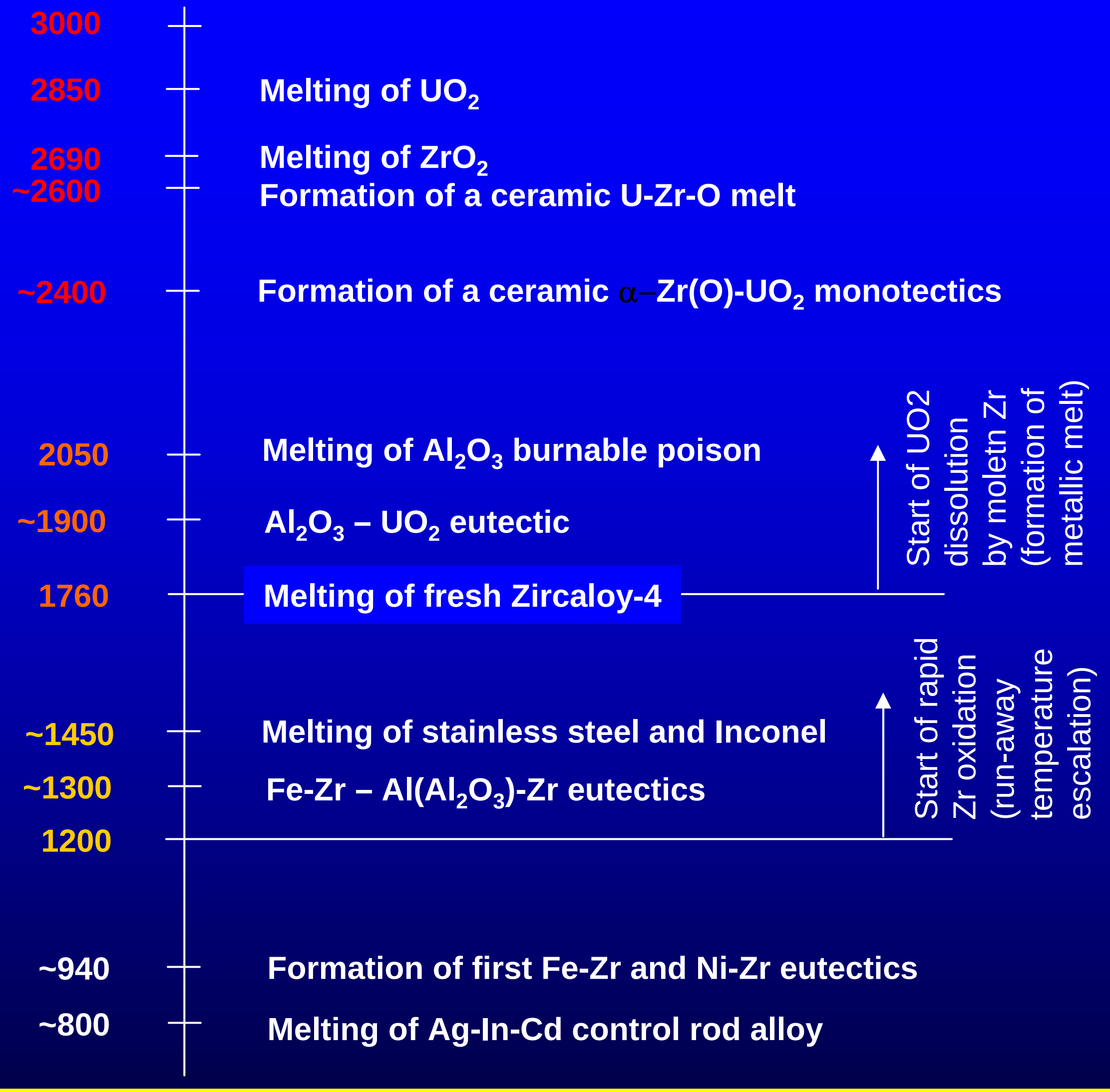
Accident Progression Phase 2

- **Major feature: Fuel melting and relocation to lower elevations of the RV:**
  - **Major changes in core geometry**
  - **Separation of metallic and ceramic materials**
  - **Wide range of temperatures**
  - **Formation of local blockages**



Accident Progression Phase 2

- Core ‘melting’ and relocation affected by eutectic interactions among various core materials



3000

2850 Melting of UO_2

2690 Melting of ZrO_2

~2600 Formation of a ceramic U-Zr-O melt

~2400 Formation of a ceramic α–Zr(O)-UO_2 monotectics

2050 Melting of Al_2O_3 burnable poison

~1900 Al_2O_3 – UO_2 eutectic

1760 Melting of fresh Zircaloy-4

~1450 Melting of stainless steel and Inconel

~1300 Fe-Zr – Al(Al_2O_3)-Zr eutectics

1200

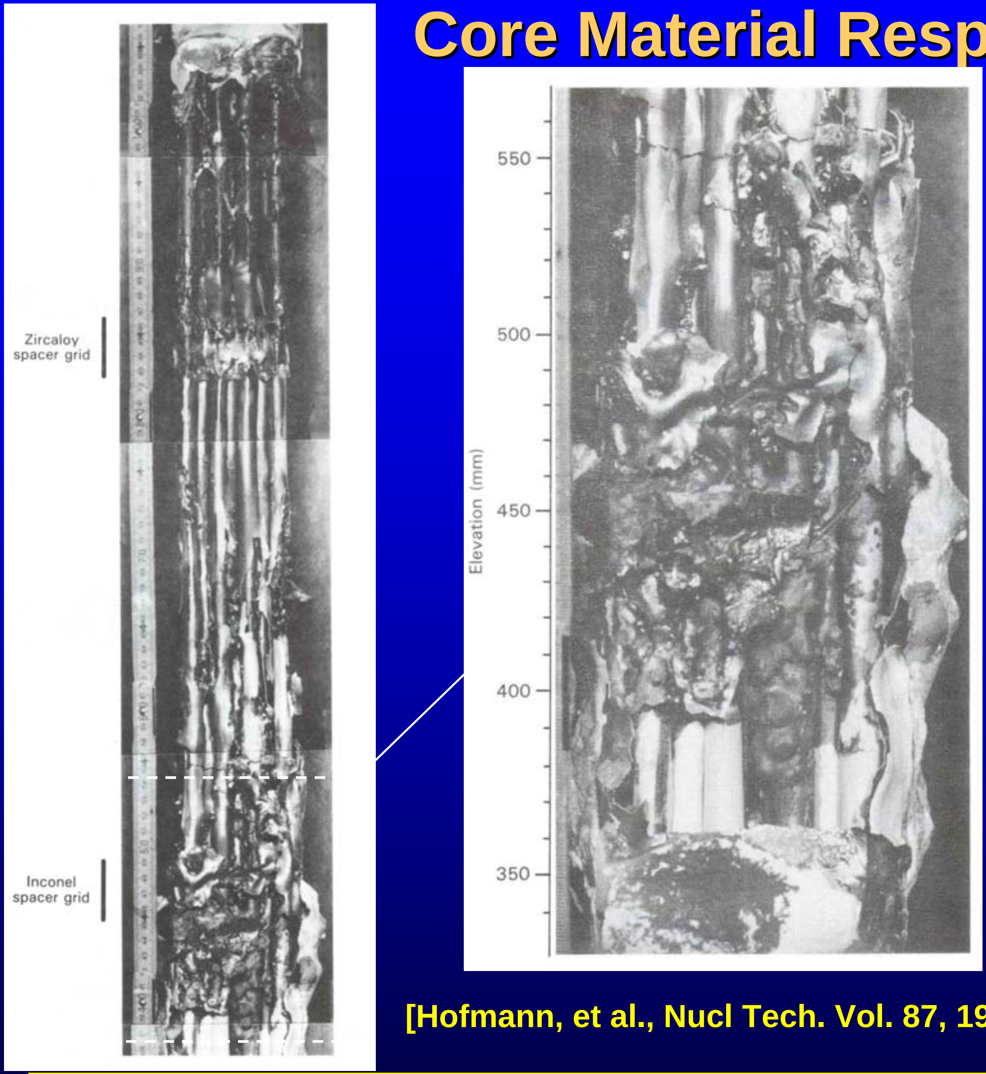
~940 Formation of first Fe-Zr and Ni-Zr eutectics

~800 Melting of Ag-In-Cd control rod alloy

Start of UO2 dissolution by moletn Zr (formation of metallic melt)

Start of rapid Zr oxidation (run-away temperature escalation)

Core Material Response to High Temperatures



[Hofmann, et al., Nucl Tech. Vol. 87, 1989]

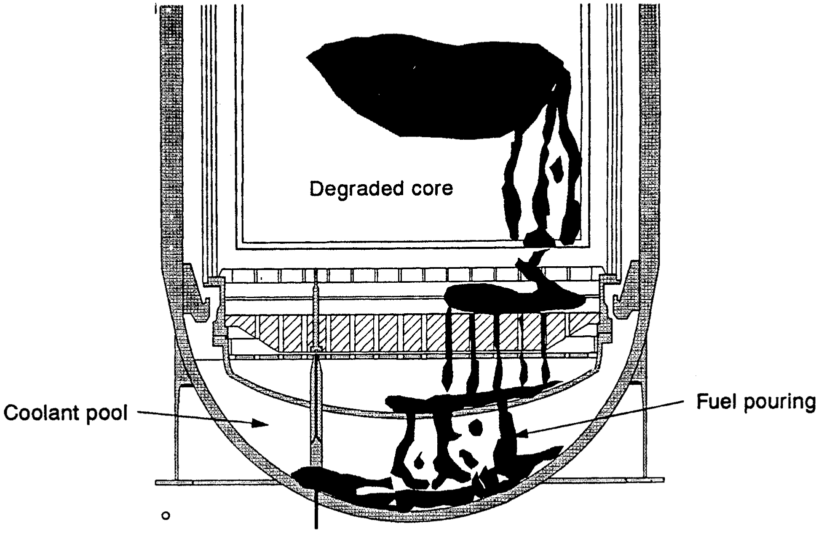
- In-pile fuel bundle degradation experiments provide the basis for severe accident simulation codes
  - ACRR (Sandia – USA)
  - PBF, LOFT (Idaho – USA)
  - CORA (KfK, Germany)
  - FLHT (PNL, USA)
- Useful literature reviews:
  - Hobbins, et al., Nucl. Tech., 95, Sept. 1991.
  - Hofmann, J. Nucl Mat, 270, 1999.

Accident Progression - Phase 3

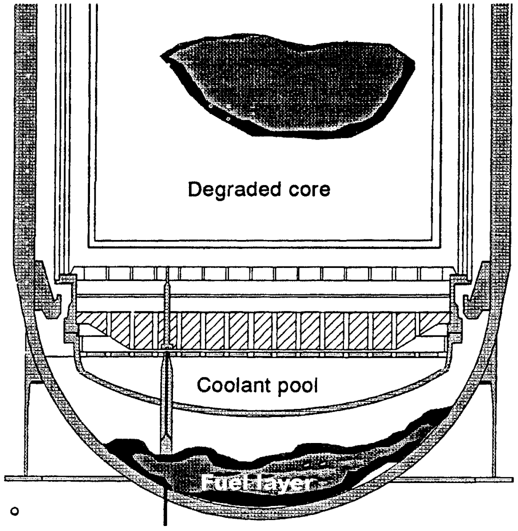
- **Major features: Molten Debris Attacks Lower Head**
  - **TMI-2 lower head did not fail in spite of molten pour of a considerable mass of material**
    - **Molten material submerged in pool of water**
    - **Crust formation against inner surface of lower head wall provided an insulating layer that limited heat transfer**
  - **Debris coolability in lower head remains a major area of research**
  - **Lower head penetrations important for some reactor vessels**

Accident Progression Phase 3

- Major uncertainties include:
  - Configuration of relocating debris/melt
  - Temperature of relocating material
  - Crust formation and heat transfer mechanisms on lower head surface



(a) during relocation



(b) after relocation

Major Lower Head Failure Research Projects

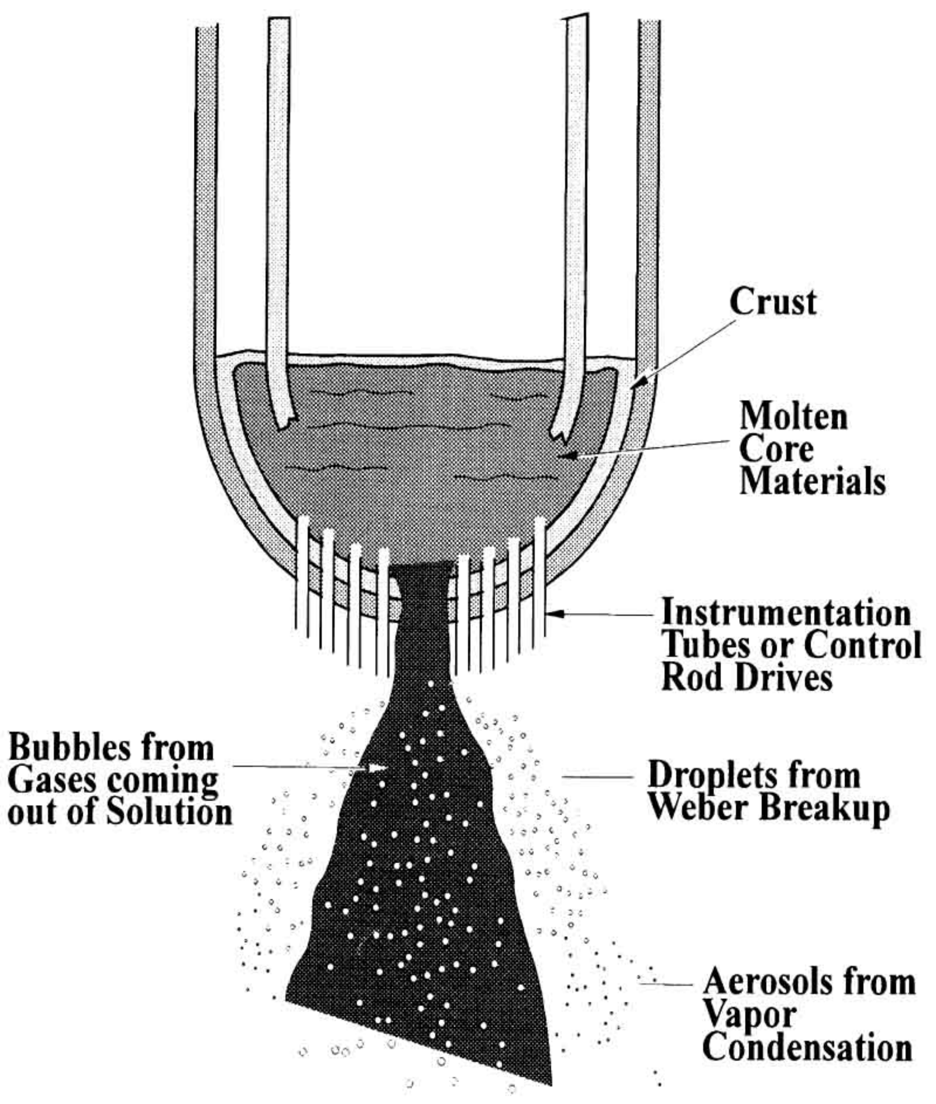
In-vessel Melt Quenching	Heat Transfer from a Molten Pool	Gap Cooling Mechanism	RPV Failure Mechanisms
FARO (JRC – Ispra, EC) **ALPHA (JAERI, Japan)**	**RASPLAV (RRC-KI, Russia)** **COPO2 (Finland)** **ACOPO (UCSB, USA)**	**ALPHA (JAERI, Japan)** **EPRI/ FAI (USA)** **RPV Programme (TUM Siemens, Germany)**	**LHF (SNL, USA)** **FOREVER (KTH, Sweden)** **CORVIS (PSI, Switzerland)**

Transition to Ex-vessel Period of Accident Progression

- **Major features: Core debris relocation into containment**
    - **If vessel failure occurs at high-pressure**
        - **Possibility of melt dispersal and thermal interactions with containment atmosphere ("High-Pressure Melt Ejection" and "Direct Containment Heating": HPME / DCH)**
    - **Vessel failure at low pressure results in gradual "pour" of debris onto containment floor**
- **After vessel failure, thermo-chemical interactions between molten core debris and concrete can dominate containment response.**

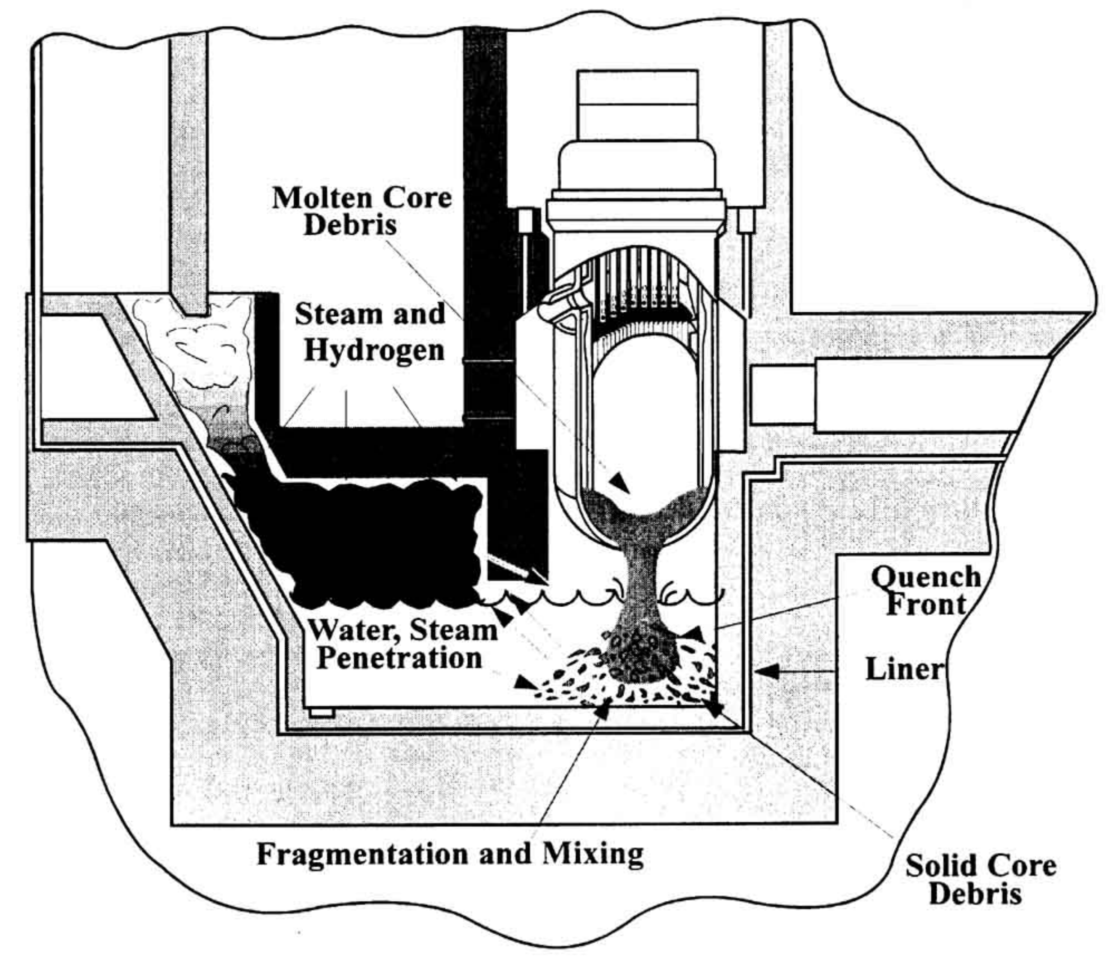
High Pressure Melt Ejection

- Can be the cause of largest pressure increase in a PWR containment
- Combines:
  - RV blowdown from high pressure
  - Steam and H_2 generation from melt-coolant interactions
  - Airborne debris particles directly heat containment atmosphere



Low Pressure Melt Release

- Debris "pours" out of RV lower head onto containment floor (cavity)
- May interact with water (if present) and quench
- Beginning of core-concrete interactions

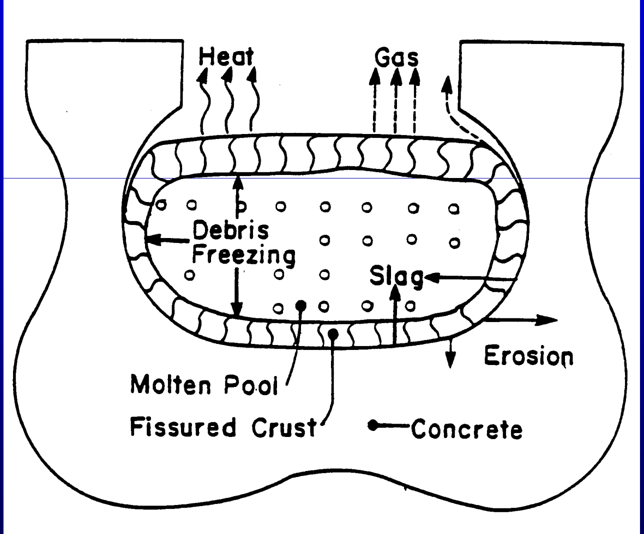


Molten Core-Concrete Interactions (MCCI)

- Exothermic chemical reactions between core debris and concrete
  - Large quantities of gas generated by concrete decomposition
  - Physical and chemical interactions between concrete decomposition gases and core debris release non-volatile fission products
  - Vertical and horizontal erosion of concrete basemat destroys containment foundation

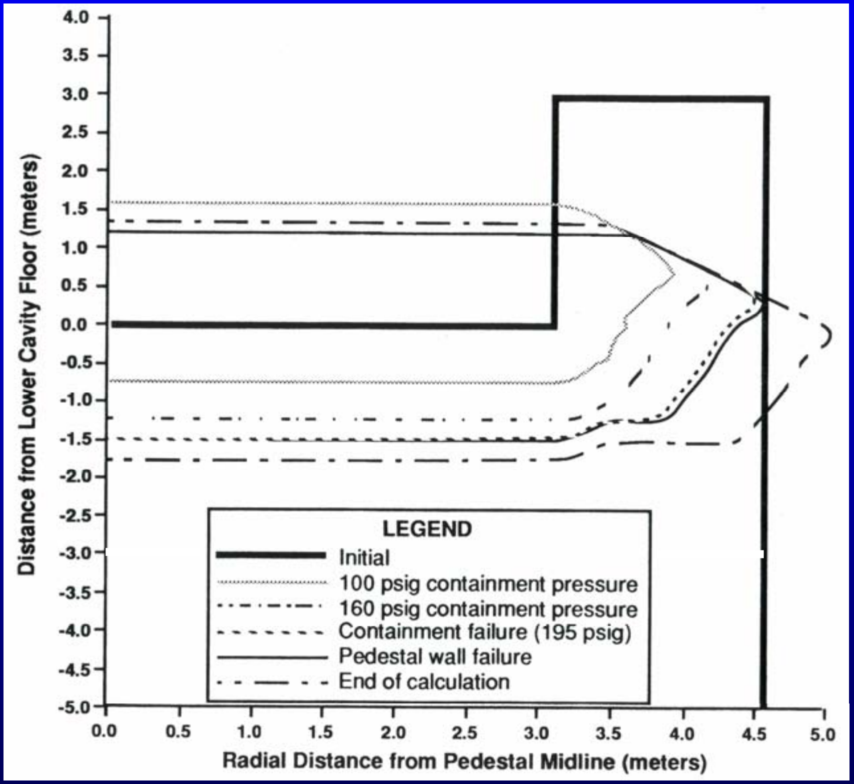
Property	Basalt (Siliceous) Concrete	Limestone Concrete
Solidus Temp (C)	1350	1420
Liquidus Temp (C)	1650	1670
Ablation Temp (C)	1450	1500

* Major components lost by decomposition: SiO_2, CaO, MgO



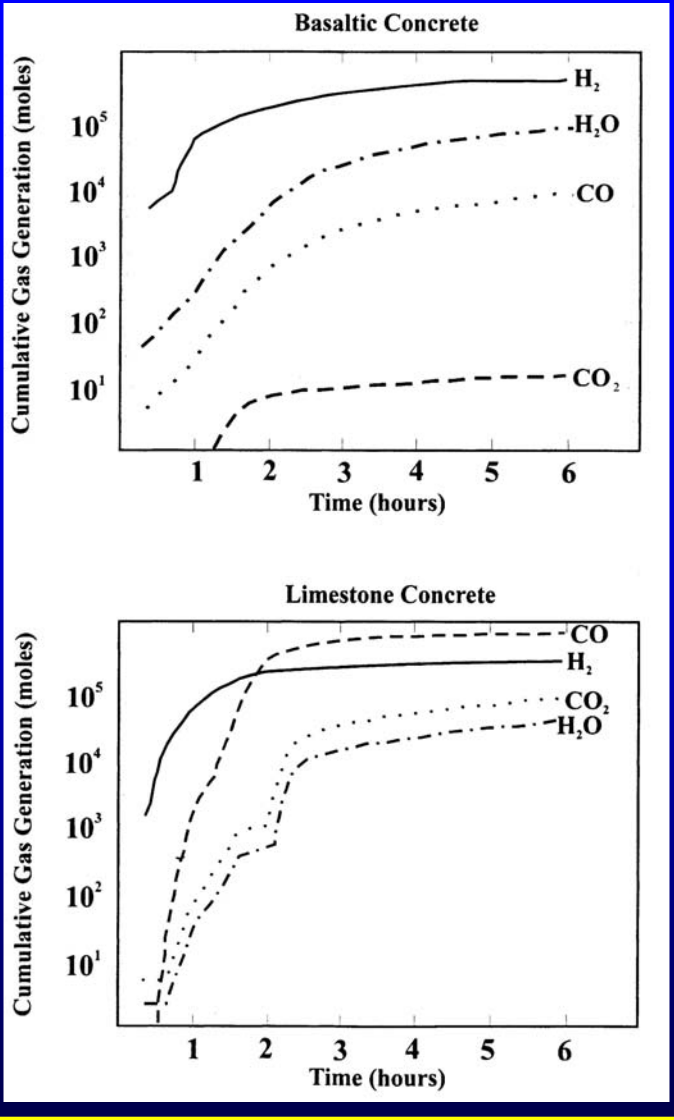
Effects of MCCI on Accident Progression

- **Containment Structure Penetration**
- **High local atmosphere temperatures**
  - **Potential for local heating of containment pressure boundary**
- **Non-condensible gas generations**
  - **Significant contributor to containment pressure late in an accident sequence**



Gas Generation from MCCI

- Quantity of gases released during MCCI depends on initial concrete composition
  - Resulting partial pressure of water vapor higher in Basaltic concretes
  - CO as contributing flammable gas more significant in Limestone concrete



Major MCCI Research Programs

Test Program	Institution	Type of Concrete	Melt Composition
BETA	**KfK/FRG**	**●Siliceous** **●Limestone/ Common Sand**	**Iron/Alumina and Steel/Oxide + Zr**
TURC	**SNL/USA**	**●Limestone/ Common Sand**	**$UO_2 – ZrO_2$ + Zr** **Stainless steel** **UO_2-ZrO_2**
SURC	**SNL/USA**	**●Limestone/ Common Sand** **●Siliceous**	**$UO_2 – ZrO_2$ + Zr** **Steel + Zr**
ACE	**ANL/USA**	**●Limestone/ Common Sand** **●Siliceous**	**UO_2, ZrO_2 etc. + Steel, Zr**
MACE	**ANL/USA**	**●Limestone/ Common Sand** **●Siliceous**	**$UO_2 – ZrO_2$ + Zr**

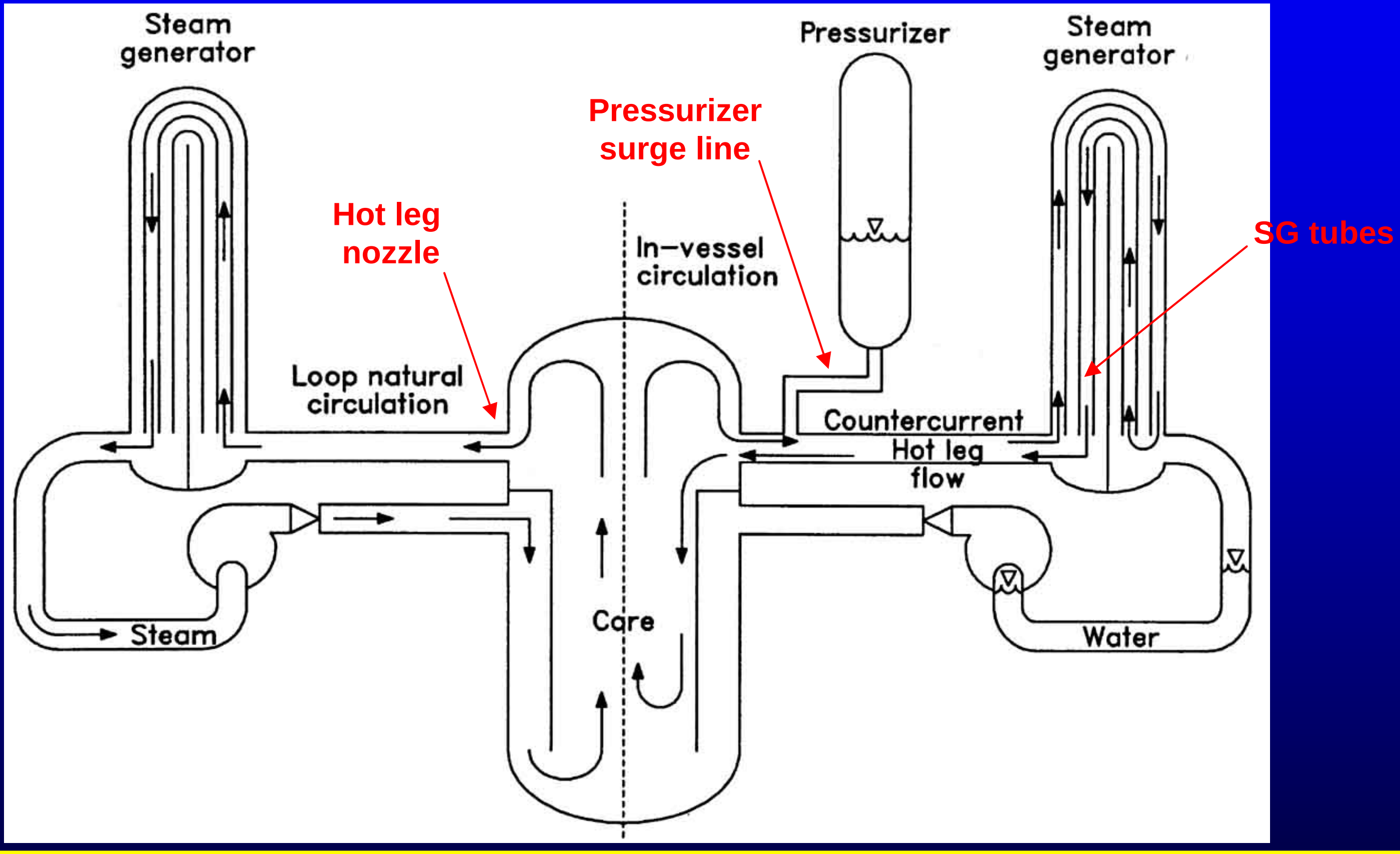
Other Severe Accident Phenomena of Interest to Level 2 Analysis

- Creep rupture of reactor coolant system pressure boundary during in-vessel core degradation
- Hydrogen combustion in containment
- Steam explosion

Induced Rupture of the Reactor Coolant System During Core Degradation

- Hot gases released from top of core during early phases of fuel damage
- Natural circulation flow patterns created
  - Hot gases cooled by transferring heat to colder surfaces
- Excess heating of pressure boundary can lead to creep rupture
  - Locations of concern: hot leg nozzles, pressurizer surge line, steam generator tubes

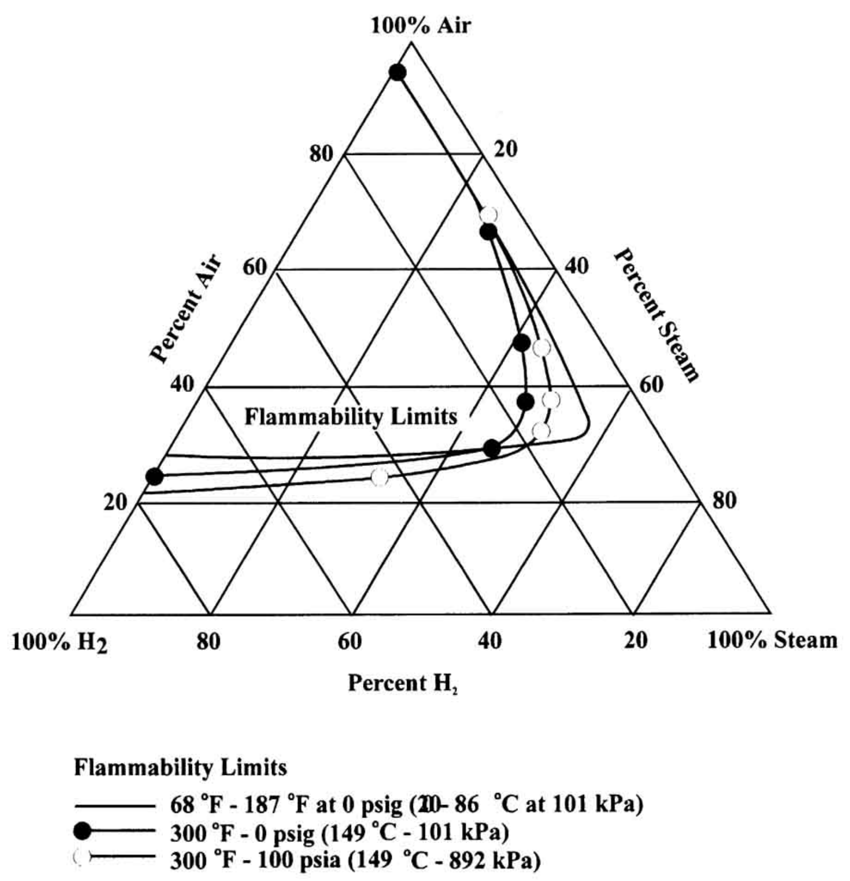
Natural Circulation Flow Patterns During In-vessel Core Degradation

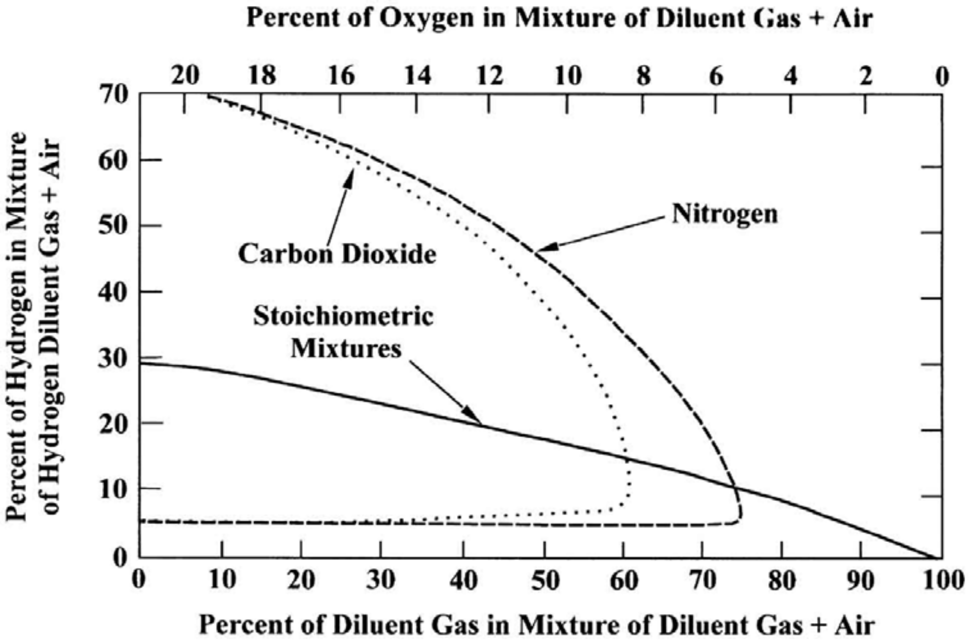


Hydrogen Combustion in Containment

- Hydrogen released to containment from RCS
  - Transients: Pressurizer relief line (via quench tank)
  - LOCA: pipe break
- Hydrogen mixes with containment atmosphere
  - Distribution and local concentrations depend on flow field in containment
    - Pressure-drive flow among neighboring compartments
    - Natural convection
    - Ventilation system
- Combustion possible when local conditions exceed flammability criteria

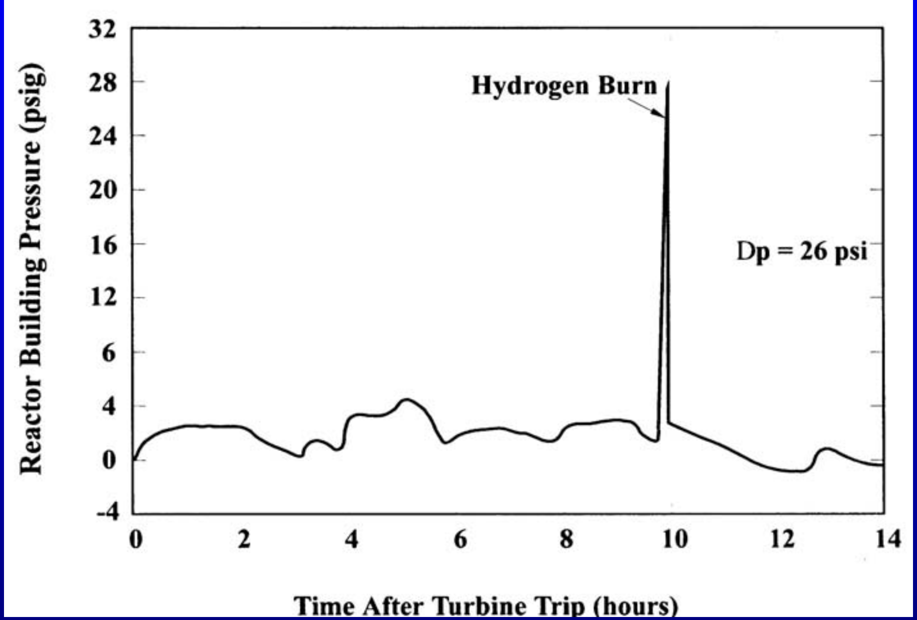
Hydrogen Flammability Criteria





Effect of Hydrogen Burns on Accident Progression

- **Combination of high "base" pressure and hydrogen burn can lead to short-lived pressure loads that challenge containment capacity**
- **In a PWR containment, this usually requires flammable mixture in a very large volume.**

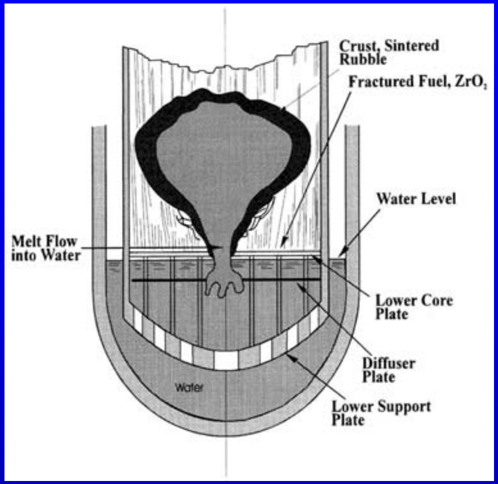


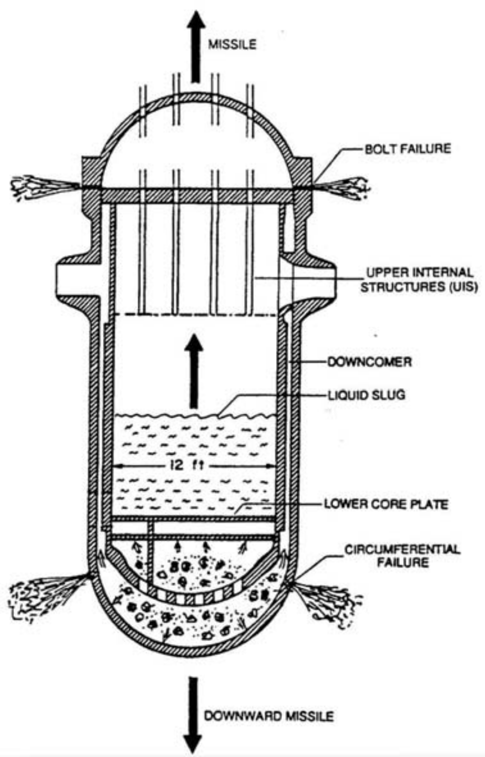
Hydrogen burn during the TMI-2 accident

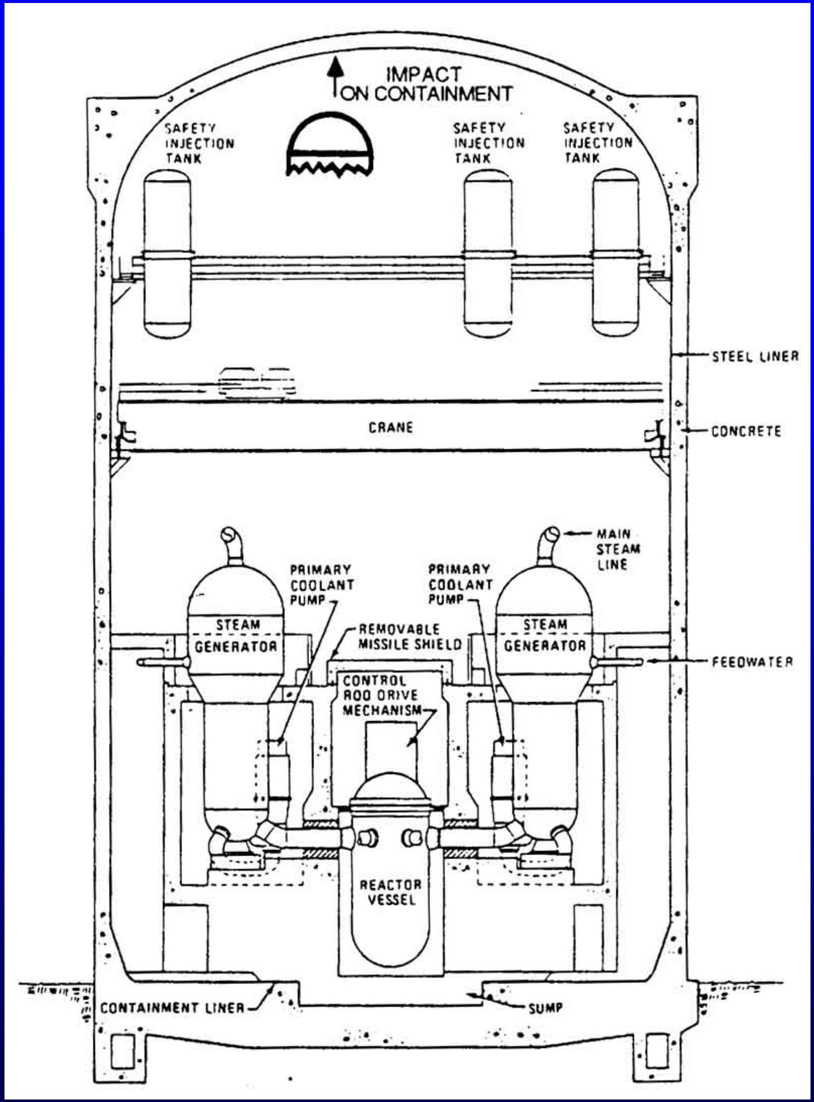
Steam Explosion

- A dynamic process that can occur when a large quantity of molten core debris relocates into a pool of water
  - In-vessel: Pour of molten material into RV lower head (Phase 2)
  - Ex-vessel: Low-pressure pour of melt into reactor cavity (Phase 3)
- A steam explosion requires four sequential phases of melt-coolant interaction to occur:
  - Course mixing of melt and water
  - Collapse of vapor film at heat transfer interface causing an accelerated energy release (“trigger”)
  - Propagation of the pressure pulse through the mixture to form a shock wave
  - Outward expansion of the shock wave (damage mechanism)

In-vessel Steam Explosion

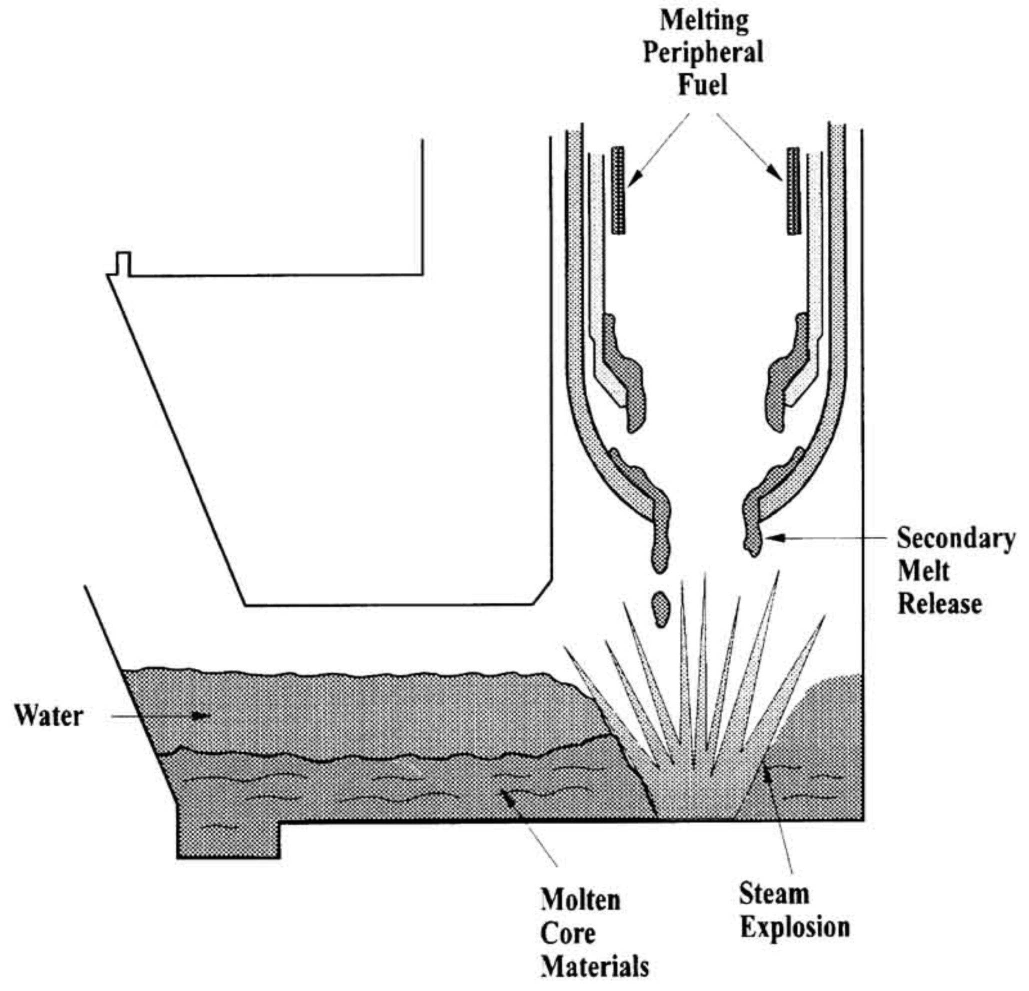






Ex-vessel Steam Explosion

- Pour of molten debris from reactor vessel into reactor cavity (full of water)
- Containment failure mechanism not clear for PWRs
    - Explosion not confined (no obvious missile)
    - Cavity walls strong



Steam Explosion a Low-Probability Event in Most Level 2 PRAs

- In-vessel steam explosion first identified in WASH-1400 (1975) as a potential containment failure mechanism (α-mode)
  - Low probability (1.E-2), but high uncertainty
  - Results of research since WASH-1400 has reduced probability and uncertainty
    - Steam Explosion Review Group (1985): 1.0E-3 to 1.0E-4
    - Steam Explosion Review Group (1995): ‘physically unreasonable’
- Ex-vessel steam explosion considered a possible failure mode for some BWR designs

Summary

- Severe accident phenomena span a wide range of technical disciplines
  - Thermal-hydraulics - Heat transfer
  - Fuel behavior - Material science
  - Reaction chemistry - Structural analysis
- General knowledge of fundamentals needed to conduct a rigorous Level 2 analysis
- Uncertainties remain in many areas, but sufficient knowledge is available to perform a credible assessment of accident progression for most sequences.