SAND2018-2625PE

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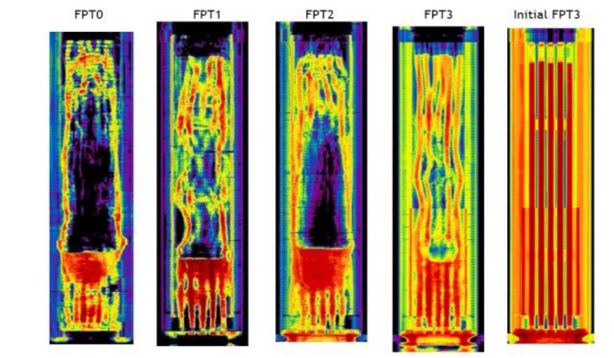

Severe Accident Phenomena

Presented at the PWR Owners Group Meeting

Denver, Colorado March 26-27, 2018

KC Wagner, Severe Accident Analysis Department

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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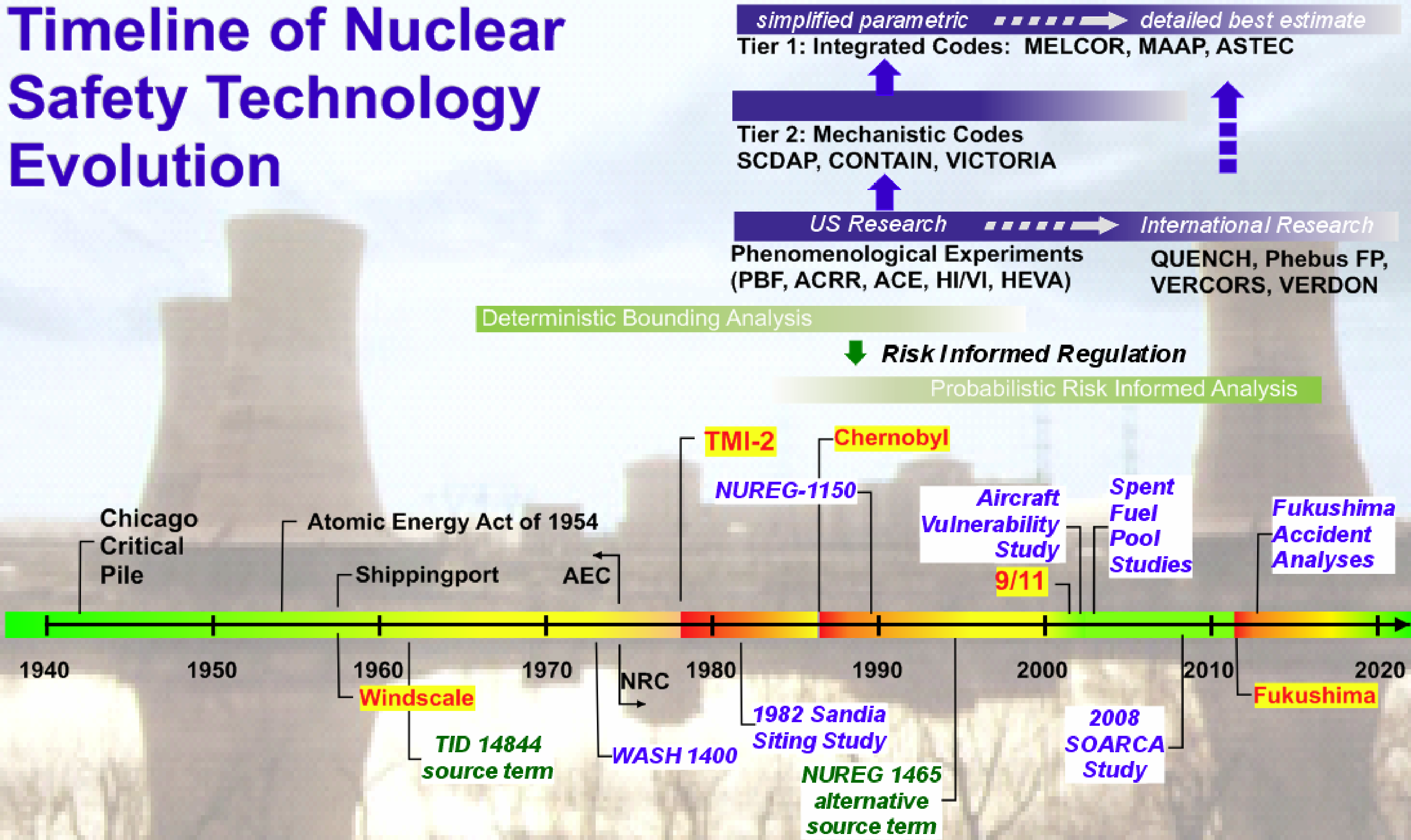
Timeline of Nuclear Safety Technology Evolution



Nuclear Power Outlook

- Optimistic
- Guarded
- Pessimistic

Emerging Issues.....

Fukushima Responses

SBO, Filtered Venting, Hydrogen control

multi-unit accidents/source terms, SAMG

Interim and dry storage

Aging of the fleet

Security and Cyber

Sandia Pioneered Research into Severe Accident Phenomena

Molten Core/Concrete Interactions - China Syndrome

MELT EXPULSION FROM A REACTOR CAVITY. This test involved 80 kg of melt expelled into a reactor cavity model from a vessel pressurized to about 80 bars.

Direct Containment Heating Experiments

Steam explosion research

Containment response to severe accident loads

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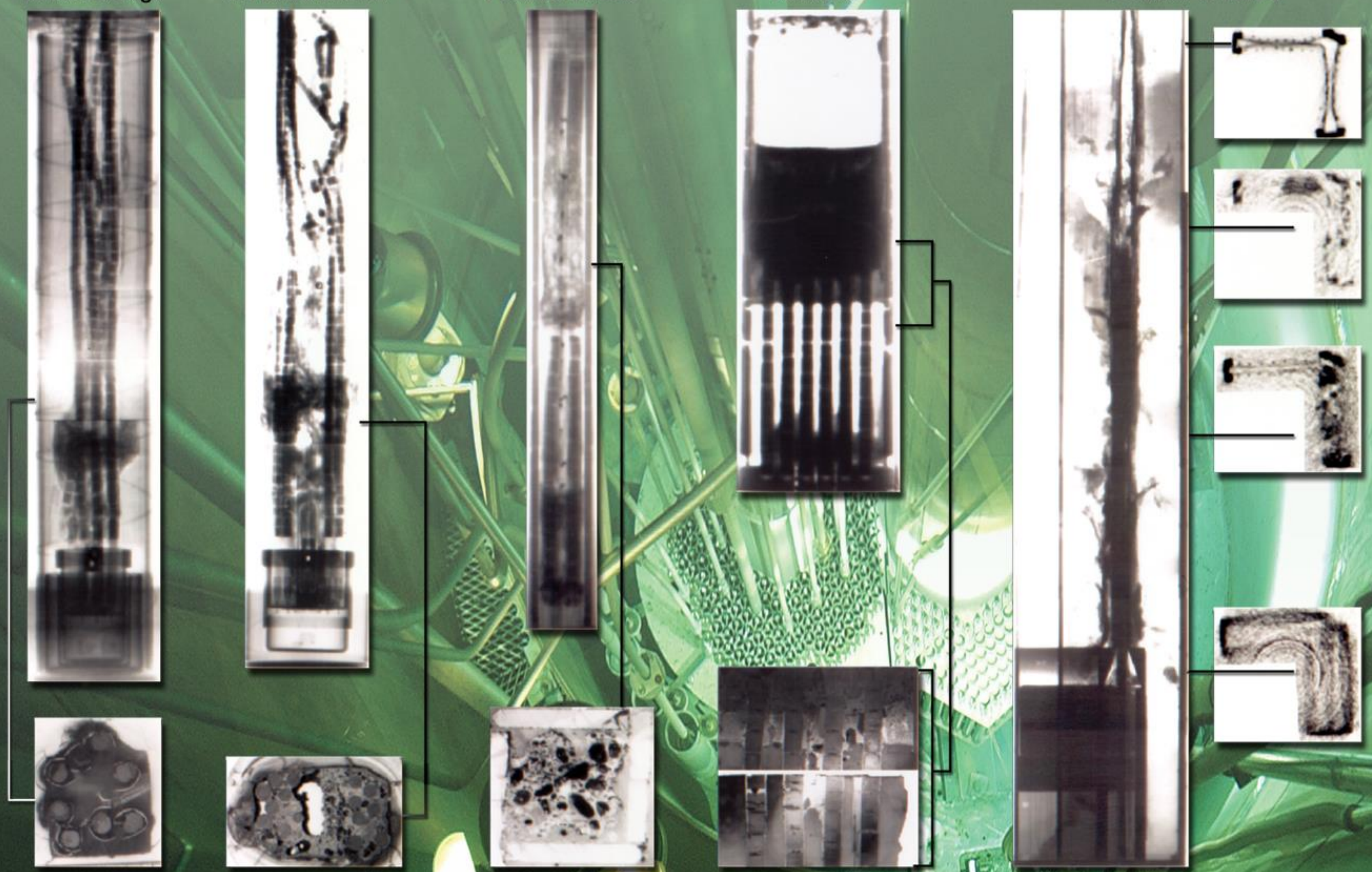
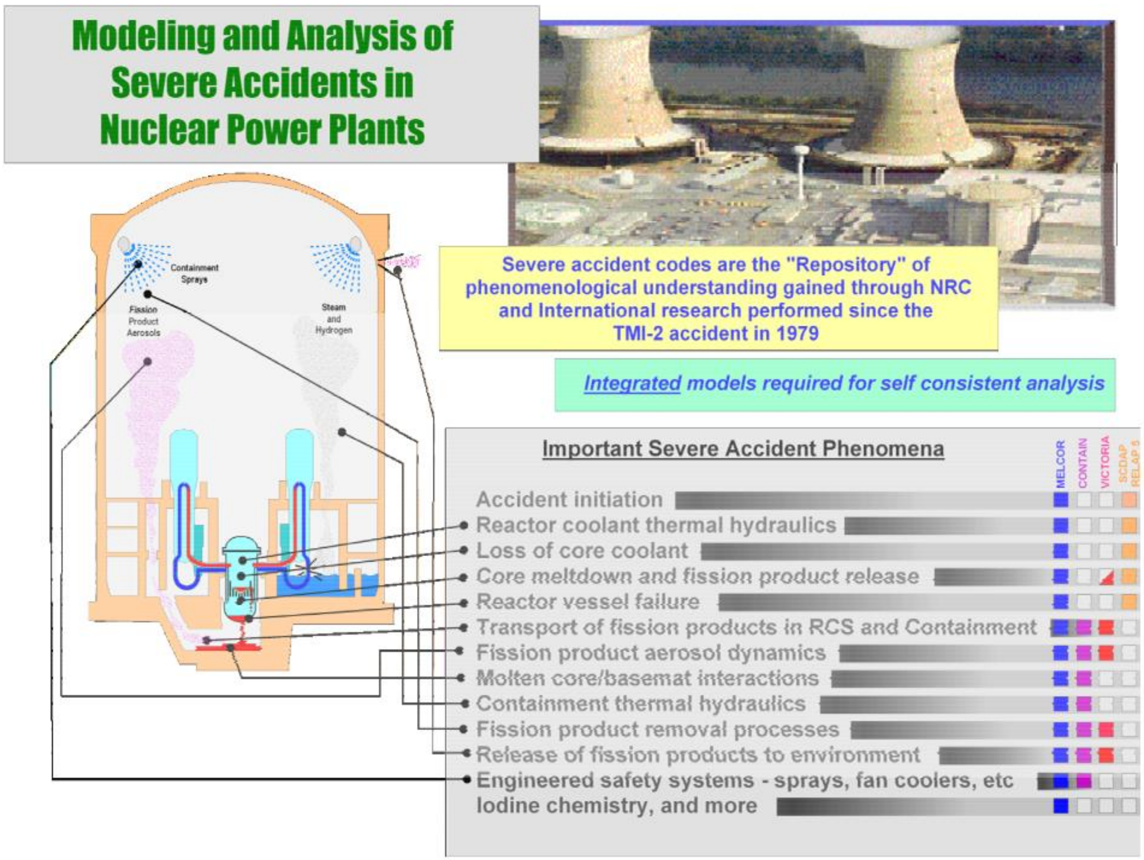
History of Core Melt Progression Research at Sandia

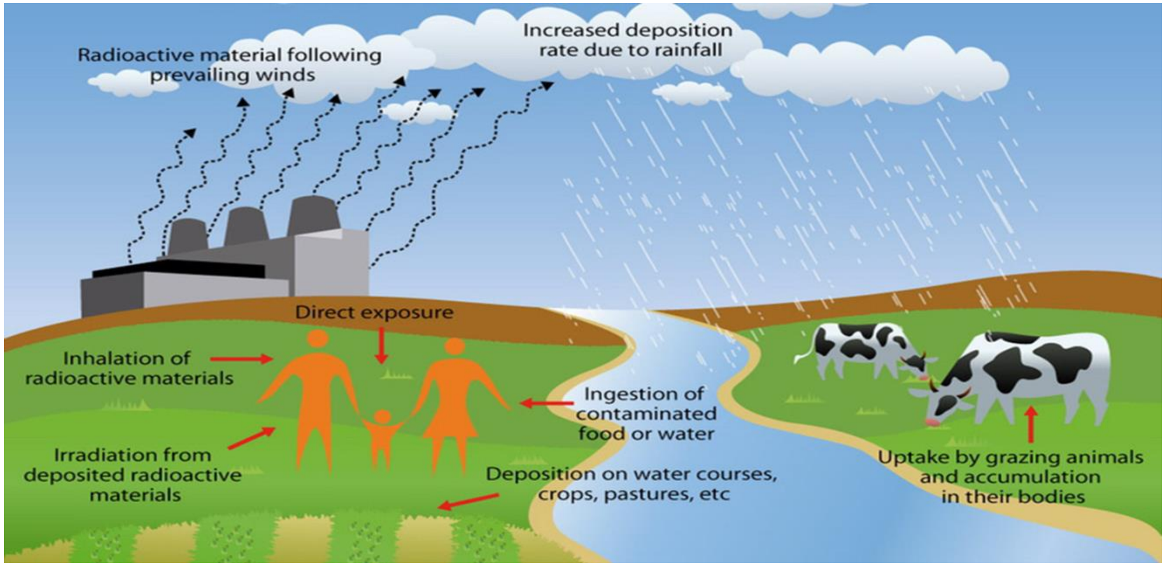


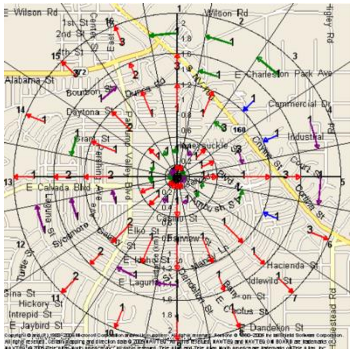
MELCOR – Severe Accident Analysis Code

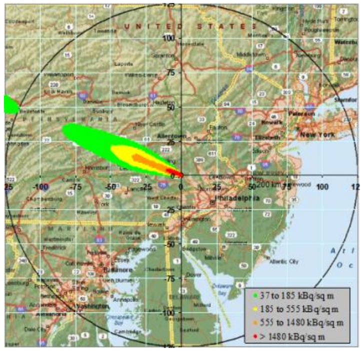


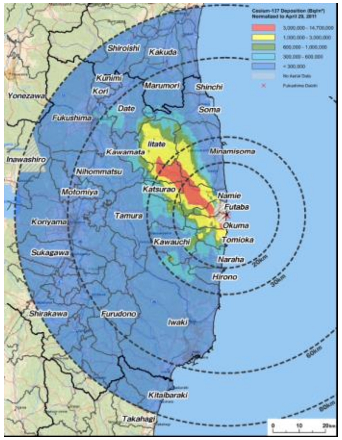
- Started in 1982 as integrated replacement for Source Term Code Package
- System level plant model of Nuclear Power Plant
- Emphasis on “best estimate”
- Repository of knowledge for future generations
- Global standard used internationally in over 31 nations
- Evolves to meet emerging regulatory issues

MACCS – MELCOR Accident Consequence Code Suite



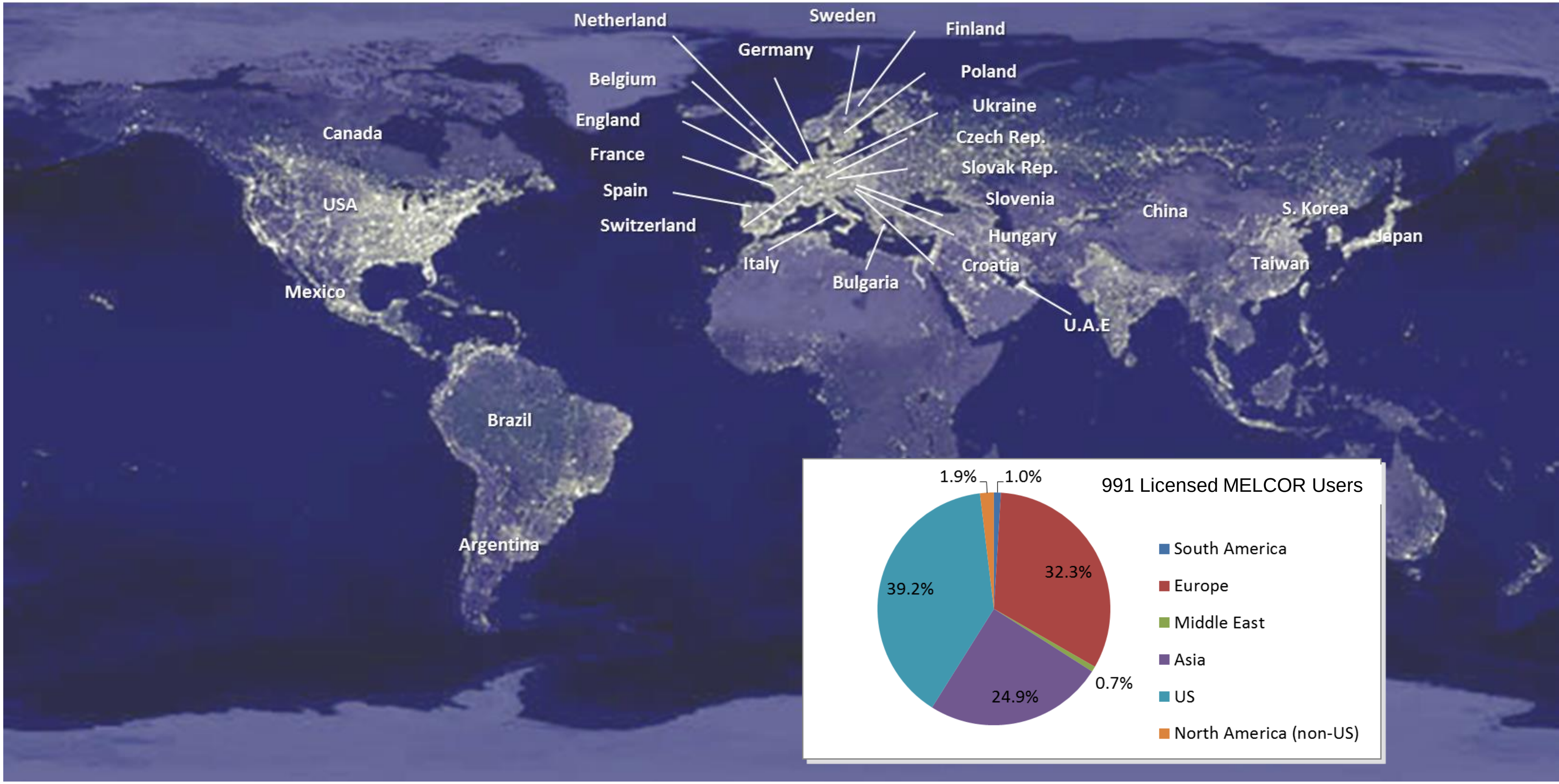






- MACCS imports source term information from MELCOR
- Calculates atmospheric transport and deposition (fallout and rain)
- Accounts for protective measures and evacuation
- Estimates health effects
  - Prompt and latent
- Estimates economic effects
  - Land contamination

MELCOR and MACCS are Used in 31 Nations Around the World



Stages of Reactor Accidents

- ***Accident initiation* and discharge of coolant to 'top of active fuel'.**
- **Stages:**
  - **1. boildown of coolant and fuel heatup**
  - **2. clad balloon and rupture**
  - **3. clad oxidation and temp. transient**

    DBA & SA

  - 4. clad melting and fuel liquefaction
  - 5. candling and accumulation of core debris
  - 6. relocation of debris from core region
  - 7. debris interactions with vessel

    SA

Cladding Oxidation by Steam

- **Becomes significant when peak fuel temperature reaches about 1000°C**
- **Reaction:**

$$Zr + 2H_2O \Rightarrow ZrO_2 + 2H_2 + heat$$

- **ΔH_{rxn} = 6.5 MJ/kg_{Zr} (Exothermic) (TNT = 4.6 MJ/kg)**
- **Reaction rate increases rapidly with temperature**
- **Oxidation reaction is autocatalytic**
  - **Exothermic oxidation increases clad temperature**
  - **Increasing clad temperature increases oxidation rate**
- **Oxidation limited by steam availability and by melting and relocation of Zr**
- **Significant quantities of hydrogen produced**

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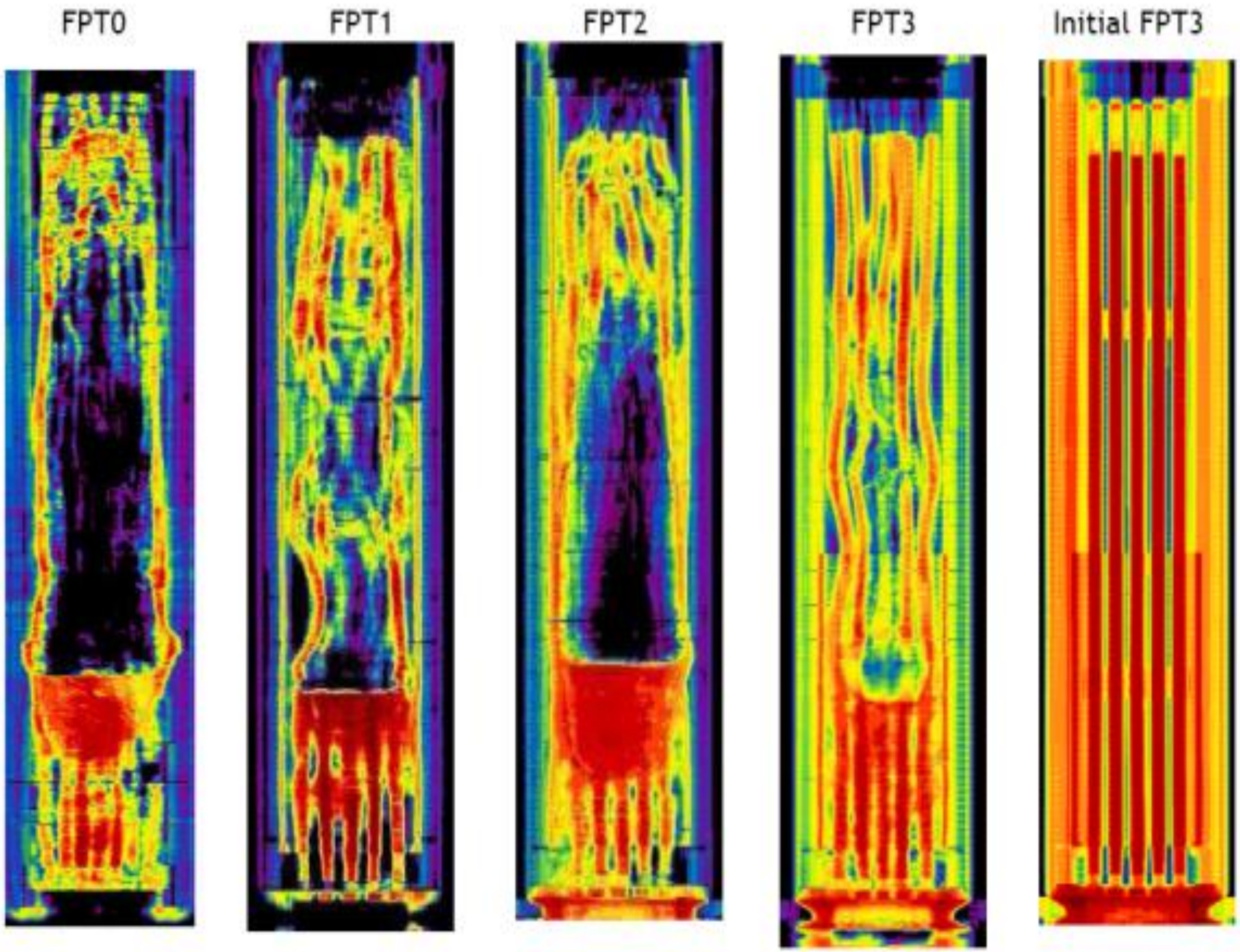
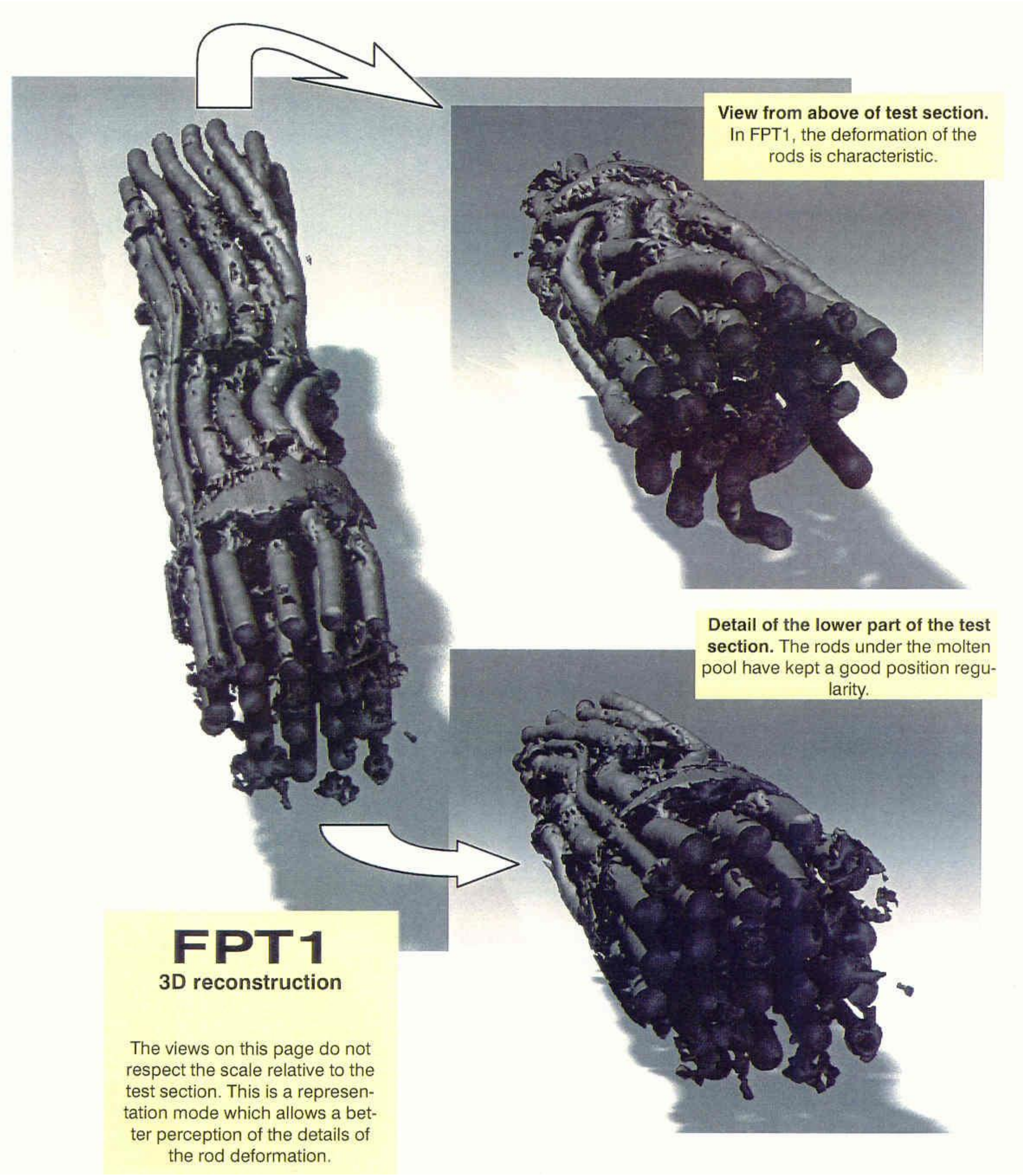
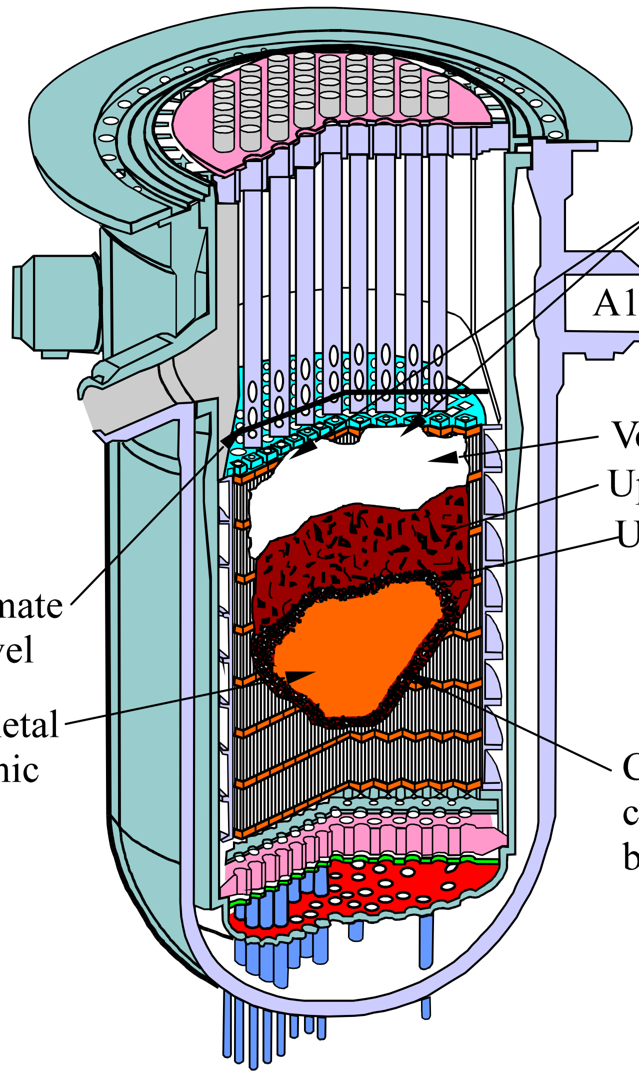
Examples of Fuel Degradation Observed in PHÉBUS-FP Tests



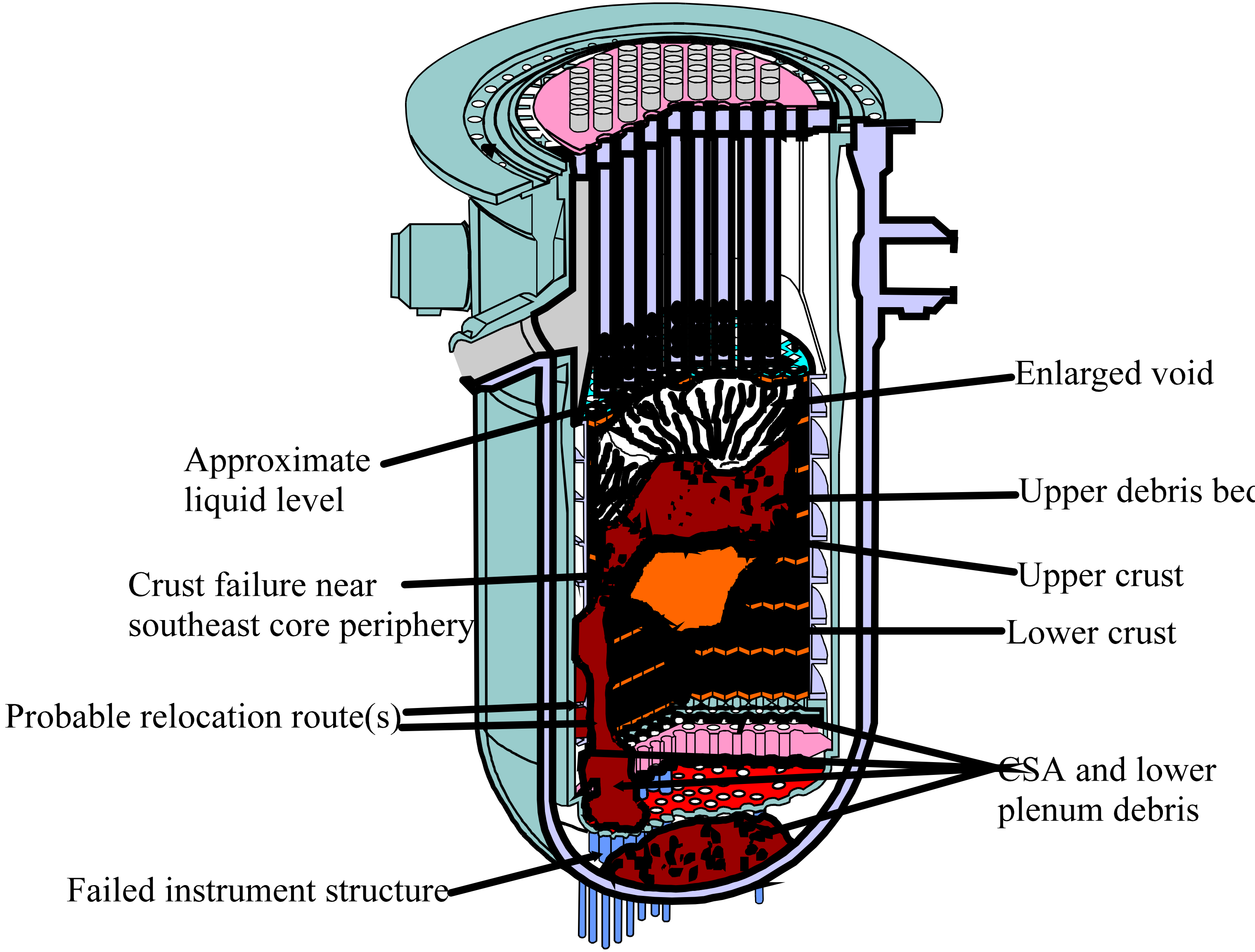
Oxidation Transient Drives Fuel Damage



- Tomography on FPT-1 bundle after fuel damage transient
- Zr oxidation drives severe damage
- Also drives thermal release of fission products



Hypothesized TMI-2 core configuration at 224 minutes (just prior to major core relocation)



Hypothesized TMI-2 core configuration after melt relocation

Lower Head Failure

- At elevated pressures, head failure by creep rupture likely if debris not cooled
  - Molten debris could be expelled under pressure
    - Direct containment heating
    - Fuel coolant interactions if cavity is flooded
- If vessel is depressurized, head failure by melting and loss of strength is likely if debris not cooled
    - Fuel coolant interactions can happen if cavity is flooded
    - Core-concrete interactions when core melt contacts cavity floor

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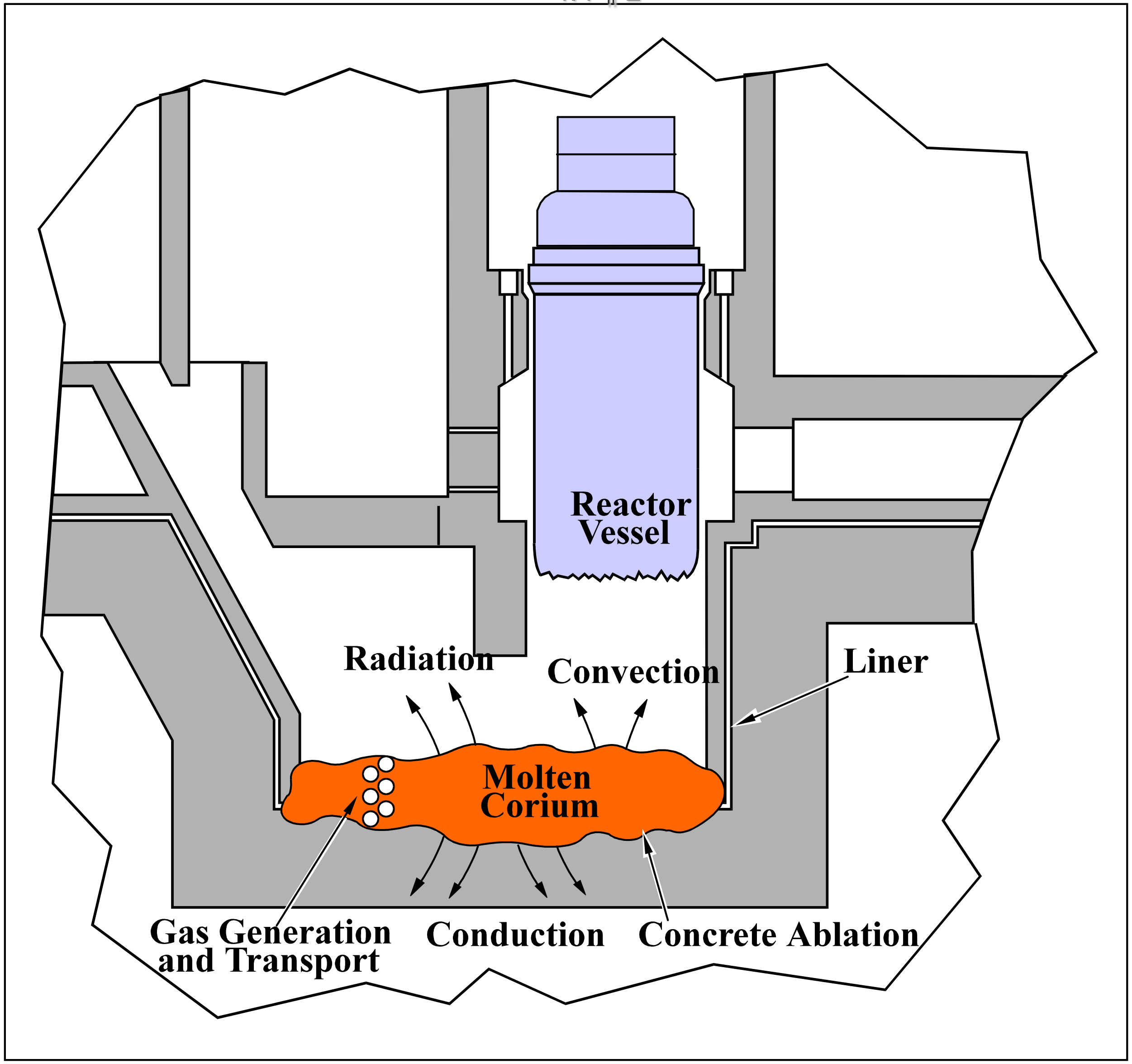
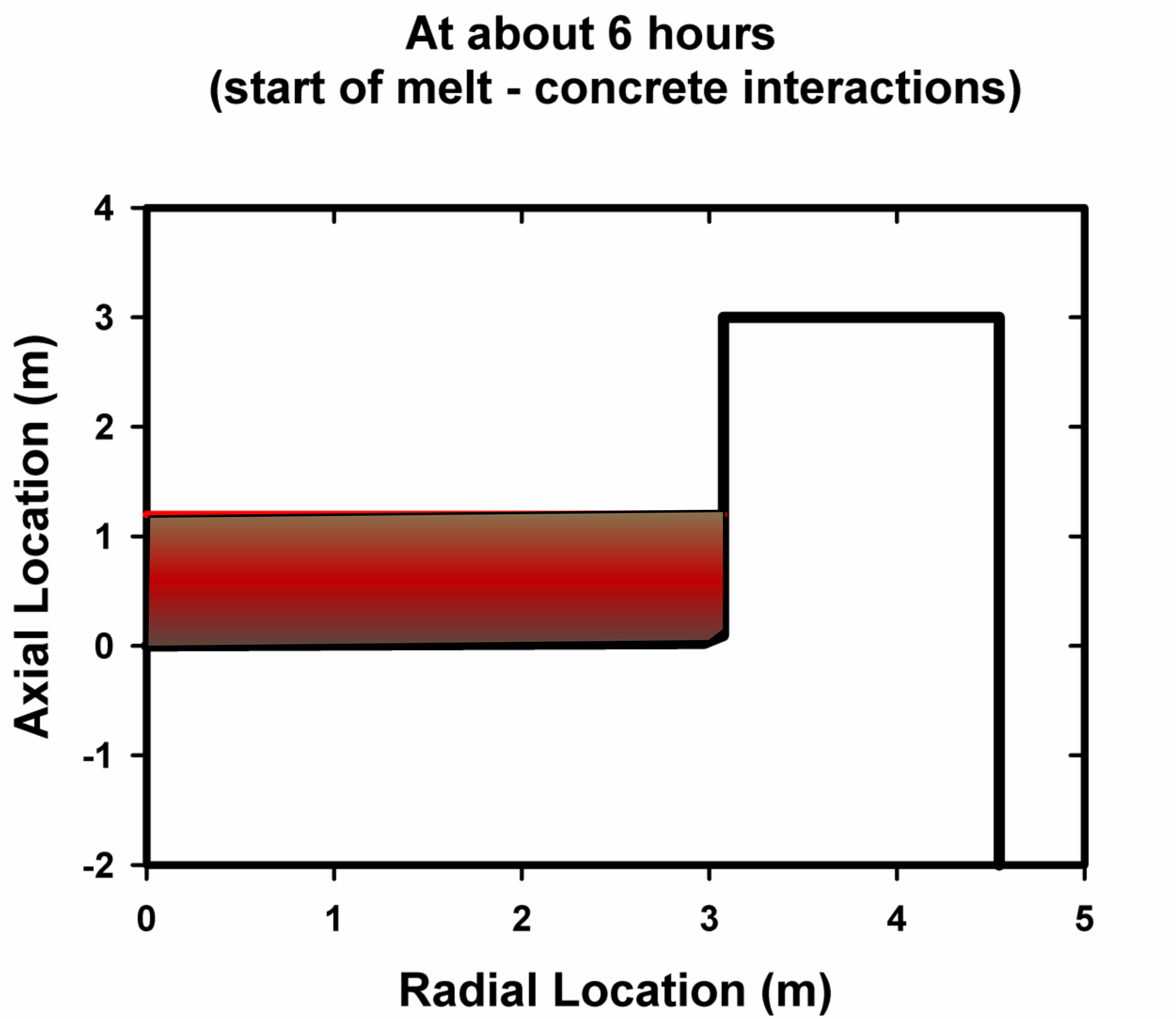


Thermal aspects of core-concrete interactions

- MCCI experiment
- Decay heat liberates water from concrete
- Metals (Zr and steel) oxidize and produce H_2 and CO
- Exothermic energy from chemical reactions

RSC: 1/02

Sandia Experiments on High Temperature Melts Poured into Concrete Crucibles


At about 6 hours
(start of melt - concrete interactions)
4
3
2
1
0
-1
-2
0
1
2
3
4
5
Axial Location (m)
Radial Location (m)

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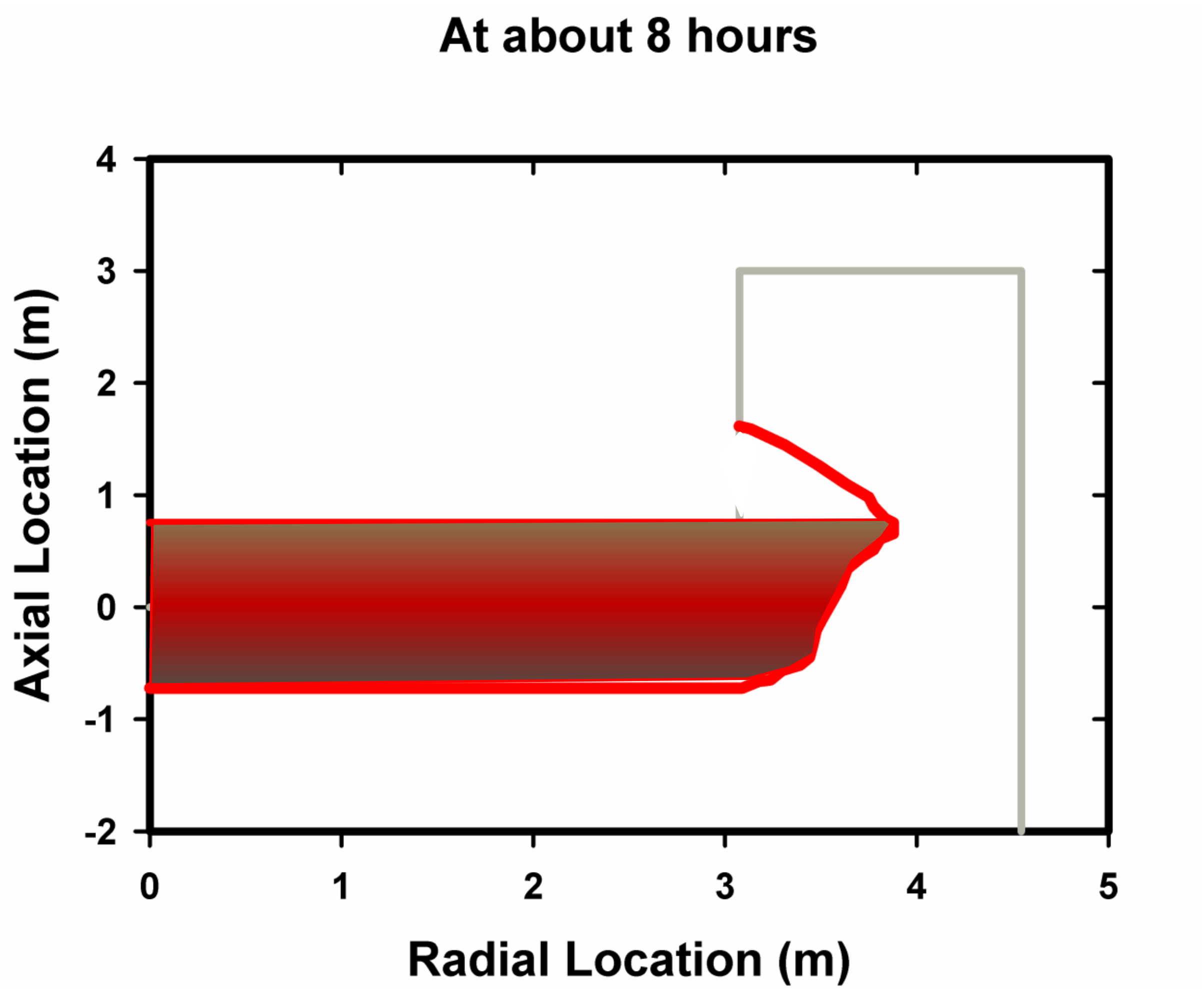
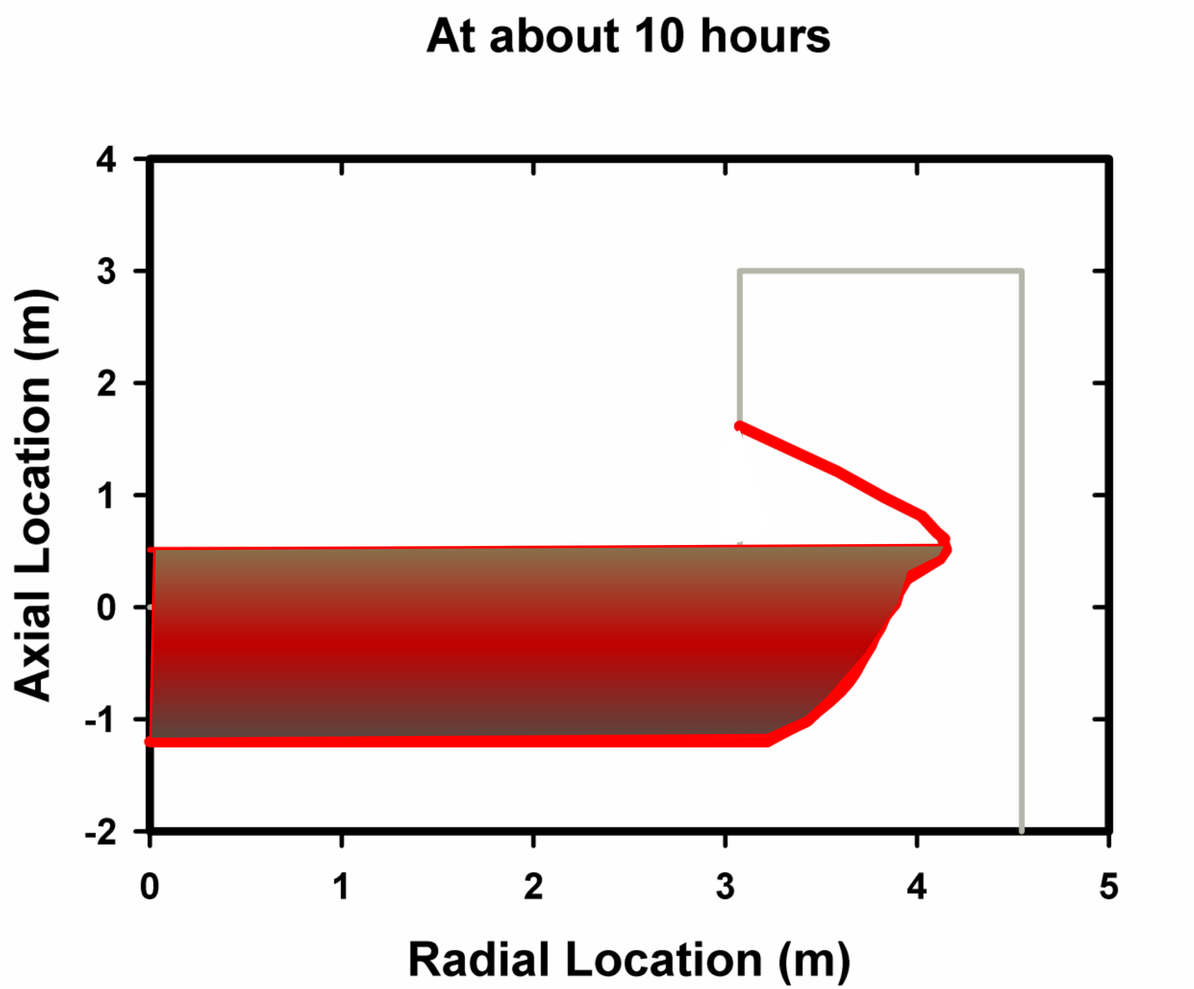
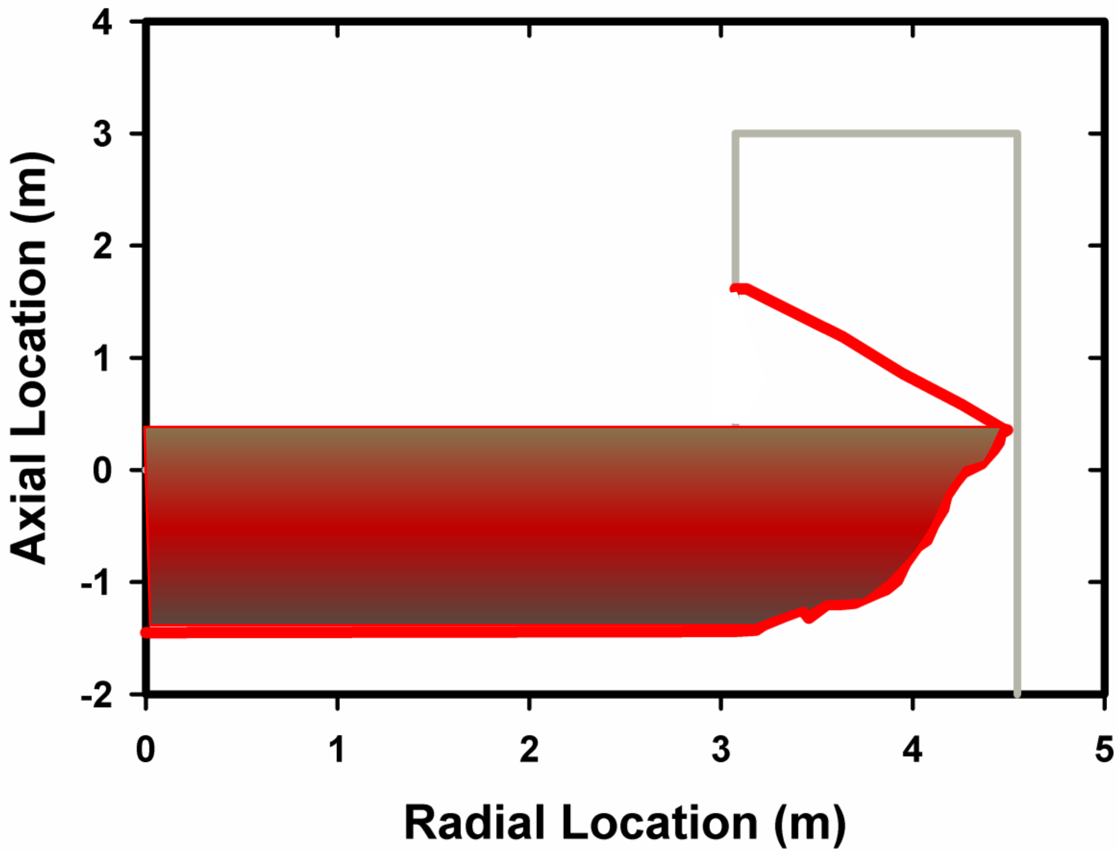
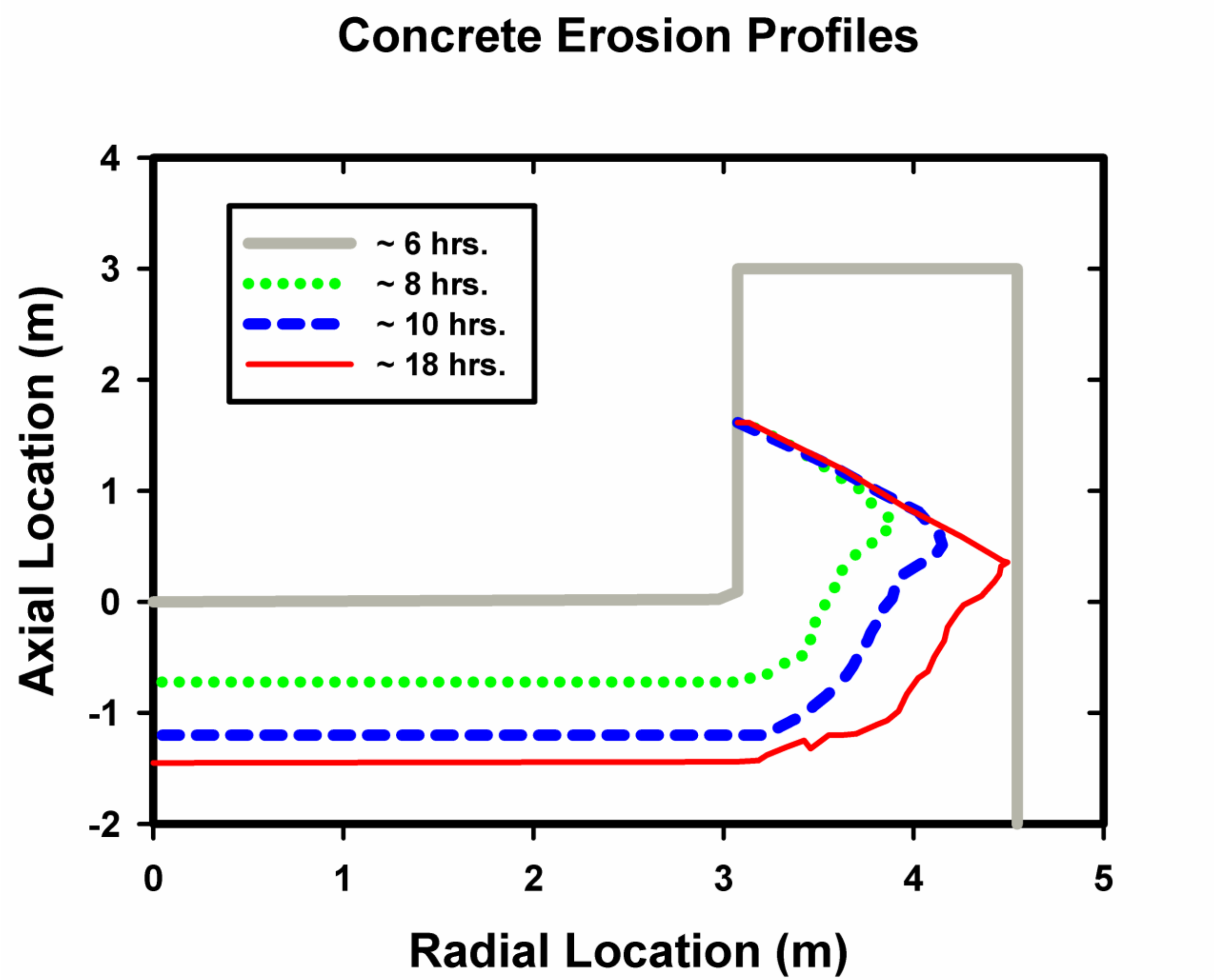



At about 10 hours
Axial Location (m)
4
3
2
1
0
-1
-2
0
1
2
3
4
5
Radial Location (m)

At about 18 hours




Concrete Erosion Profiles
~ 6 hrs.
~ 8 hrs.
~ 10 hrs.
~ 18 hrs.
Axial Location (m)
Radial Location (m)
4
3
2
1
0
-1
-2
0
1
2
3
4
5

Combustible Gas Generation

- Water and carbon dioxide are released from concrete
- Oxidation of core debris yields hydrogen and carbon monoxide (both combustible)

  $Zr + 2\,H_2O \rightarrow ZrO_2 + H_2 + \text{heat}$

  $Zr + 2\,CO_2 \rightarrow ZrO_2 + CO + \text{heat}$

  $Fe + H_2O \rightarrow FeO + H_2$

  $Fe + CO_2 \rightarrow FeO + CO$

  Cr from stainless steel also quite reactive
- Large quantities of combustible gas can be generated
- Combustible gases may burn above the molten pool or may accumulate in containment
- Combustible gases contribute to total pressure in containment
  - Burns or static overpressure can challenge containment

Deflagration versus Detonation

	Deflagration	Detonation
Ignition	**milliJoules** **empirical flammability limits**	**kiloJoules** **(or deflagration to detonation transition)**
Propagation	**Conduction** **Subsonic** **1-1000 m/s**	**Shock Heating** **Supersonic** **1500-3000 m/s**
Loads & Structural Response	**Static,** **Thermodynamic Bound**	**Dynamic** **Shock Waves** **Hard to Model (3D)**

Hydrogen Combustion Can Threaten Containment or Auxiliary Buildings

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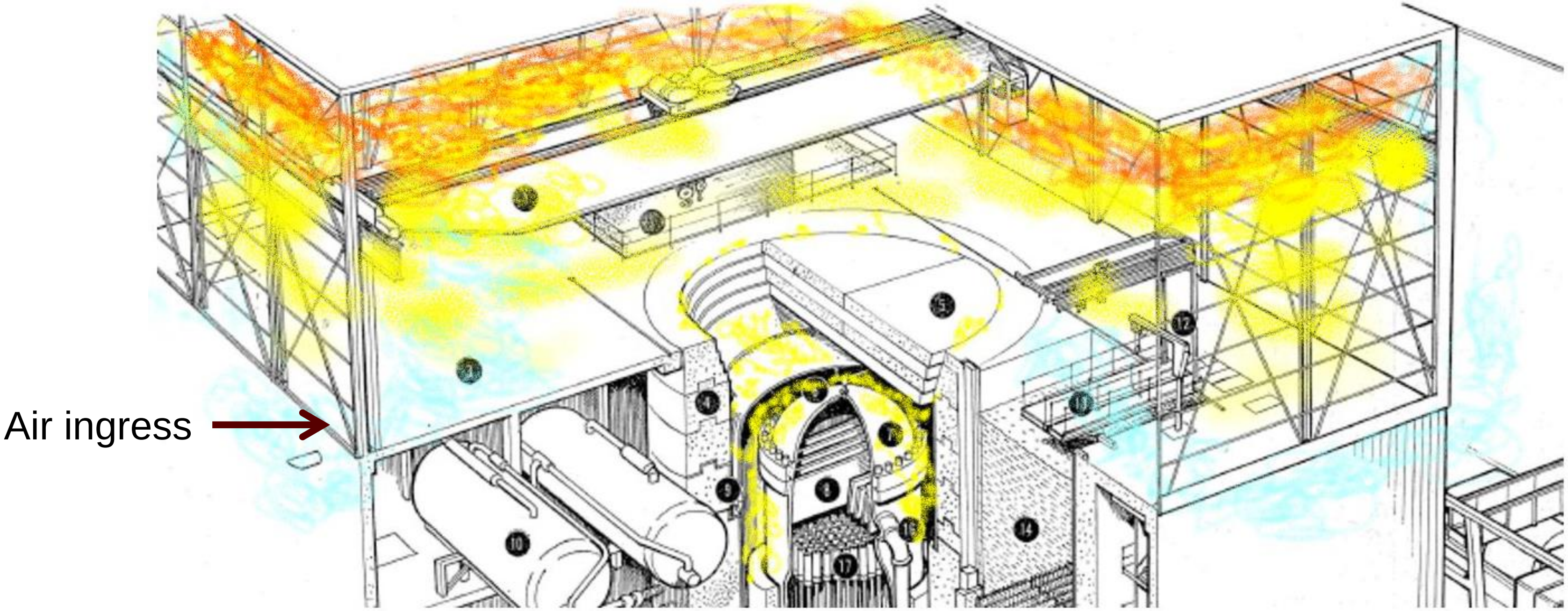
- Hydrogen combustion can challenge containment integrity by overpressure
- Detonations can produce much higher pressure loads
  - Hydrogen concentrations above 12-15%
- Hydrogen concentration can be controlled by
  - Igniters – burn hydrogen when flammable at 5-7% before detonable concentrations are attained
  - Hydrogen recombiners can passively recombine hydrogen and oxygen
    - What about sudden release of hydrogen from RCS failure ?
    - Containment de-inerting from operation of sprays ?

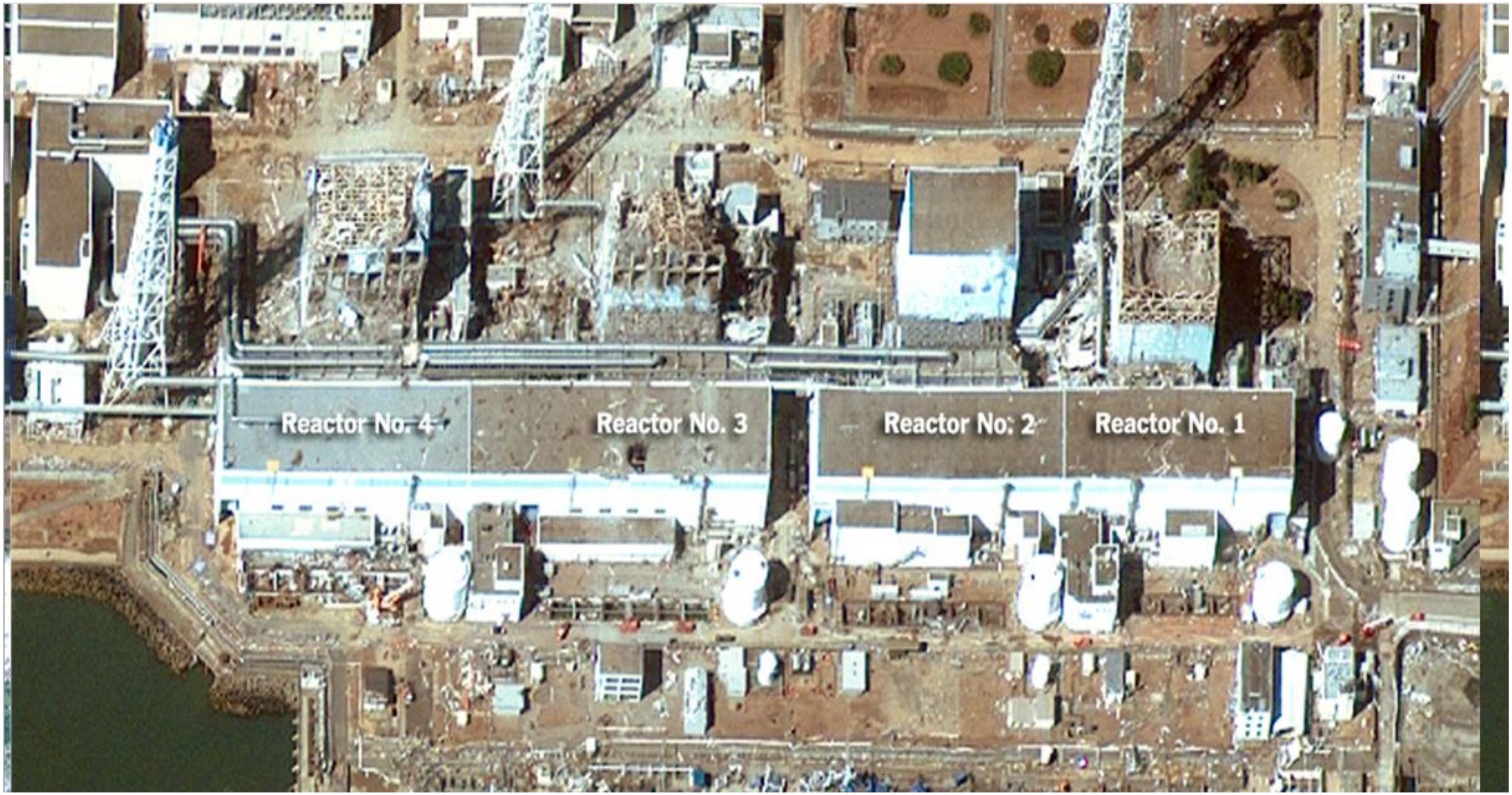
Combustible Conditions Follow PCV Venting in 1F1



- At around ~23 hours, steam and hydrogen leakage from PCV greatly reduced
  - Water injection was stopped
  - PCV was depressurized by operator venting action
- Continuing condensation without steam source….
  - Reduces steam molar fraction to below 50% in refueling bay, and
  - Produces partial vacuum that draws in outside air
- Air ingress and steam condensation leads to conditions favoring combustion
- Hydrogen stratification produces flammable or detonable concentrations of H_2/O_2

Unit 3 Hydrogen Explosion

Hydrogen Explosions

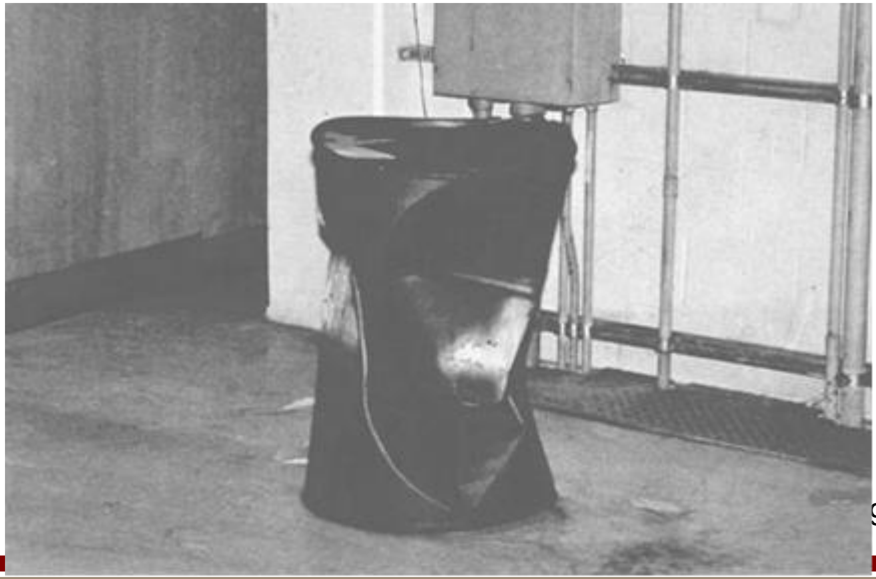


Containment Over-pressurization Led to Release of H2 into Buildings

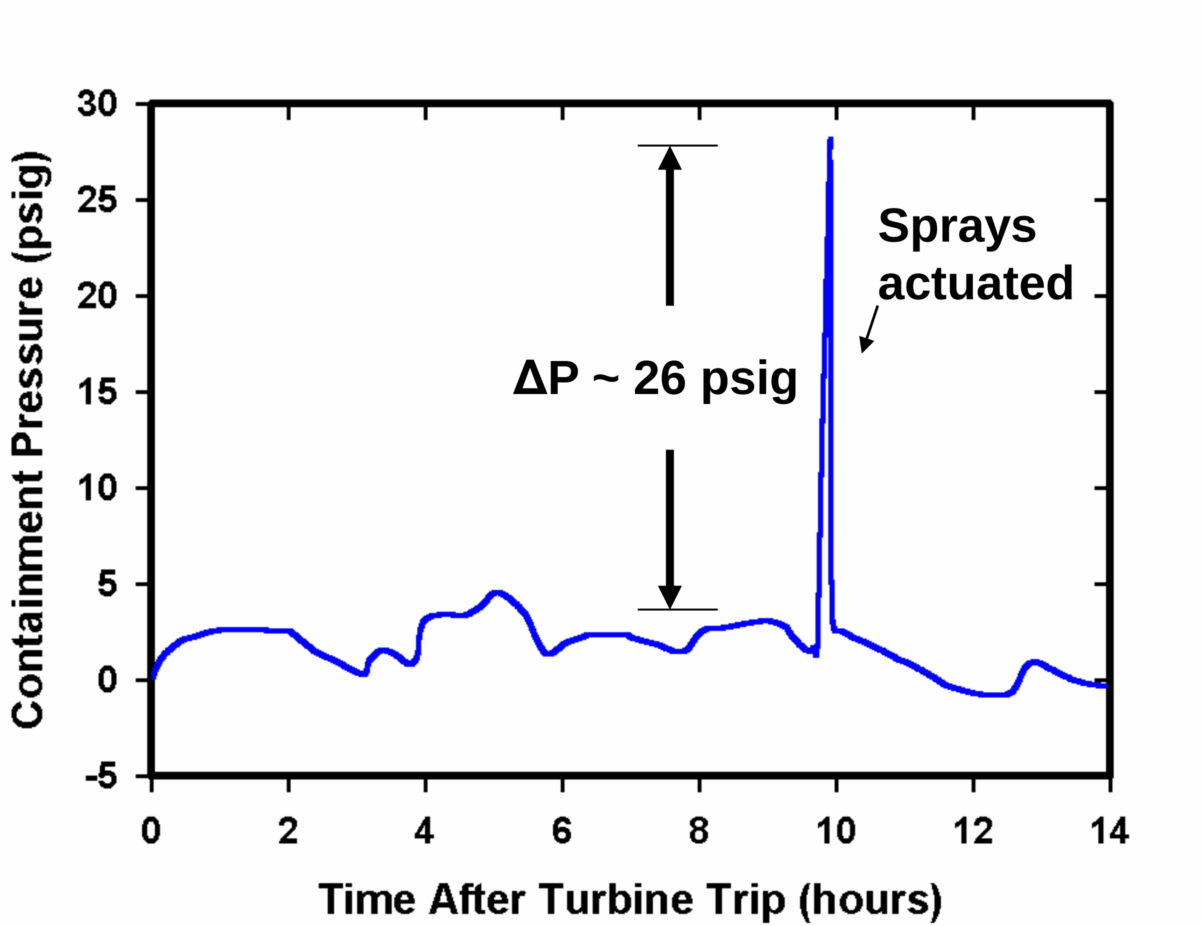
Combustion at TMI-2

Telephone in containment scorched in one area by H_2 combustion event.

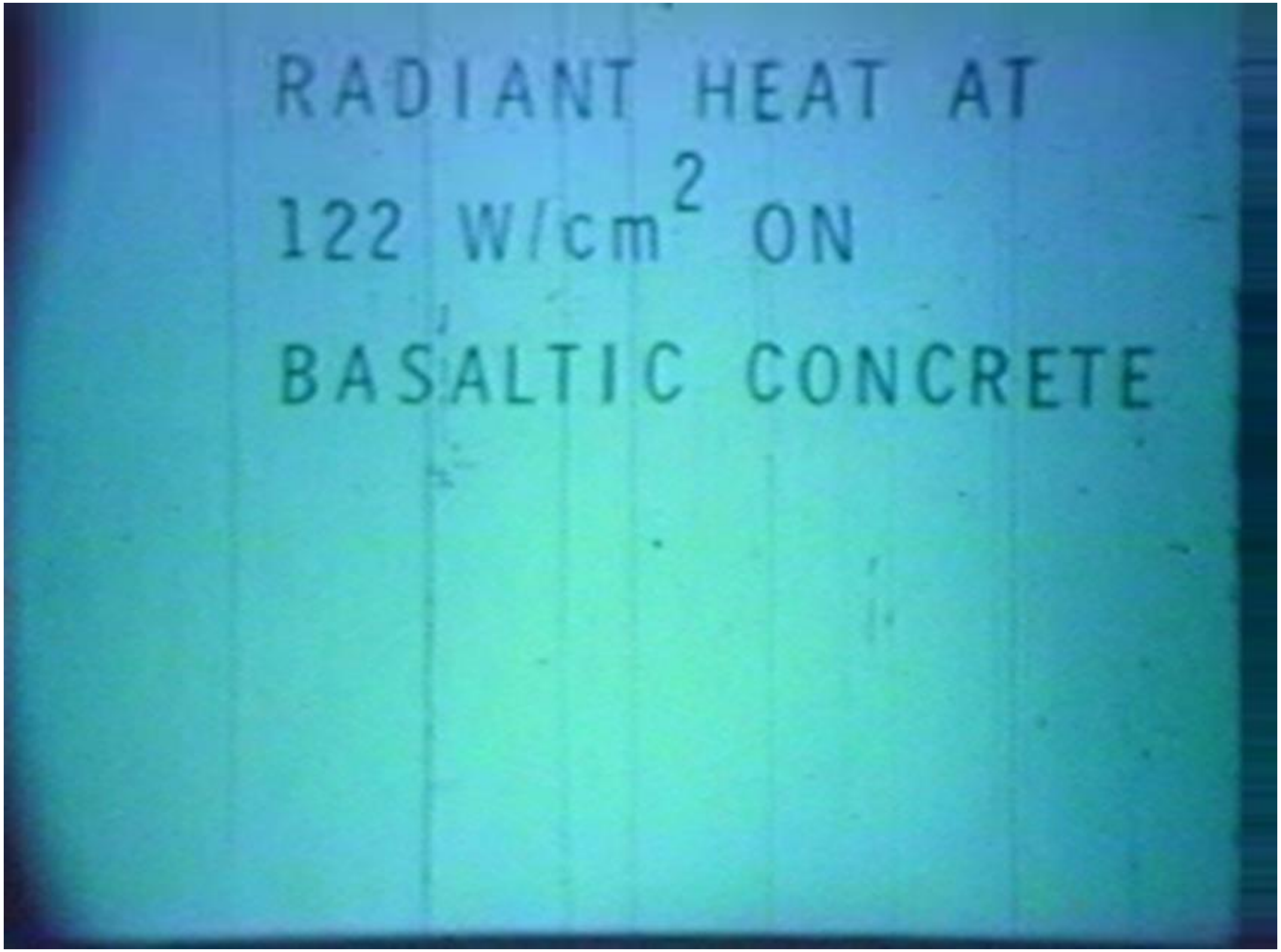
55 gal. drum collapsed by overpressure from the H_2 combustion event.



TMI-2 containment pressure versus time And the Hydrogen Burn



Concrete Exposed to Heat Flux on One Surface



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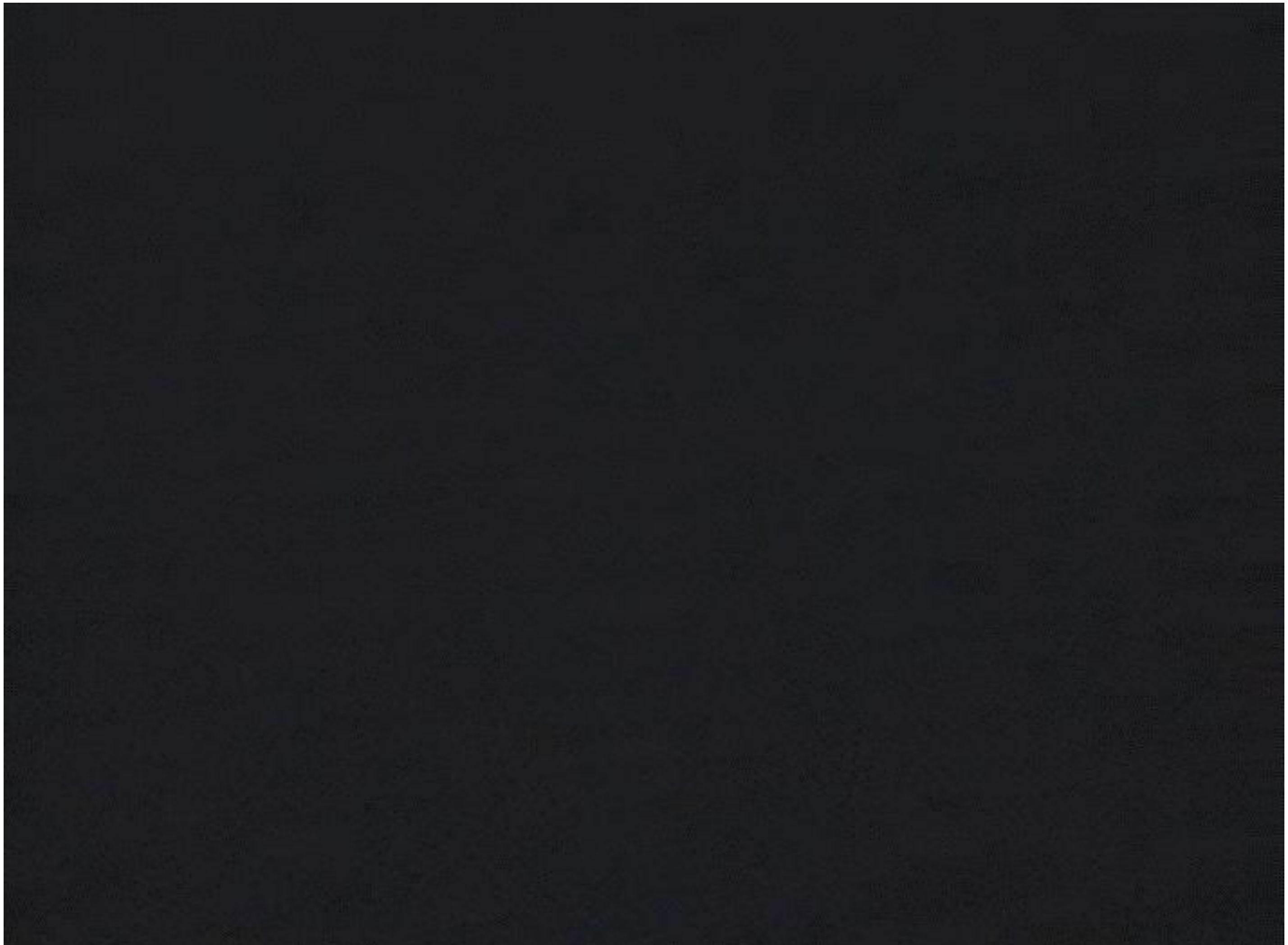

- MCCI experiment
- Decay heat liberates water from concrete
- Metals (Zr and steel) oxidize and produce H_2 and CO
- Exothermic energy from chemical reactions

MCCI Summary

- Concrete attack is primarily a thermal process
  - Can occur whether debris is molten or not
  - Considered in most accident analyses that progress to the ‘ex-vessel’ stage
- Combustible gas generation can be significant
  - Augments the hydrogen production during in vessel core degradation; may add CO to the mix of gases
- Aerosol generation can dominate radioactive releases
  - Flooding with water may not stop the core debris interactions with concrete, but it will sharply attenuate aerosol production

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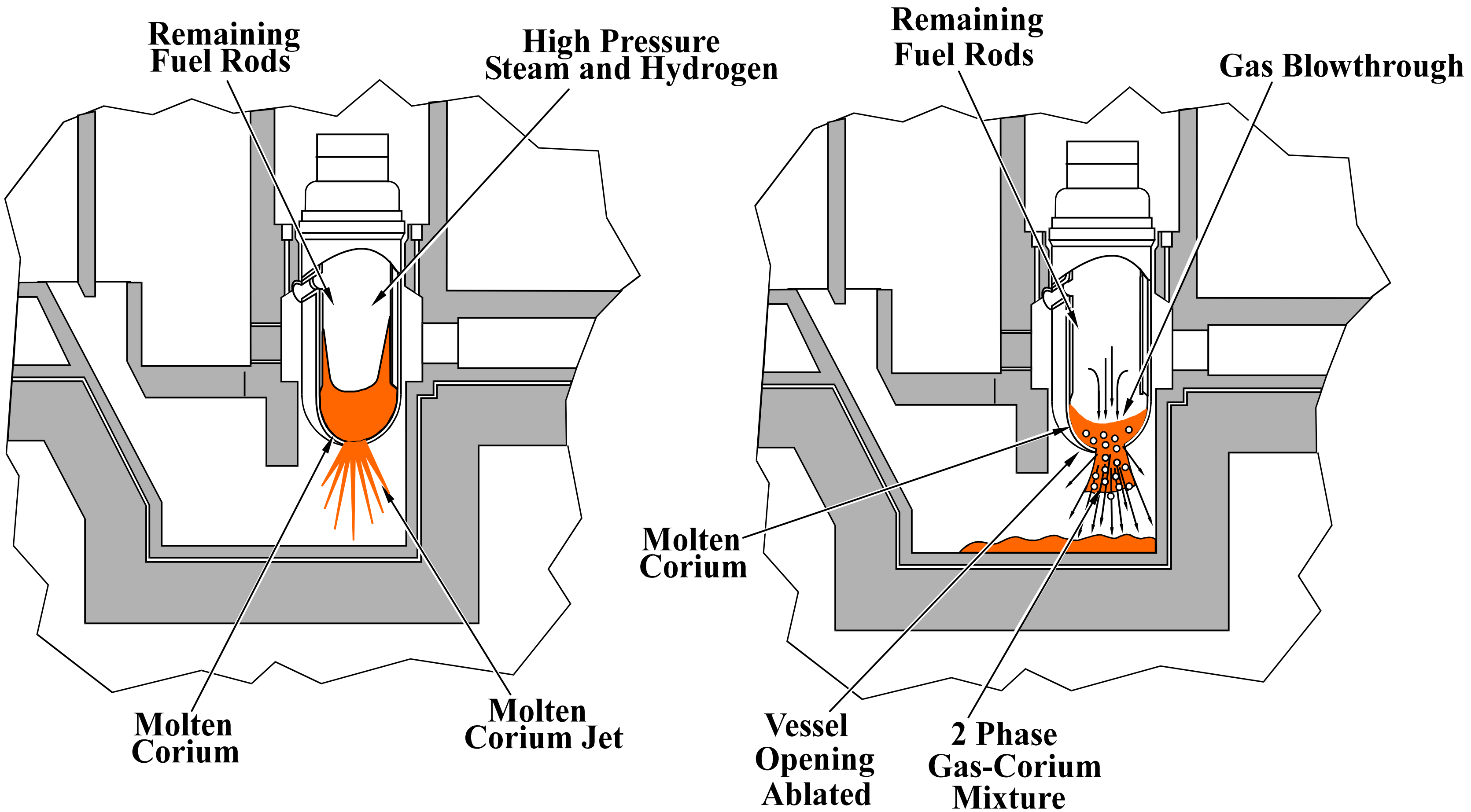
What happens when molten core debris is expelled from a pressurized vessel?

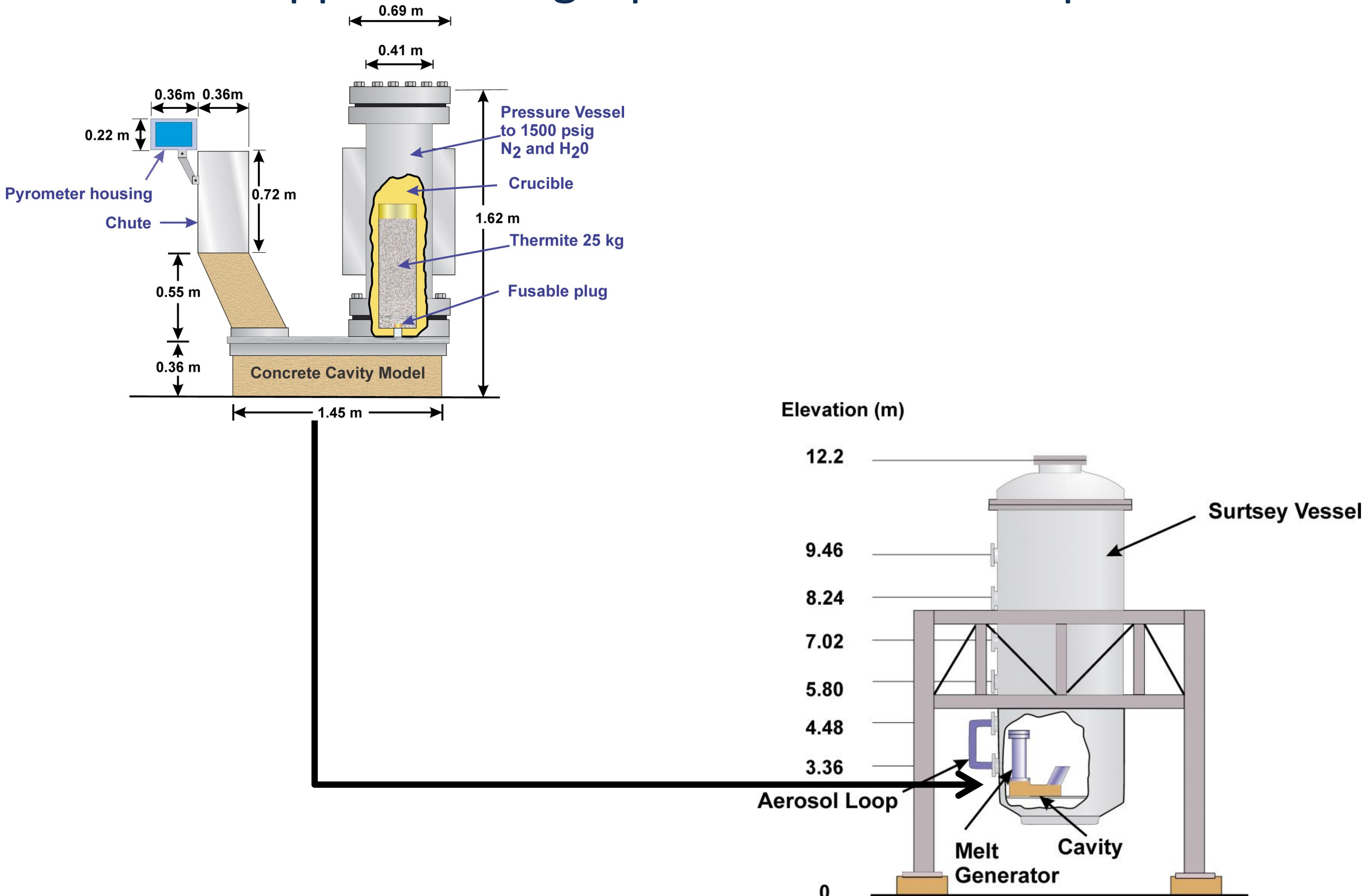
- This question was not considered prior to TMI
- The claims were:
  - Debris would flow out of cavity region and across floors within the containment.
  - The debris layer would thin out and could then be readily quenched.

Lower Head Failure



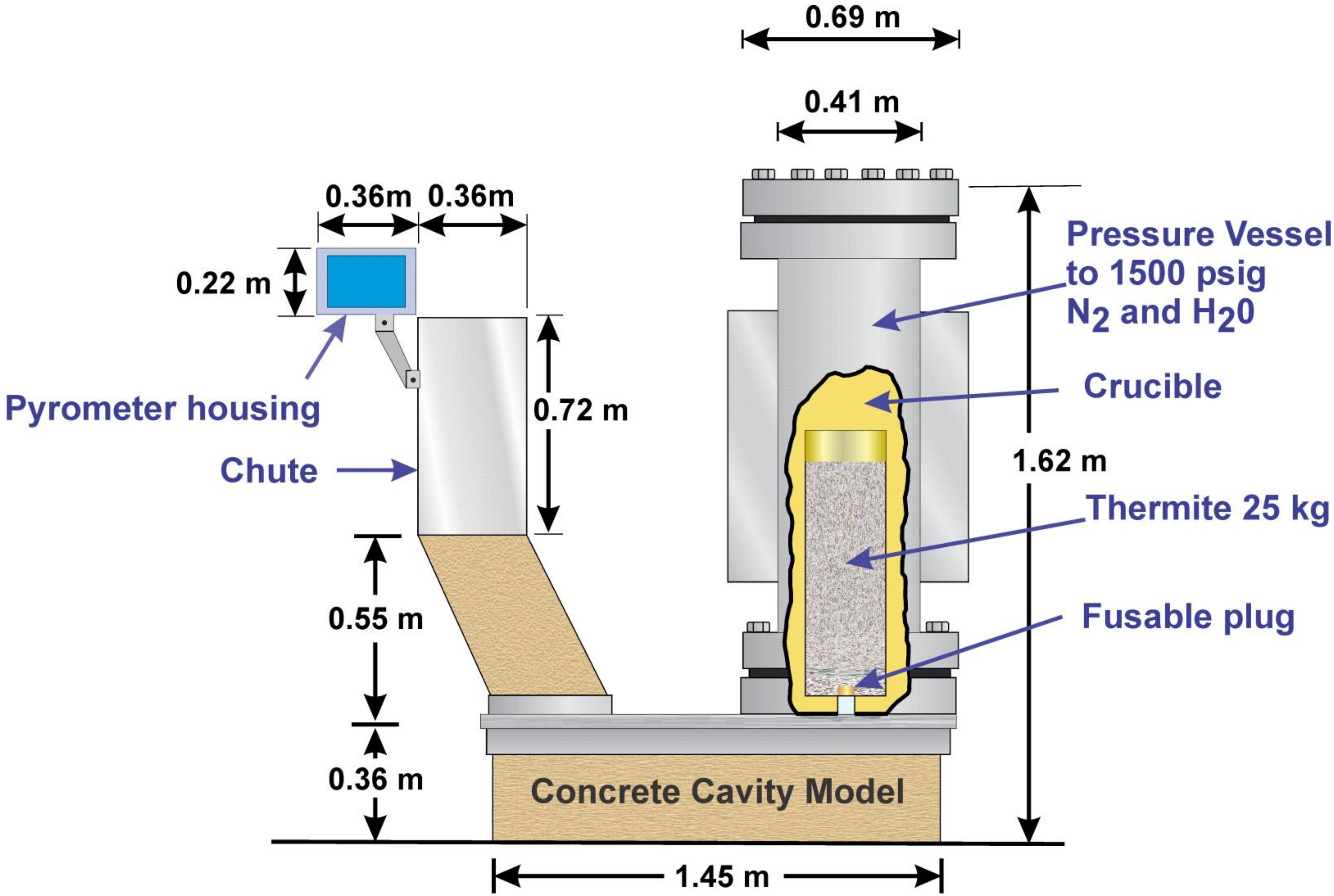
Melt Ejection Process

Sandia constructed the first test apparatus to see what happens during a pressurized melt expulsion…




DCH Tests

First Apparatus for Testing Pressurized Melt Expulsion



t = 0.1 sec.
MELT JUST EMERGING FROM CAVITY EXIT.
VELOCITY = 30 m/sec.
VERTICAL SCALE IS 38 METERS.

t = 0.5 sec.
MELT EJECTION FROM CAVITY COMPLETE.
AEROSOL CLOUD BEGINS TO FORM.

t = 1.0 sec.
EJECTED MELT REACHES MAXIMUM HEIGHT.
PARTICLES BEGIN SEPARATION FROM AEROSOL.

t = 1.5 sec.
SEPARATION COMPLETE.
PARTICLES FOLLOWING PARABOLIC TRAJECTORIES.

MELT EXPULSION FROM A REACTOR CAVITY. This test involved 80 kg of melt expelled into a reactor cavity model from a vessel pressurized to about 80 bars.

Pressurized Melt Ejection

- Lofts fine particles of debris that can react exothermically to heat and pressurize the containment
  - Thus, Direct Containment Heating
  - Heating depends on how much reactive metal is present in the debris
  - Hot particles can ignite pre-existing hydrogen in the containment atmosphere

Crucial Safety Issue: Can pressurized melt ejection lead to early containment failure?

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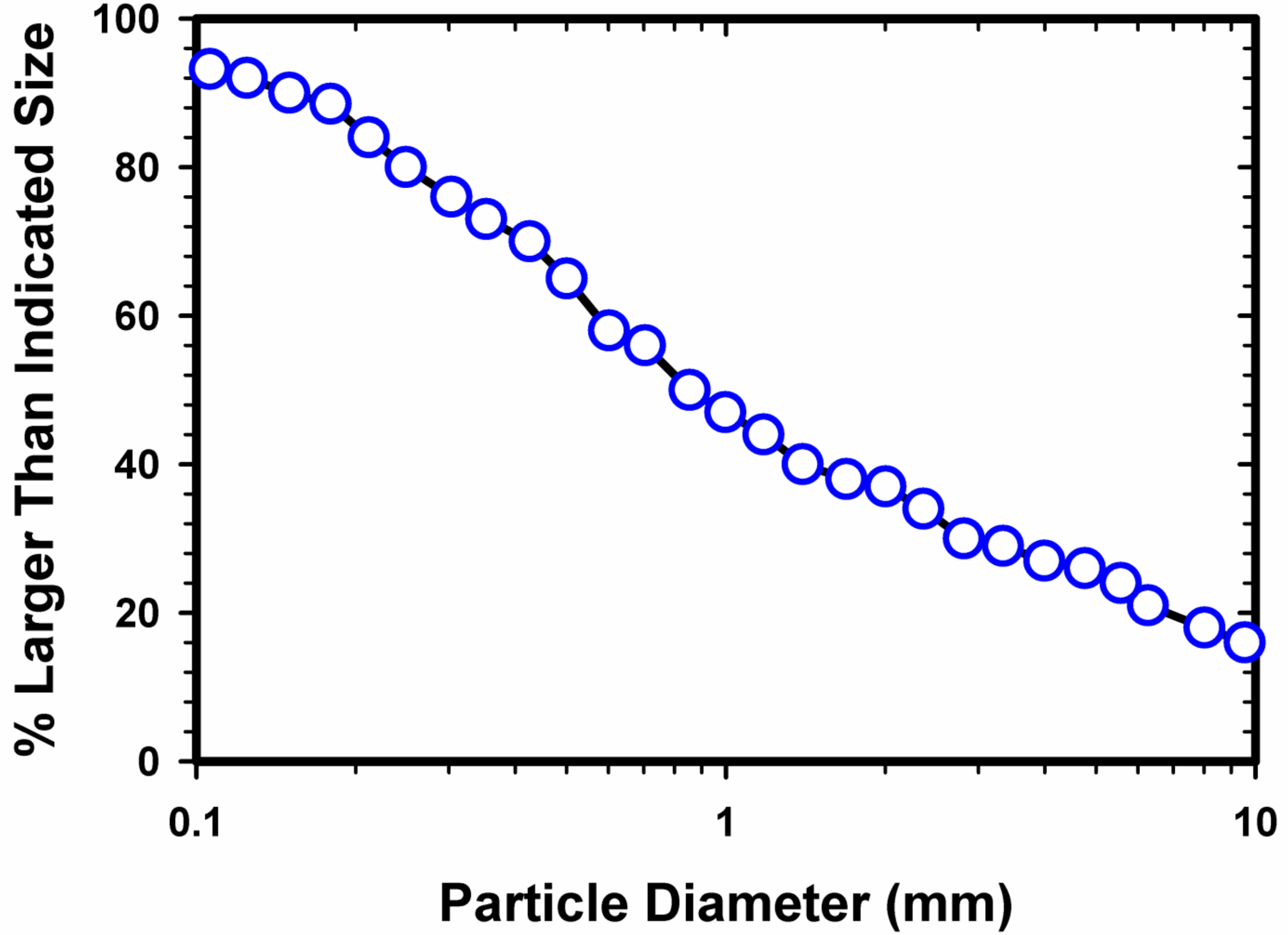
80 kg of melt expelled into reactor cavity with a pressure vessel set to approximately 80 bars.


IET-1

Size Distribution of Debris



Pressurized Melt Expulsion/and Ejection

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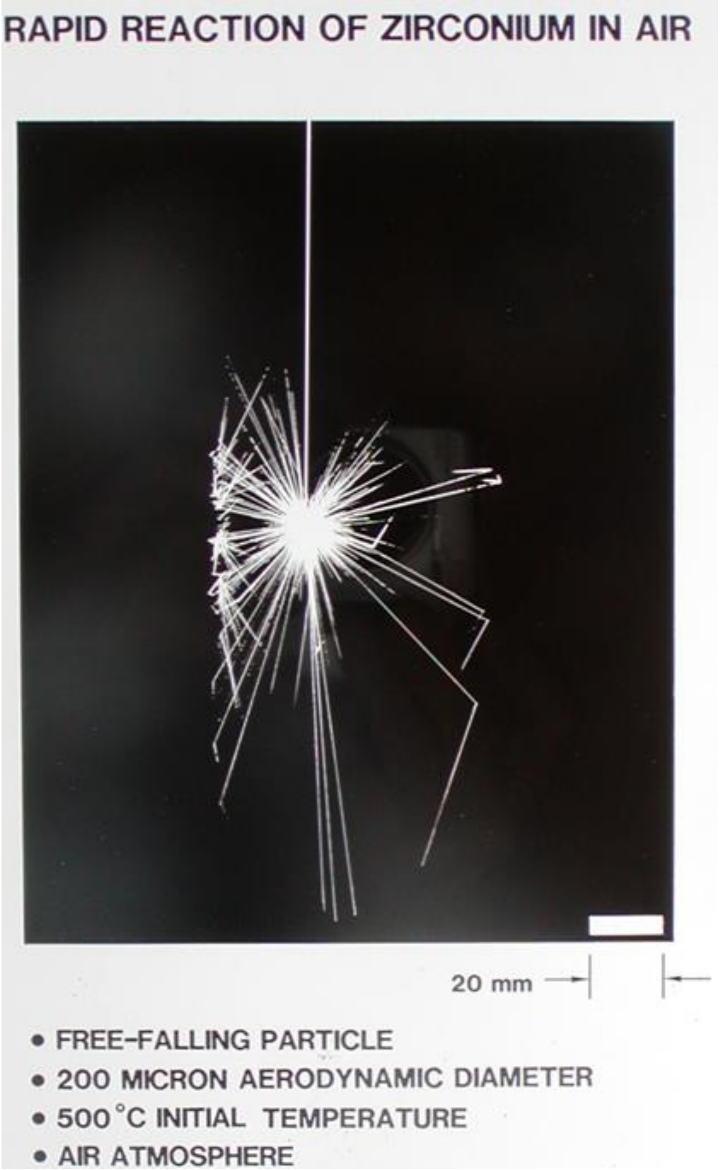
- Expulsion
  - The tests showed that the debris was dispersed as fine particles.
  - Particles were hot (or even molten) and consisted of metals, fuel, core, and structural materials.

- Ejection
  - Ejection lofts fine particles which can then react exothermically. This results in direct containment heating (how much heating depends on the amount of reactive metals).
  - Additionally, hot particles can ignite hydrogen trapped in containment.



Important Pressurization Factors

- System pressure at the time of vessel penetration
- Amount of core material present (especially metals like steel or zirconium)
- Amount of hydrogen accumulated in containment
- Compartmentalization around reactor cavity

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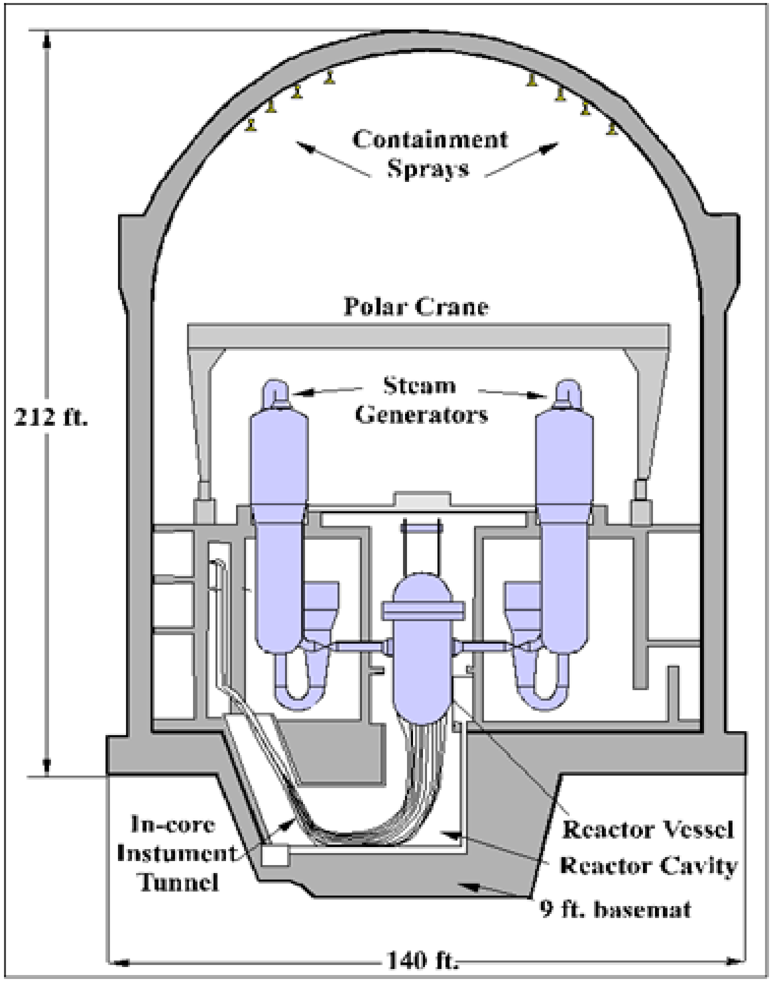
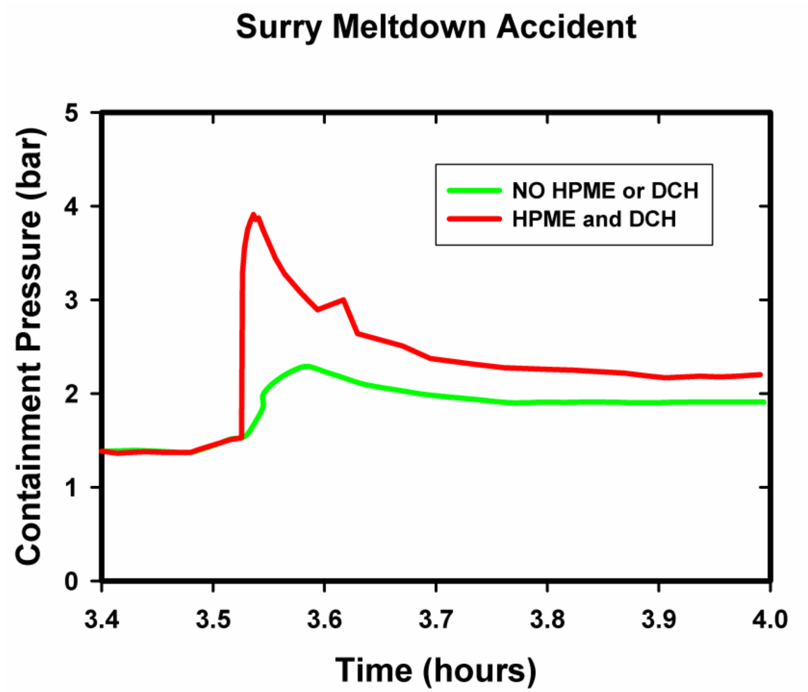
Direct Containment Heating (DCH)

- The level of DCH depends on how long the particles are suspended in the atmosphere
- Melt droplets that pass into the dome region are suspended the longest and heat the atmosphere the most.



Model Tests for DCH Showed:

- Particles respond in-elastically when colliding with structural surfaces
  - Instrumentation tubes from vessel don't affect heating
  - Particles hit surfaces and fall to the floor
- Particles consume oxidant faster than it can be resupplied
- Particles thermally saturate the compartment atmosphere faster than heat loss by conduction in structures



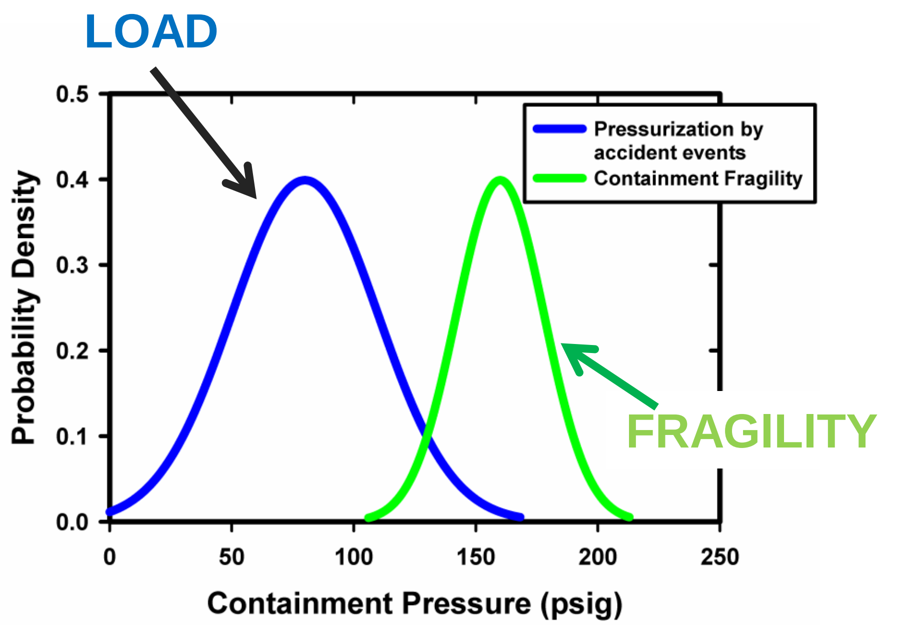
Pressurized Melt Ejection

- Lofts fine particles of debris that can react exothermically to heat and pressurize the containment
  - Thus, Direct Containment Heating
  - Heating depends on how much reactive metal is present in the debris
  - Hot particles can ignite pre-existing hydrogen in the containment atmosphere

Crucial Safety Issue: Can pressurized melt ejection lead to early containment failure?

Analysis of Containment Failure Probability

- Comparison of pressurization and containment fragility curves
- Ratio of 99th percentile LOAD to 1th percentile FRAGILITY
- Show ratio <1 for 95% of accident scenarios



Intentional RCS Depressurization

- Proposed as a mitigation strategy for PWRs
- Pros:
  - Reduces DCH probability
- Cons:
  - In-vessel steam explosions more likely at low pressure
  - Potential for inadvertent LOCA
- Currently no regulatory requirements in the USA
  - Modern PWRs (AP1000) include provisions for depressurization

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DCH Summary

- DCH not likely to challenge most large-dry PWR containments
- Several steps in DCH process
  - melt ejection
  - reactor cavity interaction
  - containment atmosphere response
- Intentional depressurization possible mitigation strategy
- No regulatory requirements in USA
  - Not typically considered in accident analyses that progress to the ‘ex-vessel’ stage

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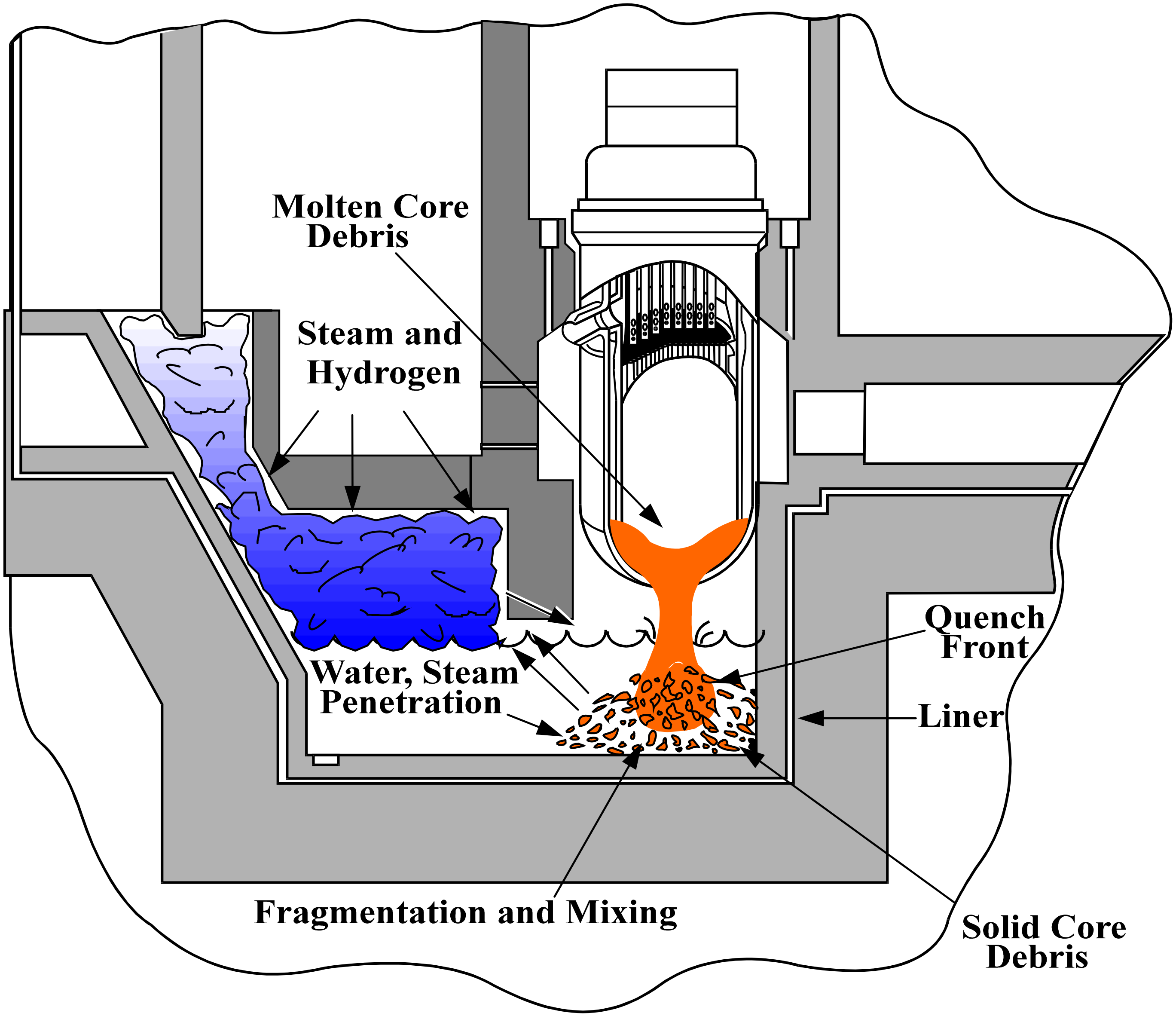
Quenching

- Generally a desirable outcome
- Radioactive release is reduced
- Resulting steam spike usually doesn’t threaten containment
- Concrete attack is mitigated
- Note: Continued cooling requires heat
- removal and a source of water
- What Affects Debris Coolability:
- Particle size, depth of debris, and crust formation.



Molten Core Quenching Process

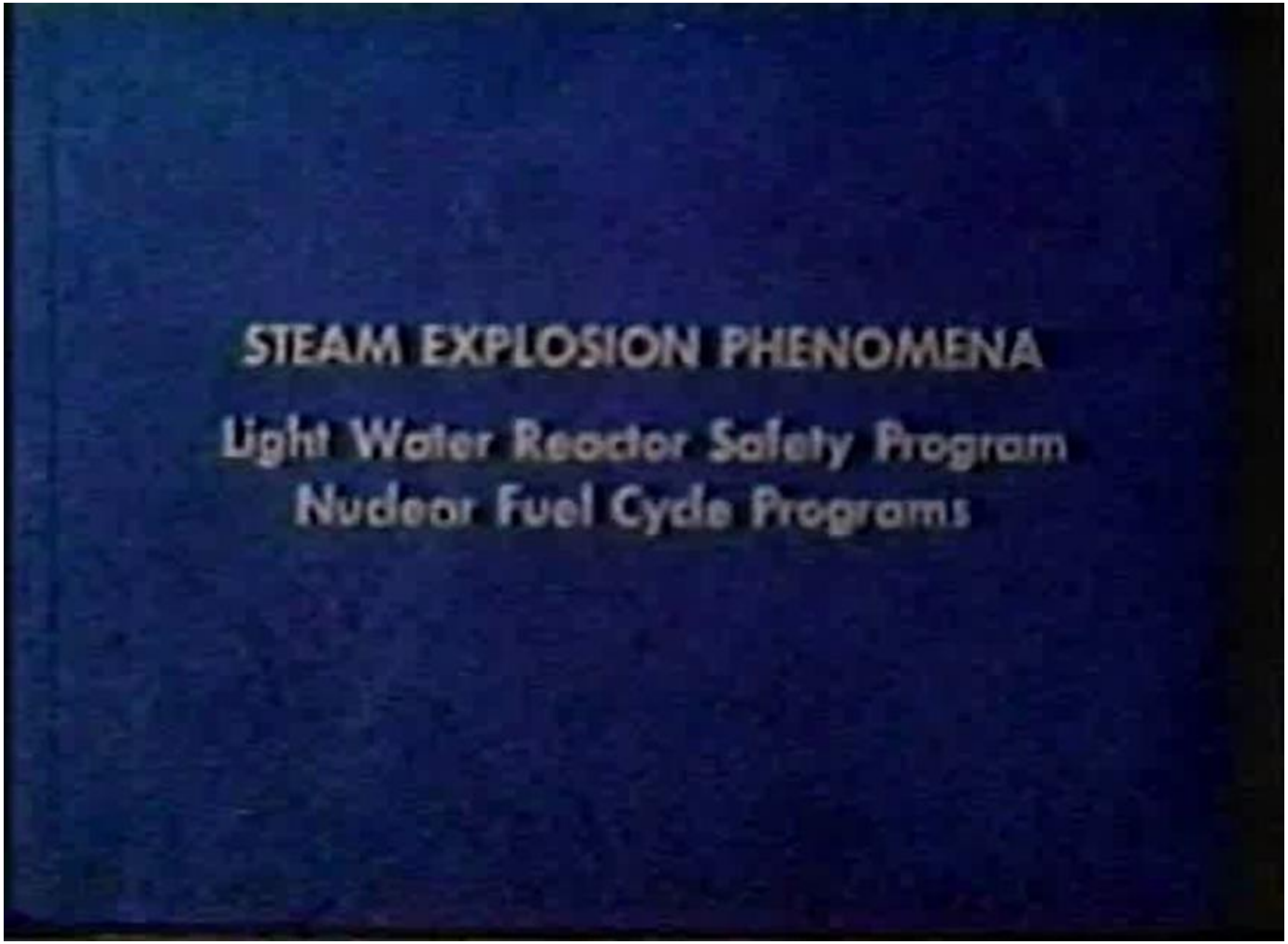
Ex-Vessel Steam Explosions

- Rapid quenching
- Several containment threats
  - Shock waves failing containment
  - Failure of vessel supports
  - Missile generation
  - BWR drywell/pedestal failures

Steam Explosion Experiments

- Performed for
  - Masses from 50 mg to 160 kg
  - Variety of melts, melt temperatures, contact modes
- Coarse fragmentation occurs readily mixing melt and water
- Triggering
  - Easier to trigger at lower pressures
  - Easier in subcooled than in saturated water
  - Insensitive to melt temperature
  - Multiple explosions may occur
- Conversion ratio (kinetic energy/thermal energy)
- Significant hydrogen production given metallic melts

Steam Explosion Experiments

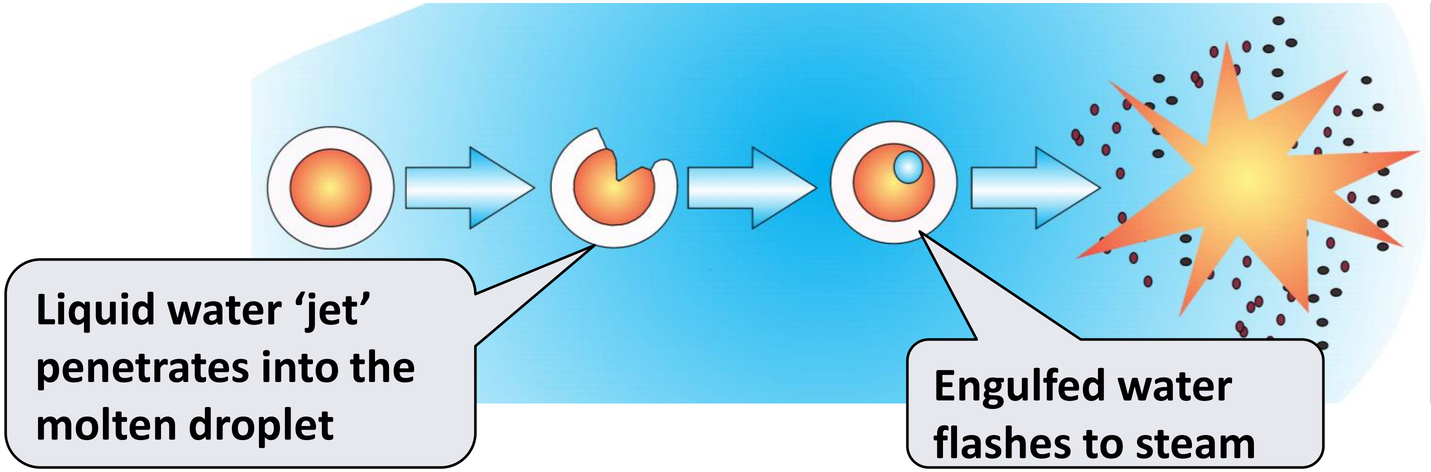


Factors Affecting Ex-Vessel Steam Explosions

- Amount of water available
- Melt composition
- Cavity or pedestal geometry
- Shock wave transmission through water
- Pouring rate and contact mode
- Fraction of core participating

Steam Explosion Triggers

- Destabilization of vapor film
- Produced by
  - Natural oscillations of film
  - Shock waves from falling objects
  - Melt contact with bottom surface
  - Turbulence generated in part of mixing region



Physics of ex-vessel steam explosions is the Same as that of in-vessel steam explosions

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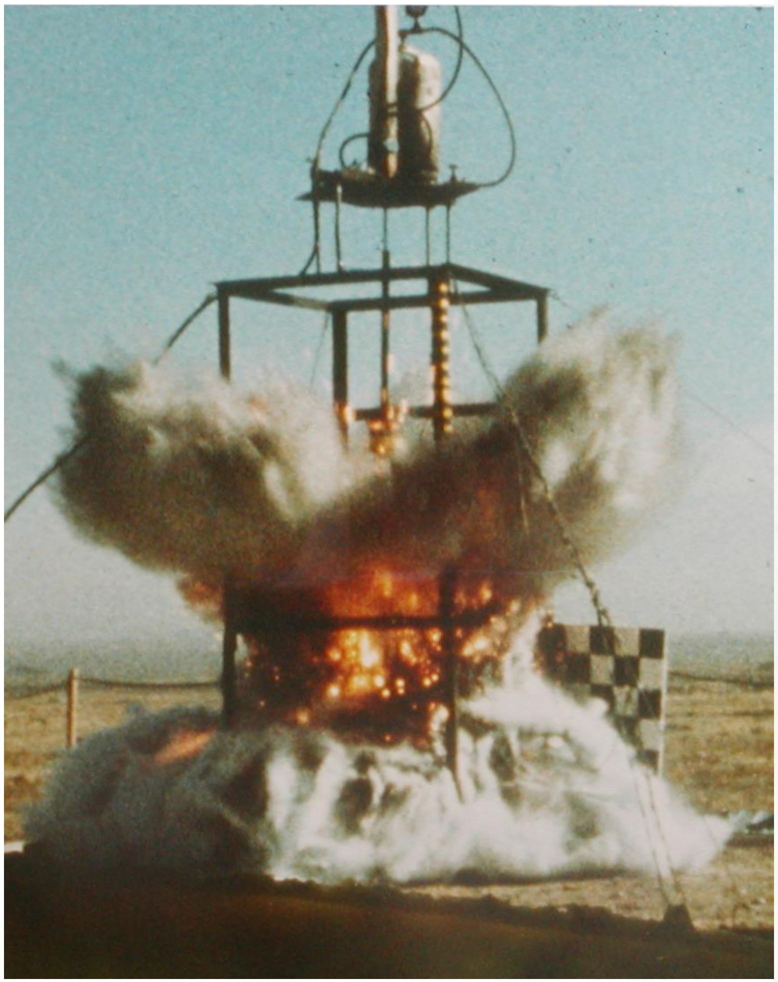

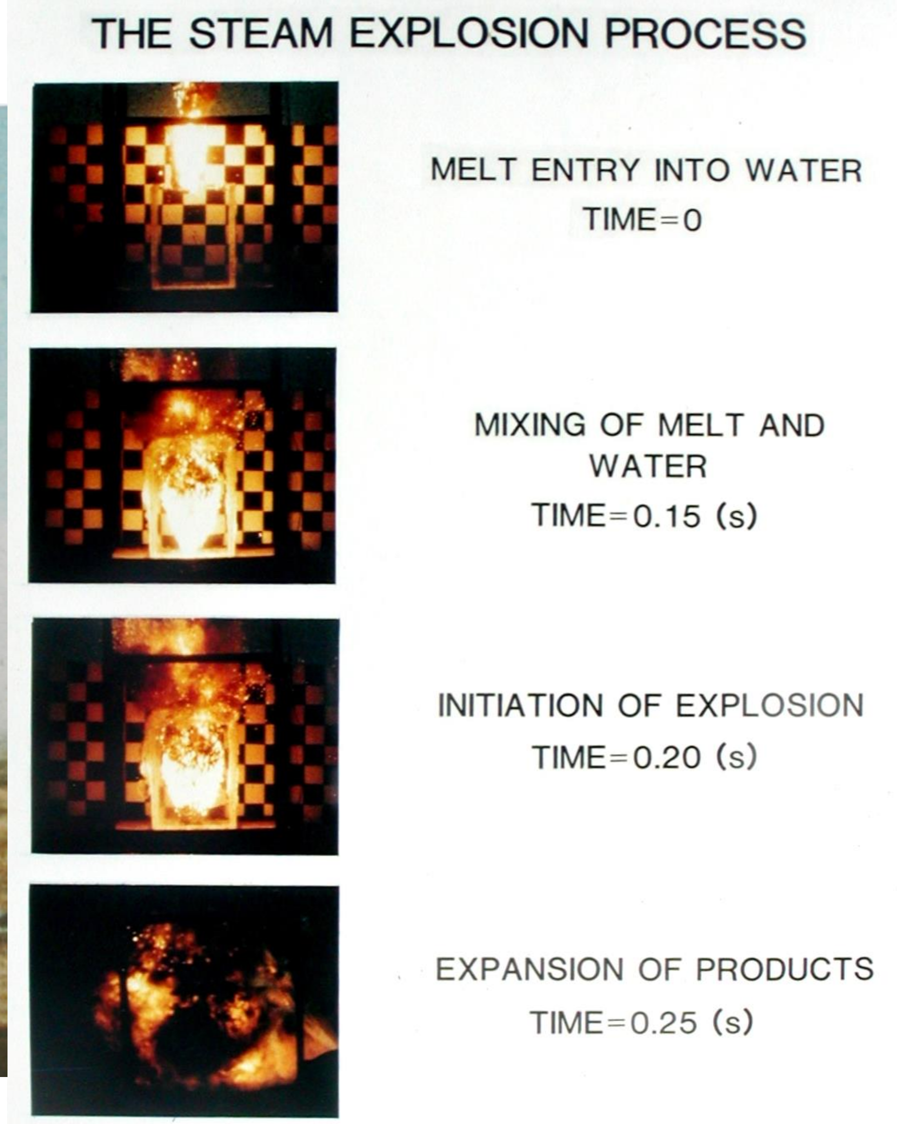

Pressure Pulse from a Steam Explosion Test