Combustible Gas and Nuclear Safety – Selected Issues

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Hydrogen and Combustible Gas Issues and Nuclear Facility Safety Panel Session
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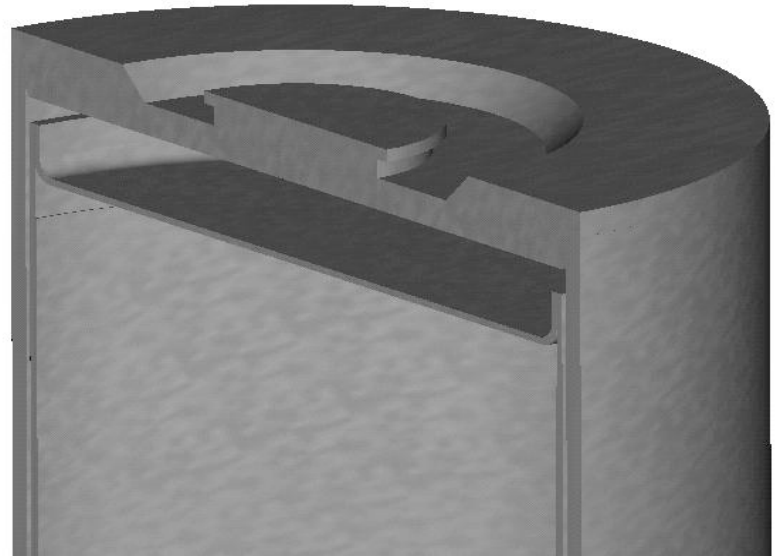
Research Topics

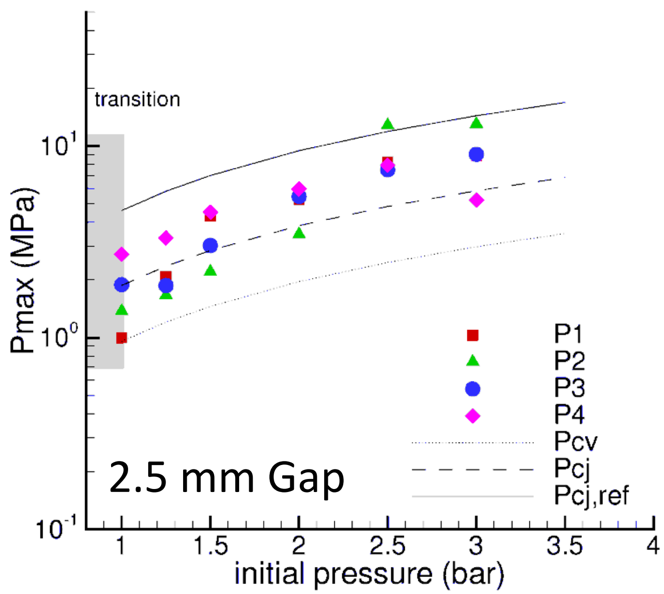
- Composition and distribution of flammable atmospheres
- Ignition sources and likelihood of ignition in passive systems
- Effectiveness of deliberate ignition or recombination?
- What is the most severe explosion hazard possible? Is detonation possible?
- Evaluation of structural loading and thermal response of equipment

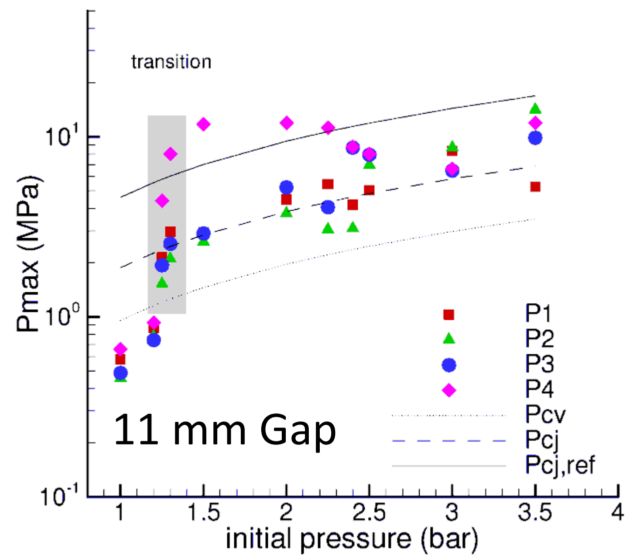
Selected Issues For Today

- Structural margin and integrity following internal explosions
  - Containers
  - Processing facilities
- Dispersion and multiphase dynamics
- Combustible gas generation and mitigation during severe accidents in NPP
  - Fukushima follow up

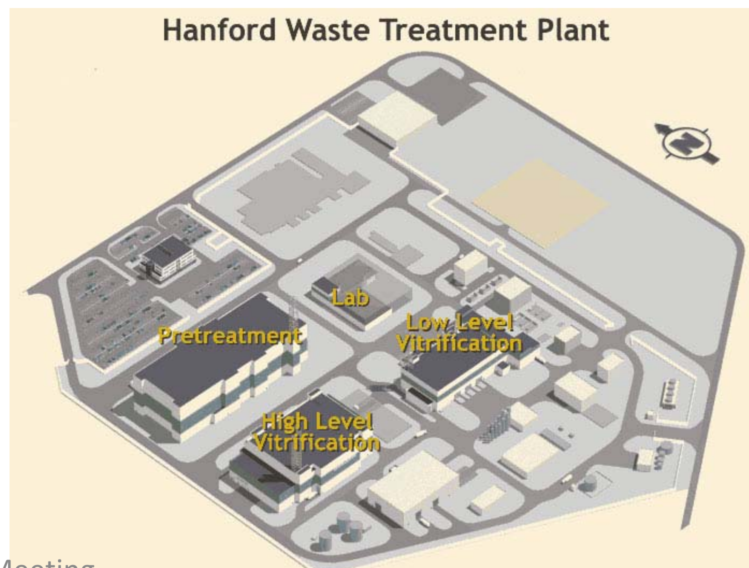
Explosion Hazards in Containers







Explosion Hazards in Waste Storage and Treatment Facilities



Hanford WA Pu-239 from 1945 to 1989

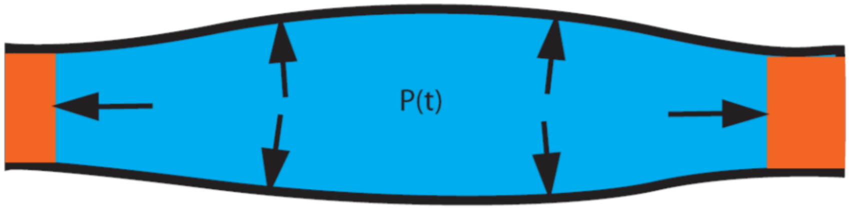
2 x 10^8 ℓ radioactive waste in leaking tanks

WTP convert to glass, 36 tonne/day in 2014

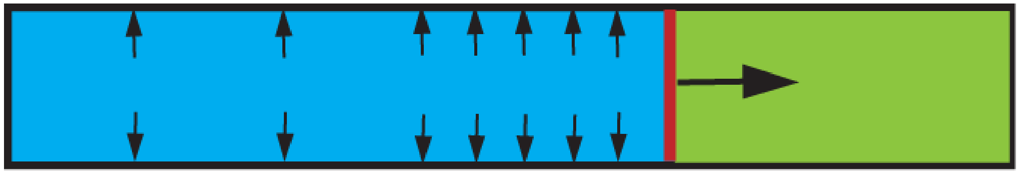
Radiolysis and chemical reaction create H_2, N_2O, O_2.

Explosion Scenarios

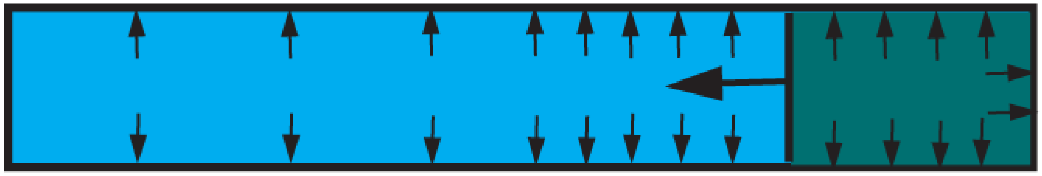
Slow Explosion or Deflagration



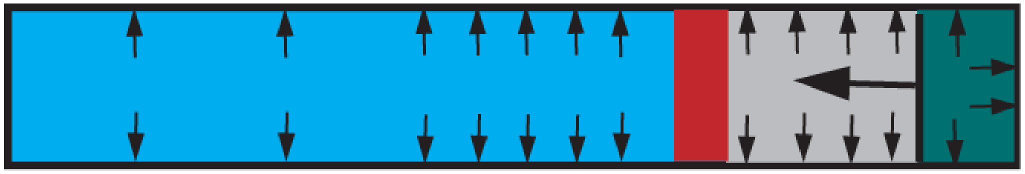
Fast explosion or
Detonation



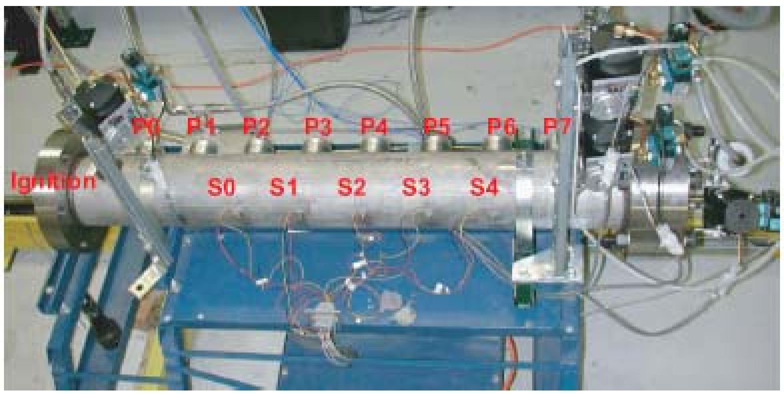
Detonation reflecting to
Create shock wave

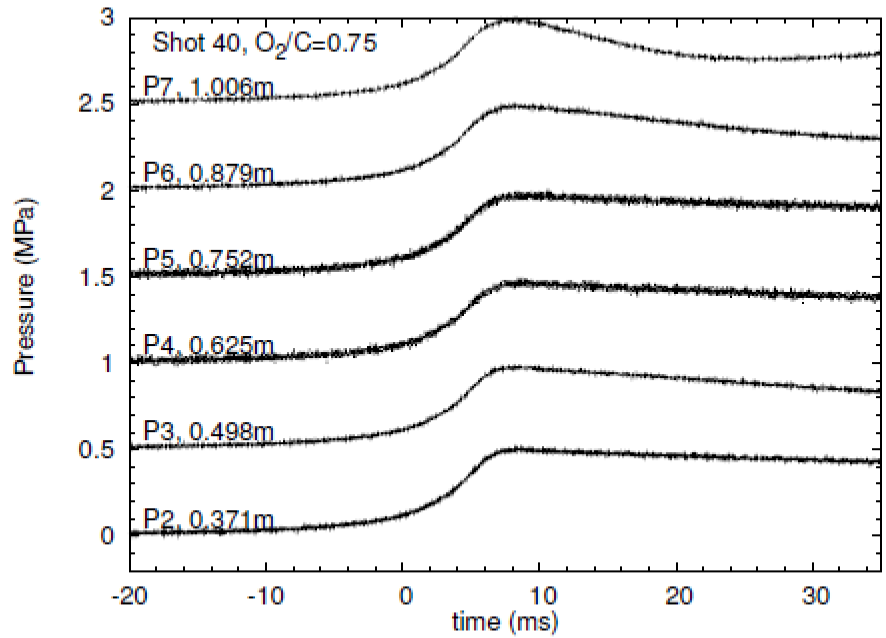


Deflagration-to-Detonation
Transition followed by
reflection (DDT/Pressure Piling)

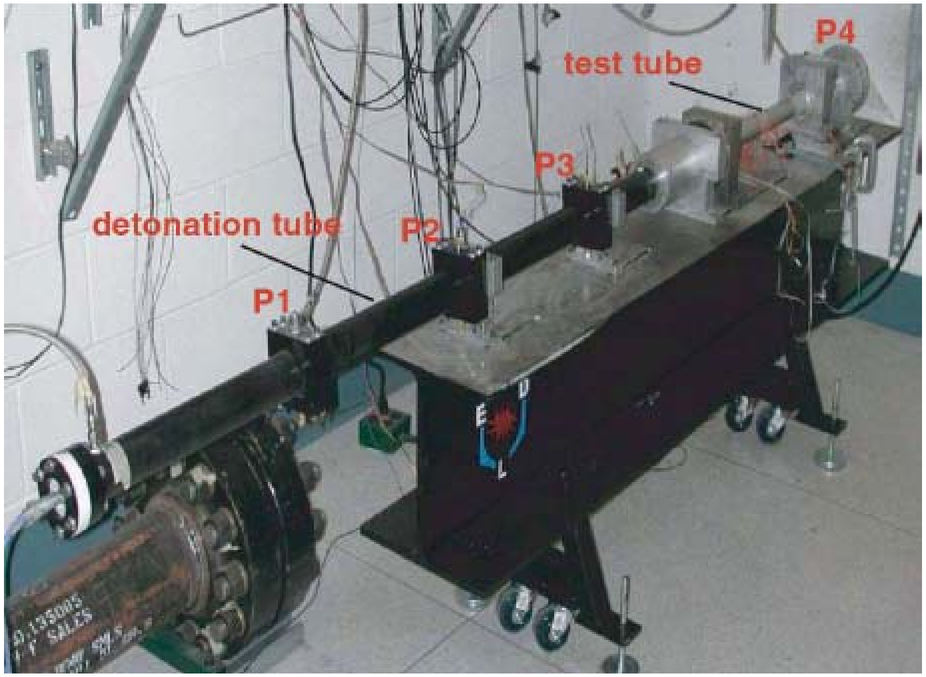


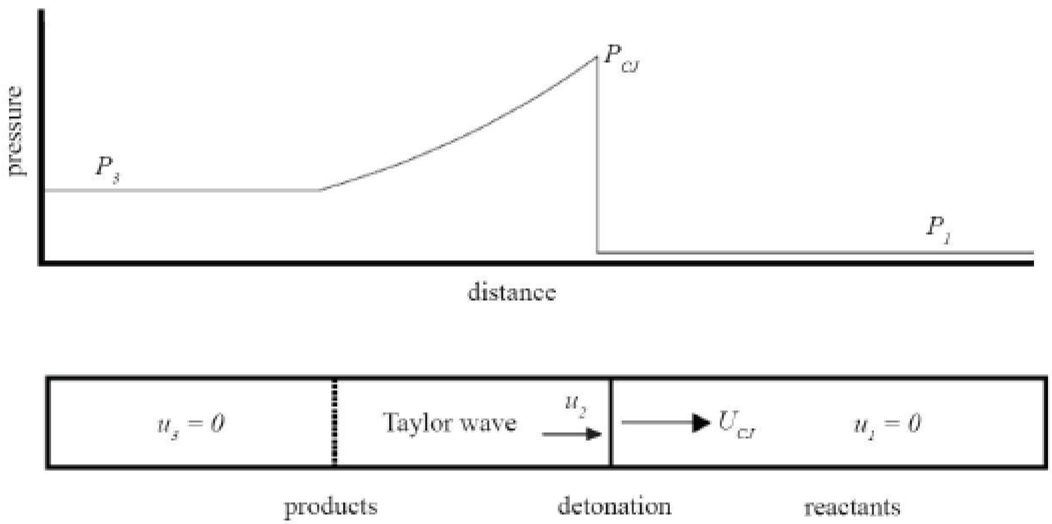
Deflagration (slow) are quasi-static

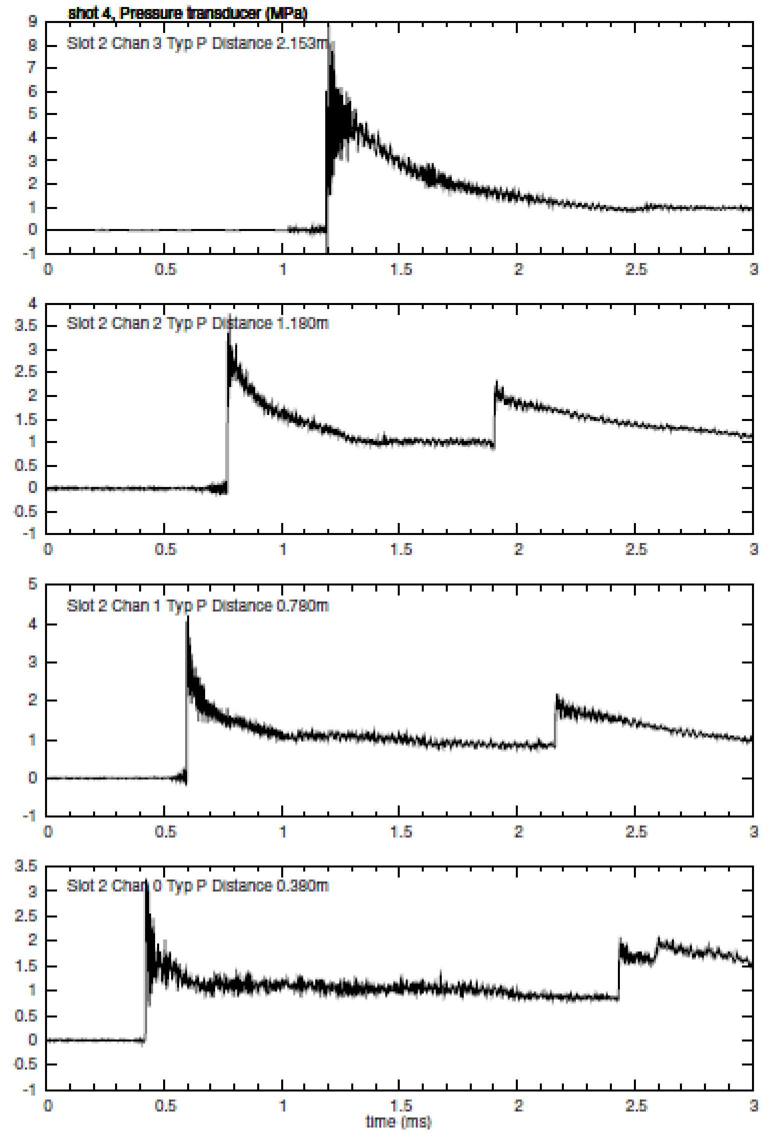




Detonations are pressure waves

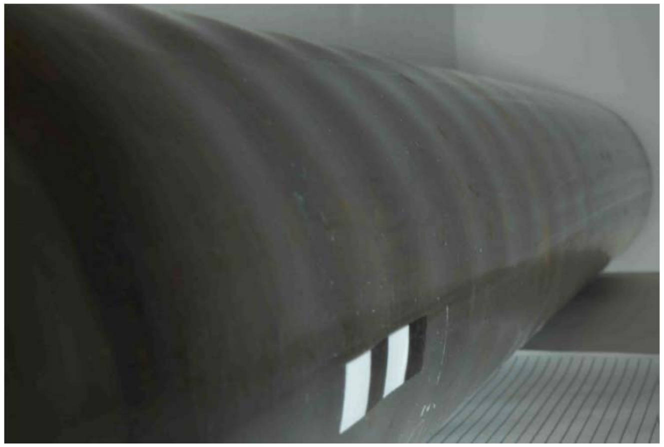


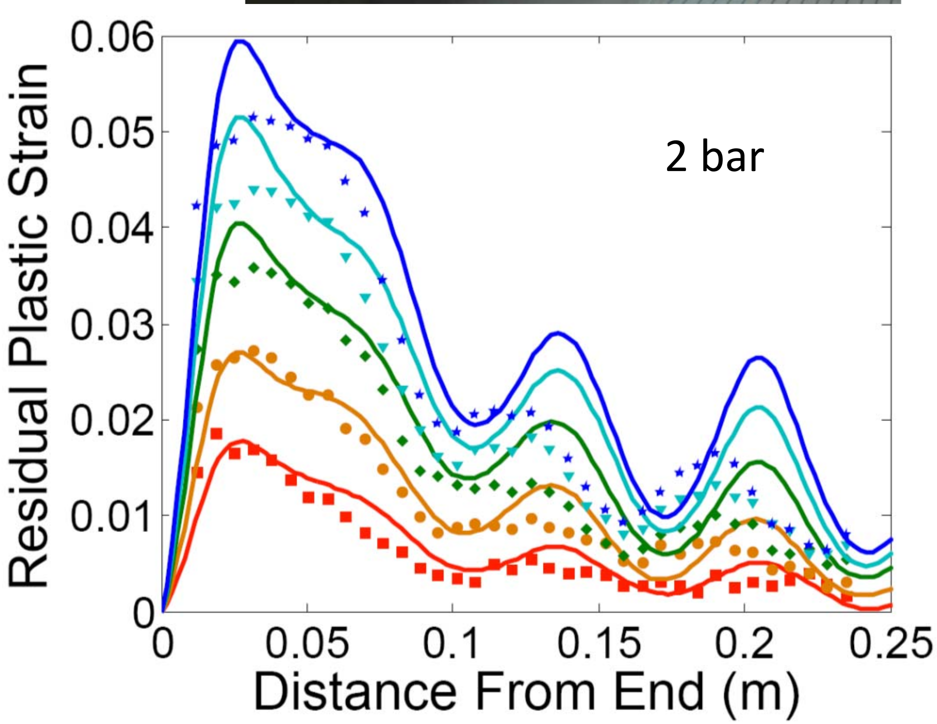


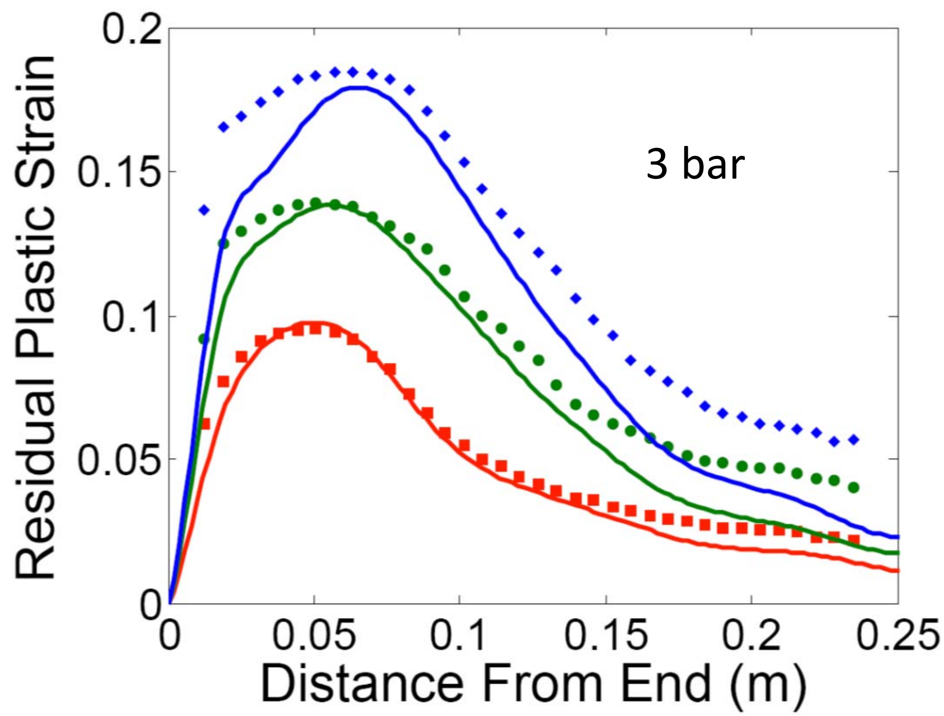


Plastic Deformation Validation

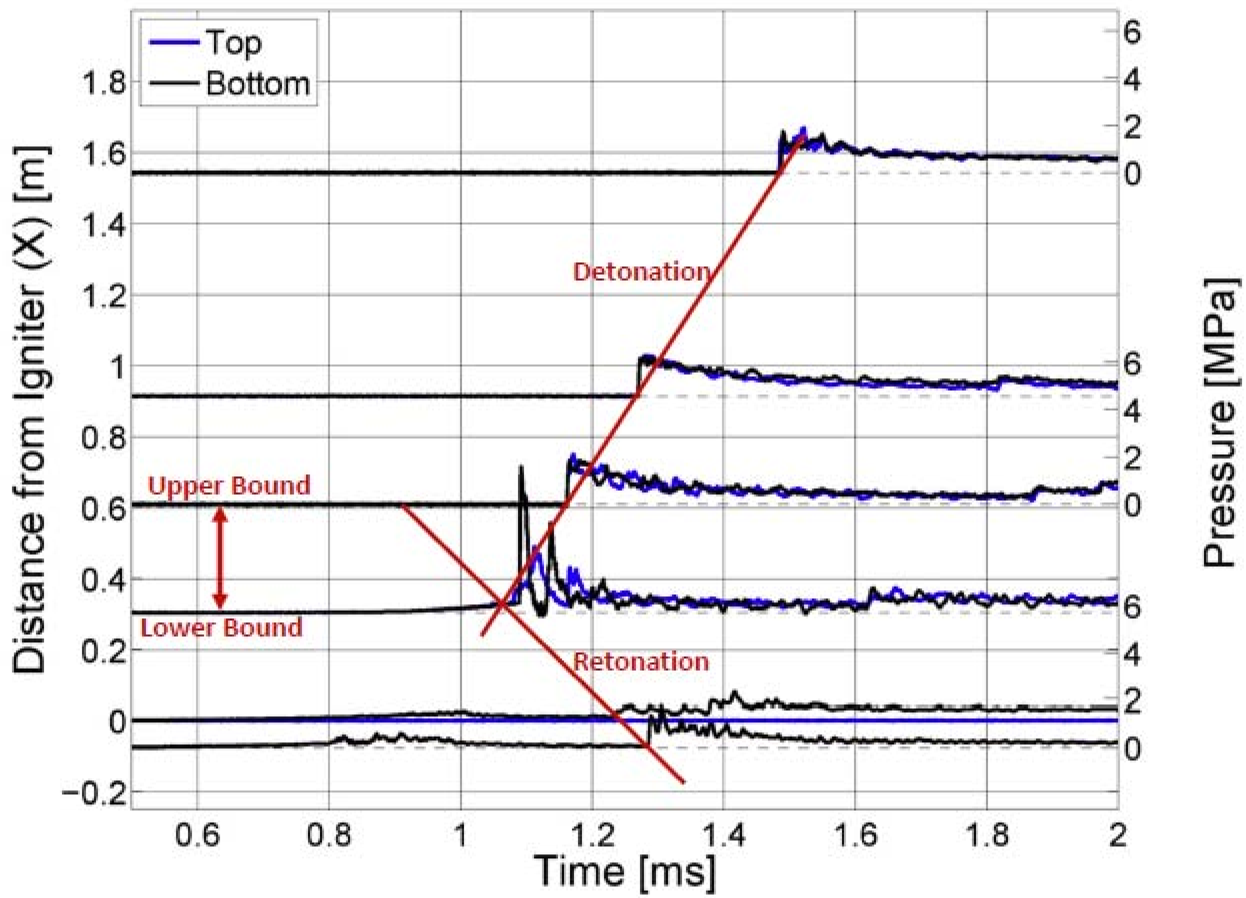
LS-Dyna Simulation







Transition to Detonation



Plastic Deformation and Rupture

- What are the rupture mechanisms and thresholds for detonation loading inside pipings and containment structures?

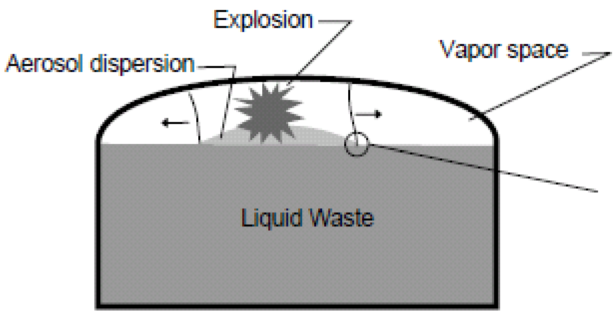
Applications:

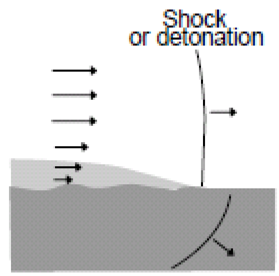
Disposal/Destruct systems

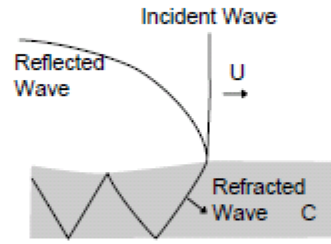
Explosive Effects Mitigation

Incident Analysis

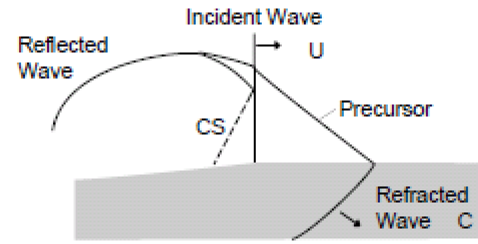
Explosion Over Liquid Surface





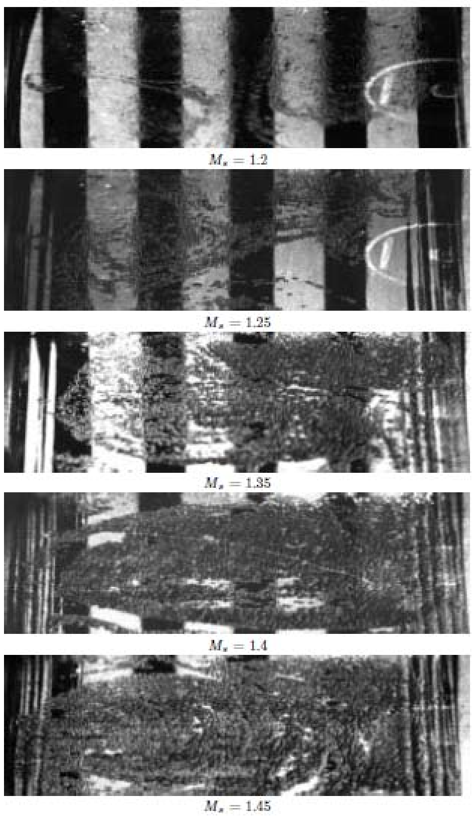


Regular Refraction U > C

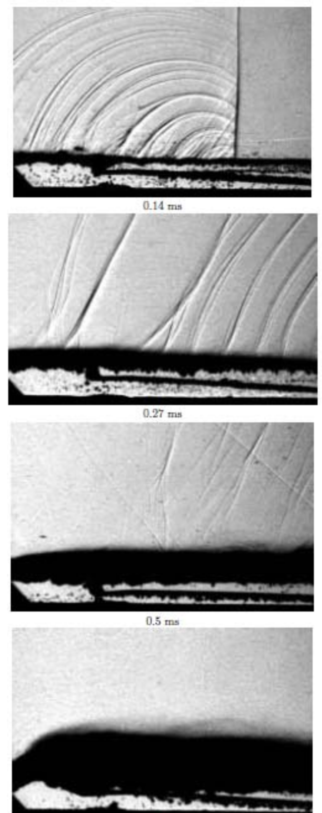


Irregular Refraction U < C

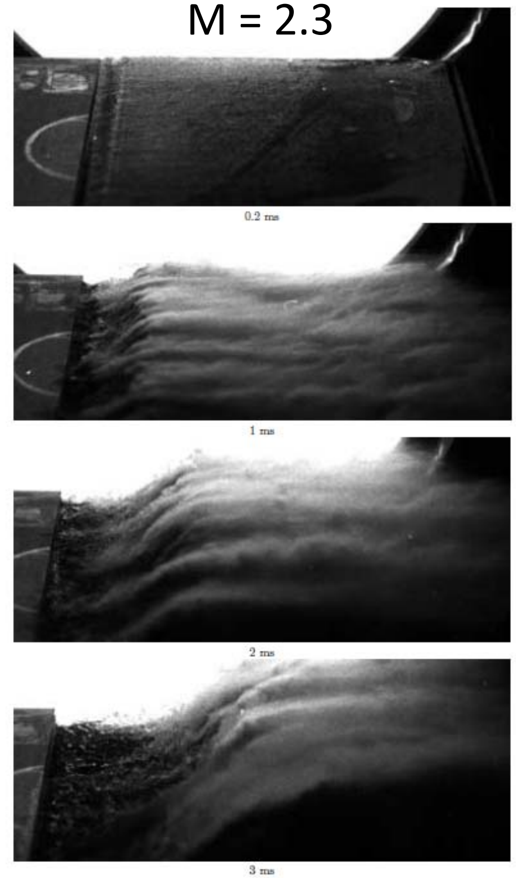
0.5 ms



M = 2.3

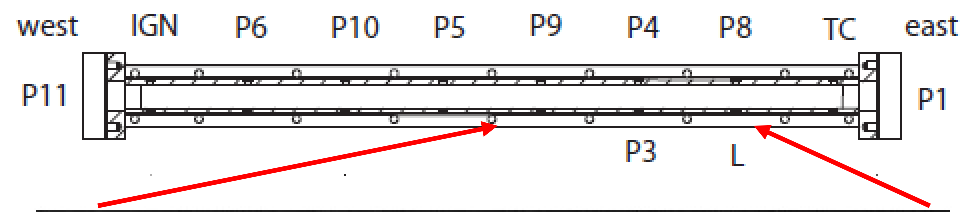


M = 2.3

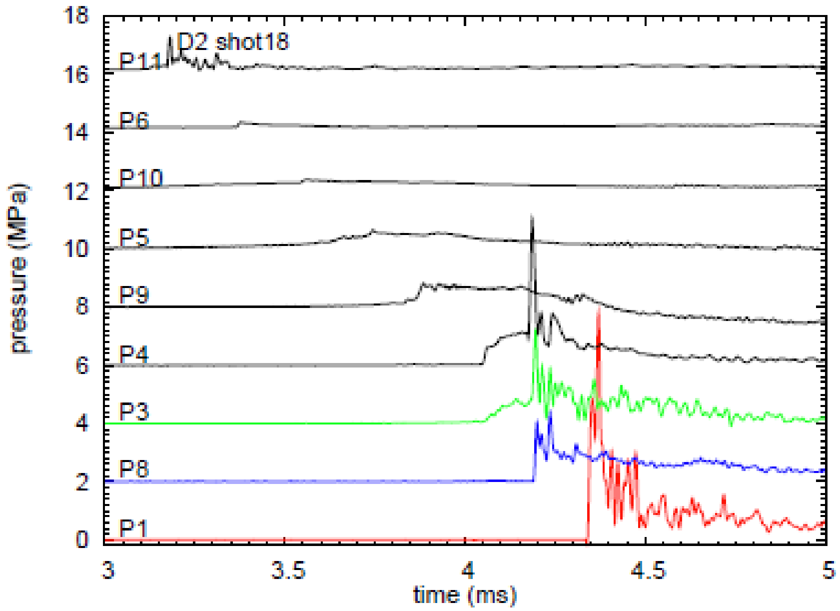


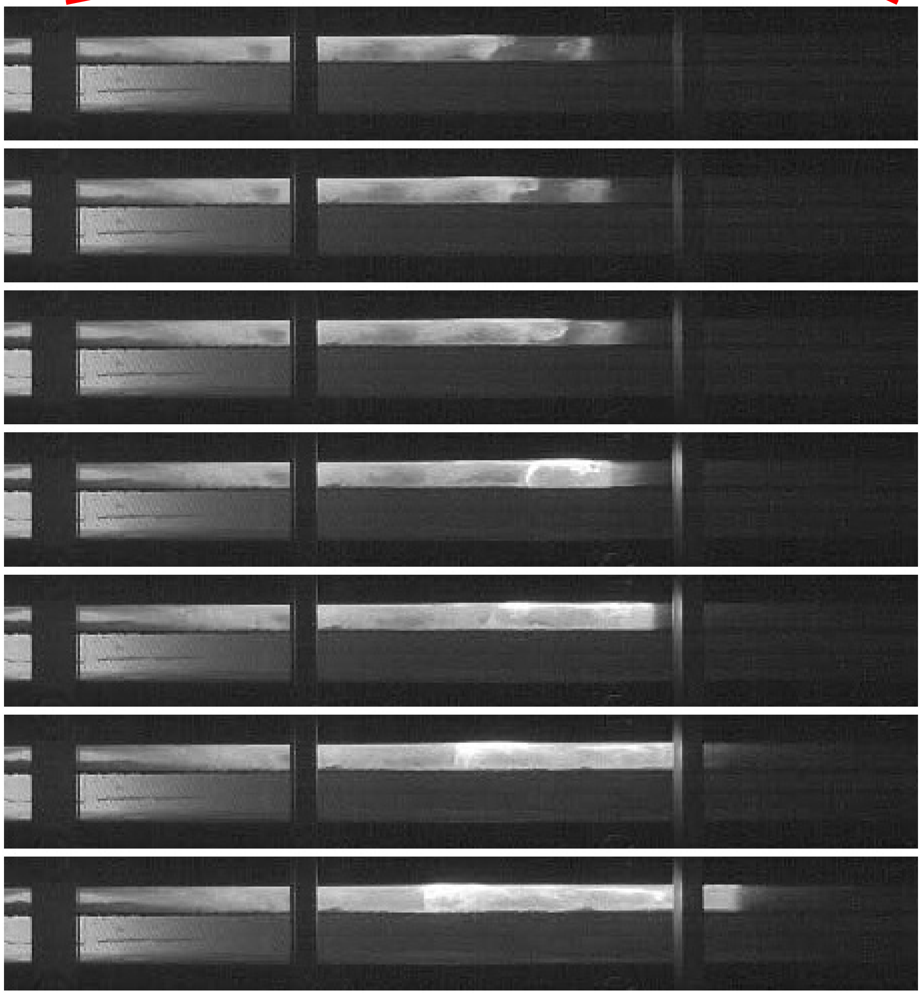
Teodorcyzk and Shepherd 1994-5

DDT over water layer



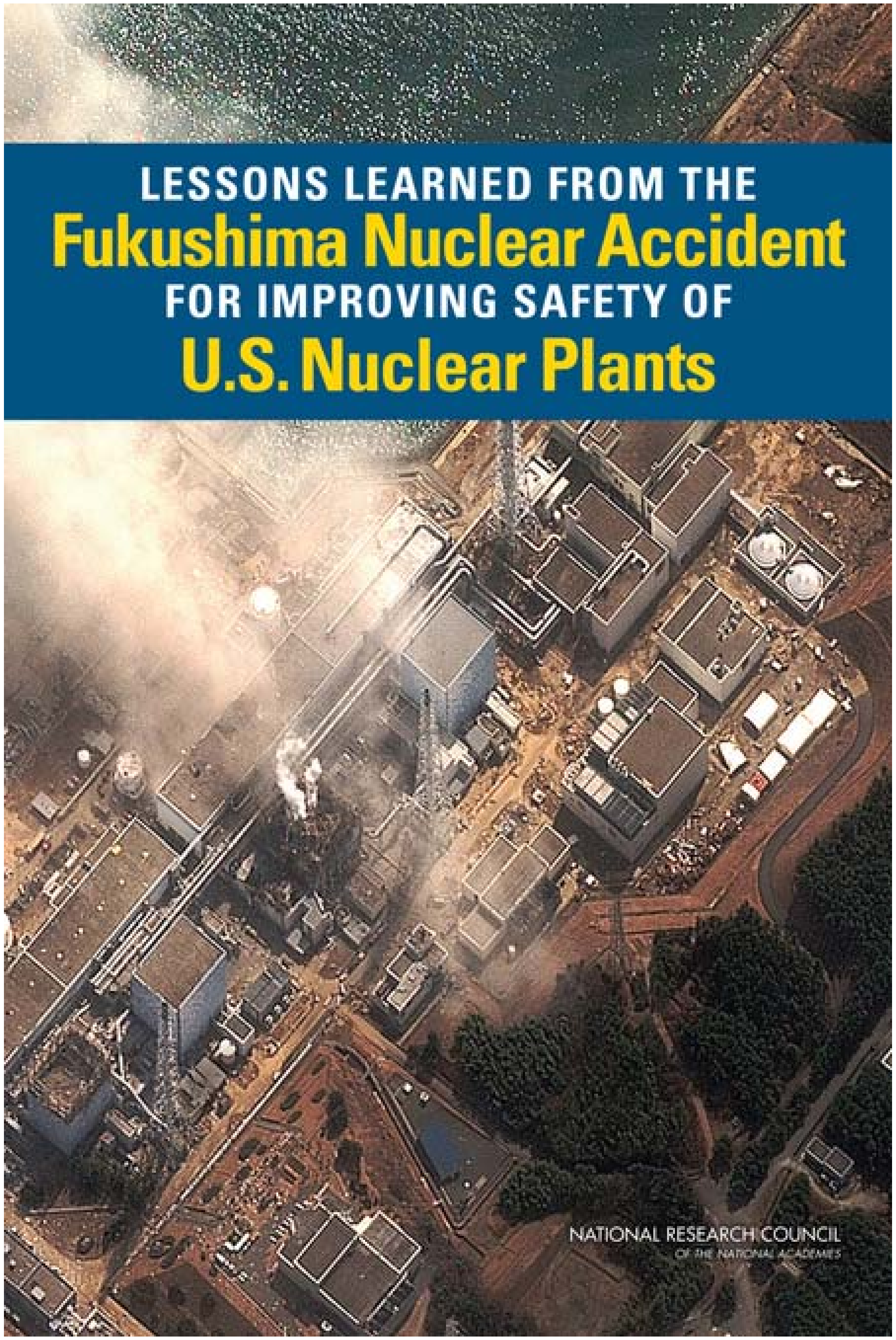
H2-N2O 15 mm gas layer
above 35 mm water layer





Explosion Hazards In Nuclear Power

NY Times – DigitalGlobe


LESSONS LEARNED FROM THE
Fukushima Nuclear Accident
FOR IMPROVING SAFETY OF
U.S. Nuclear Plants
NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

Common Lessons

- DC power failure and lack of backup crippled response
  - No status, no control, limited communications
- Interaction of logic control circuits with power failures (AC and DC) leading unanticipated and unknown valve status
- Inability to transition to ad hoc cooling in a timely fashion.
  - Difficulty in securing ad hoc DC and air power for valves
  - Lack of pre-placed resources and planning for ad hoc responses
  - Limited access to reactor buildings, multiunit competition
  - Uncertain flow paths for cooling water
  - Low pressure of ad hoc injection (fire truck pumps)

"Coordination of depressurization and low-pressure water injection proved impossible to accomplish under the conditions at the plant following the tsunami…"

Figure 3.9 (TEPCO)

Hydrogen Explosions

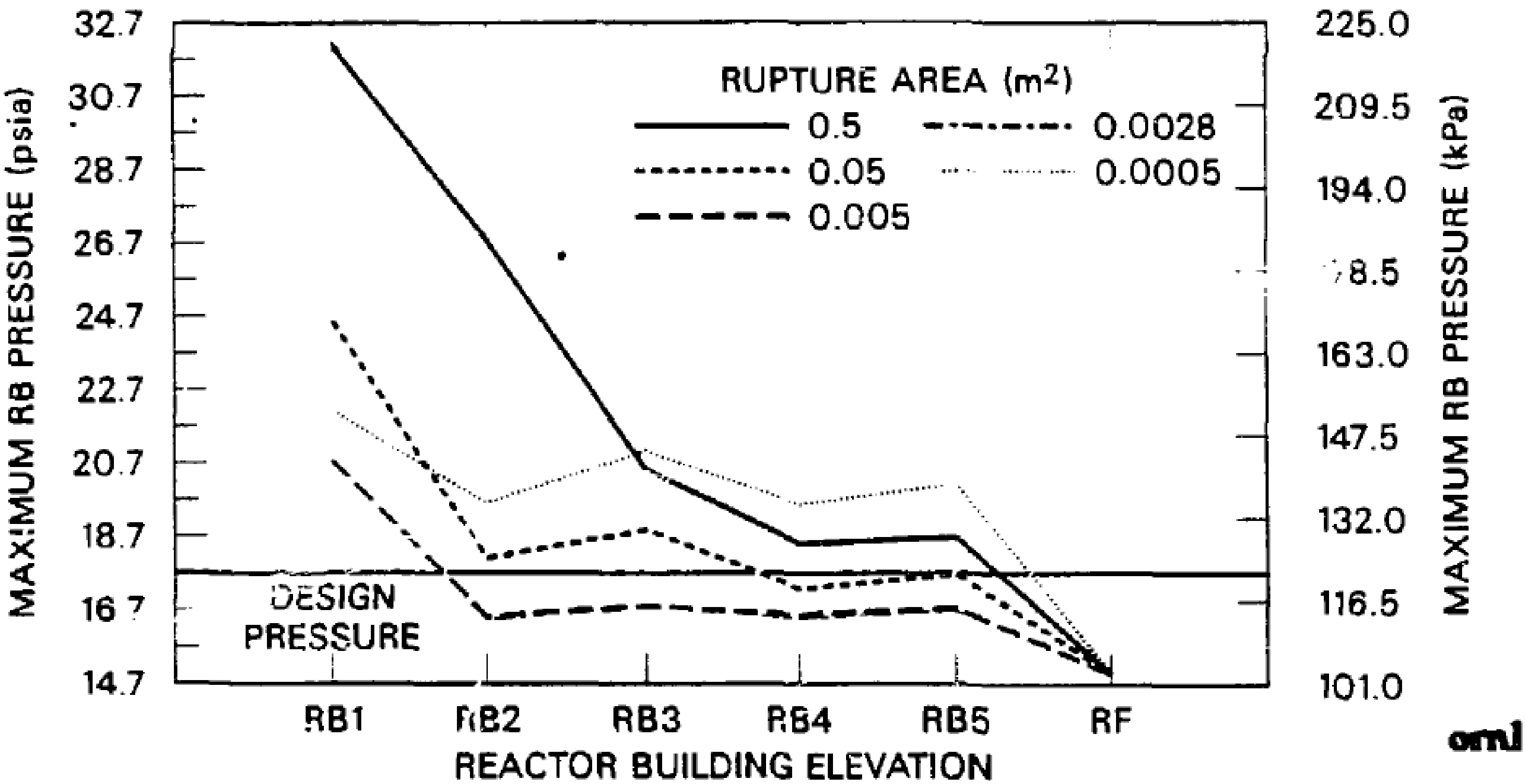
The hydrogen explosions in Units 1, 3, and 4 had a significant impact on the accident response

- – Injured workers
- – Destroyed equipment, water line, power cables
- – Prompted evacuations

- Explosions were unexpected by operators and Emergency Response Center staff
- Explosions should not have come as a surprise

> Hydrogen explosions were a "game changer" in responding to the accident.

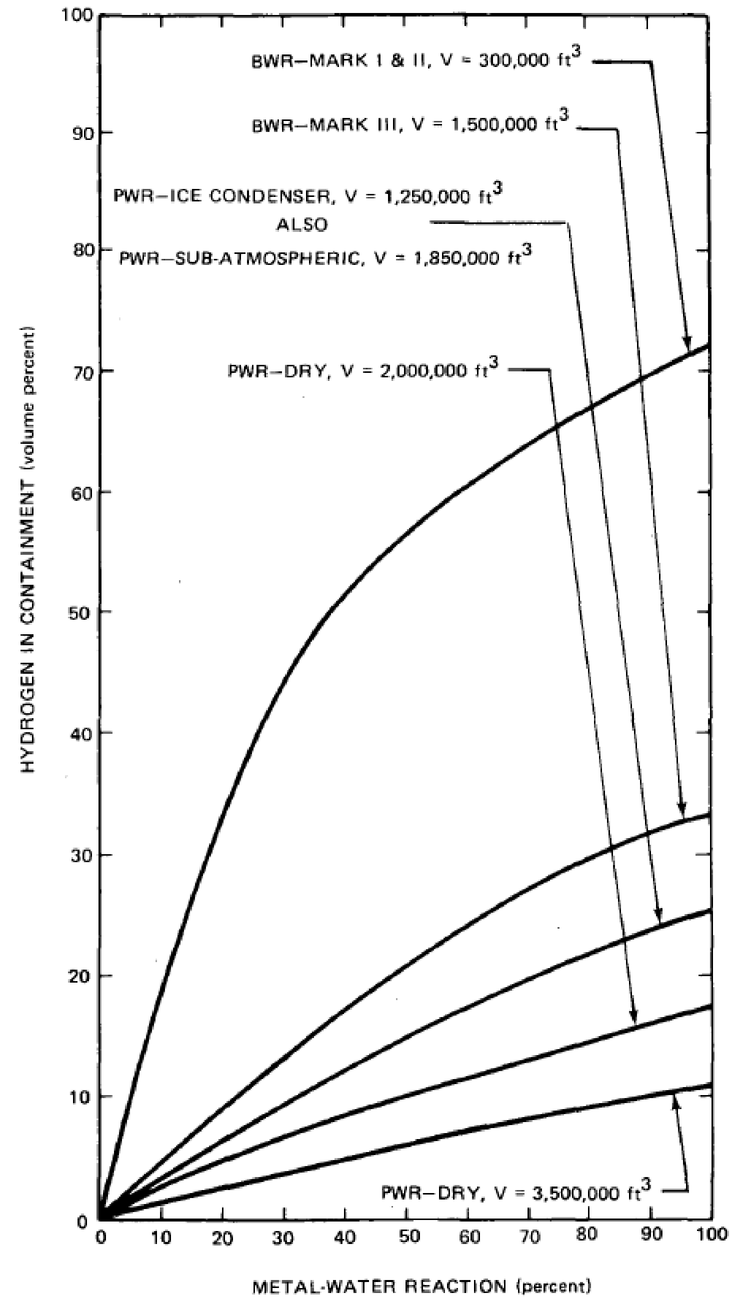
Deflagrations Easily Fail Secondary Containment in Mark I BWR



S. Greene CONF-8806153-1 ORNL

Containment Size

- Mark I primary is 300,000 ft^3
- Smallest of all designs
- Quickly reaches high H2 concentration if core overheats
- All Mark I reactors operate with inert – N2 filled – primary systems



LWR H2 Manual NUREG/CR-2726

Observations

- Fuel pin overheating and H2 production occurs very rapidly (~1 hr) once pins are no longer covered by water
  - Deflagration and FP release with 24 hr of SBO predicted (SAND2007-7697)
- Volume of refueling bay (~10^6 ft^3 or 2.8 x10^4 m^3) is 3 X larger than primary containment but pressure is nearly atmospheric.
- Inventory of Zr initially in each reactor, H2 assuming 100% reaction and expansion to NTP.

Unit	ZR (tonne)	H2 (tonne)	H2 (m^3)
1	44	2	23804
2 or 3	60	3	32612

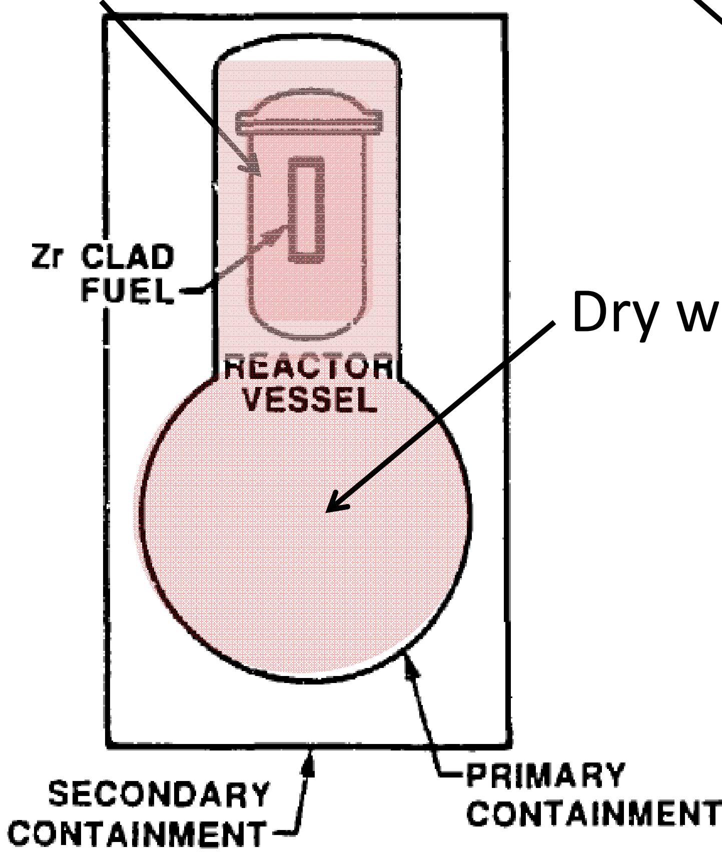
Where Can the H2 go?

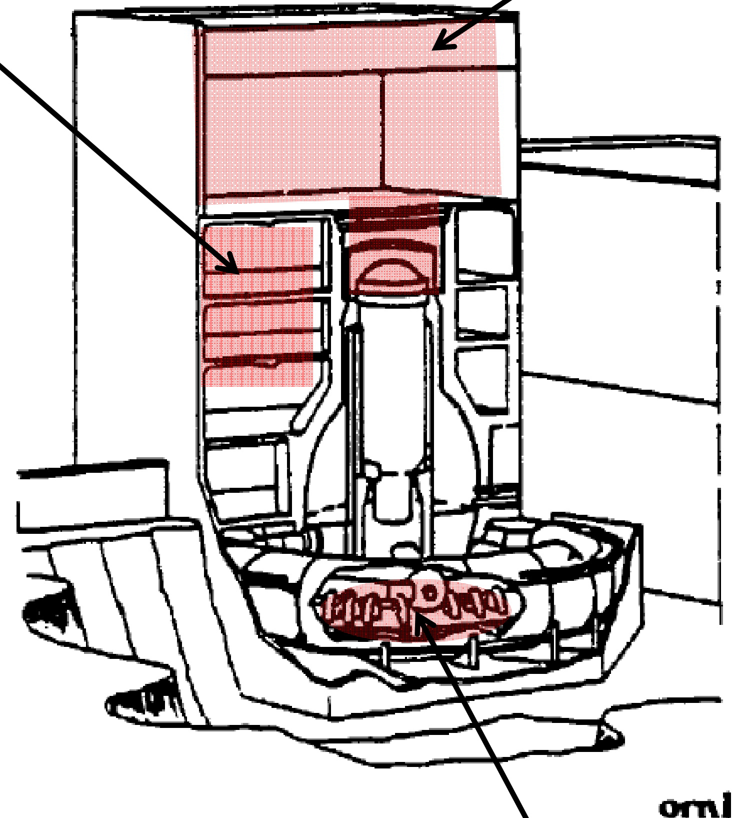
Reactor
Pressure vessel

Secondary containment

Refueling bay

Dry well

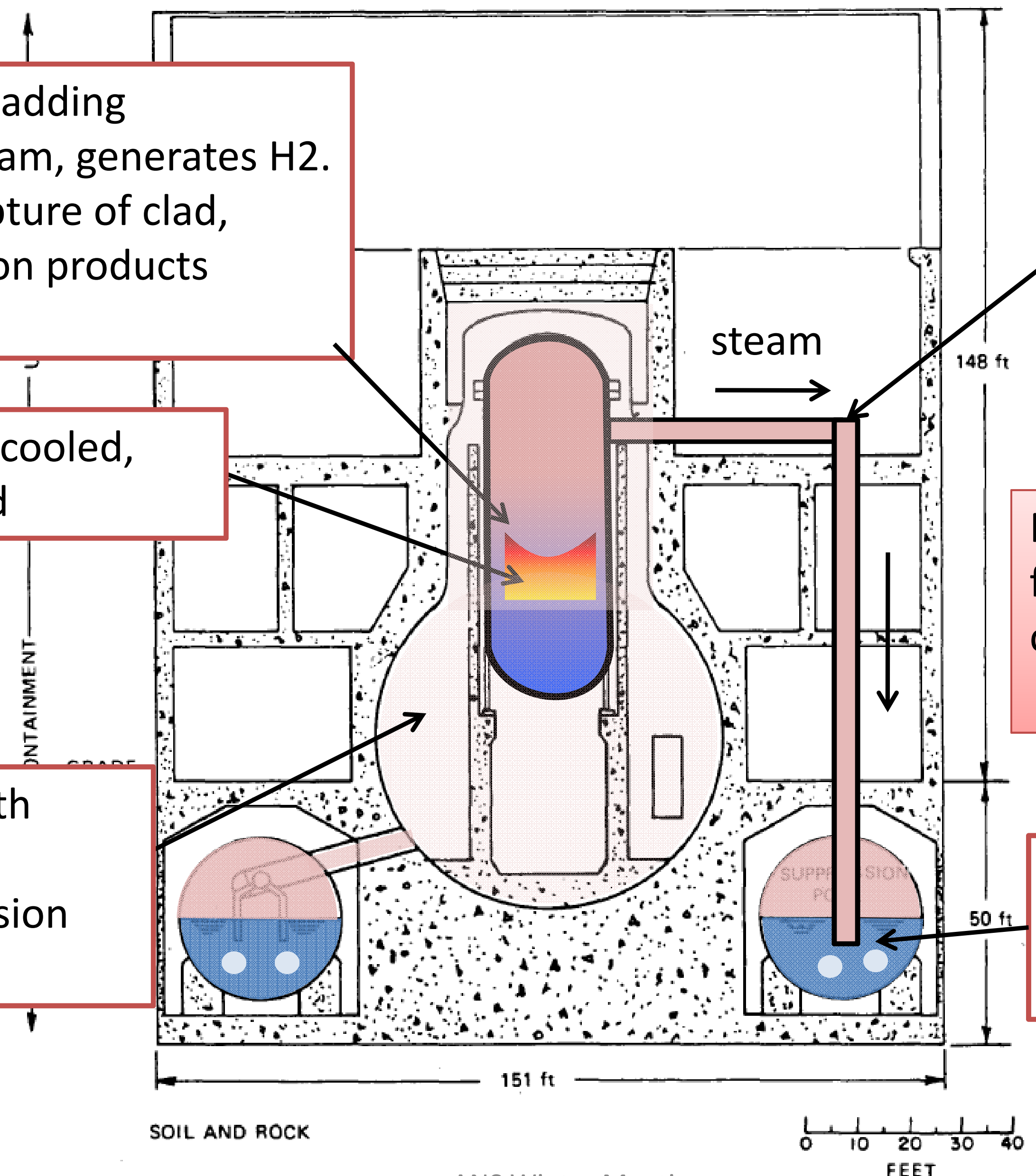




S. Greene CONF-8806153-1 ORNL

Above suppression pool

Damaged core releases fission products, generates hydrogen



Exposed fuel cladding oxidized by steam, generates H2. Ballooning, rupture of clad, release of fission products

Core not being cooled, highly damaged

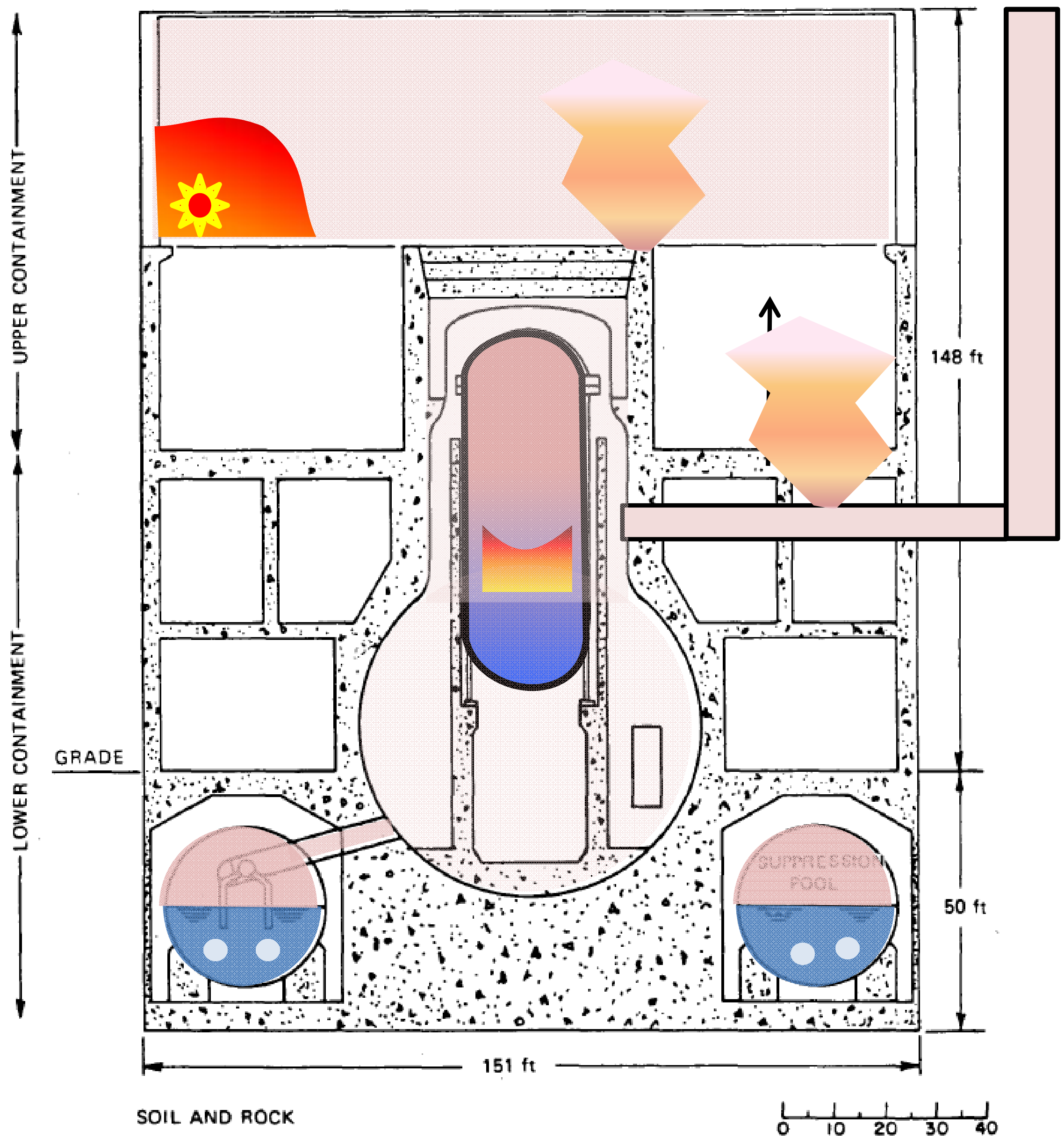
Dry well filled with nitrogen, steam, hydrogen and fission products

Mixture of steam H2 and fission products (FP) flow out of reactor

Pressure approaching failure level in primary containment

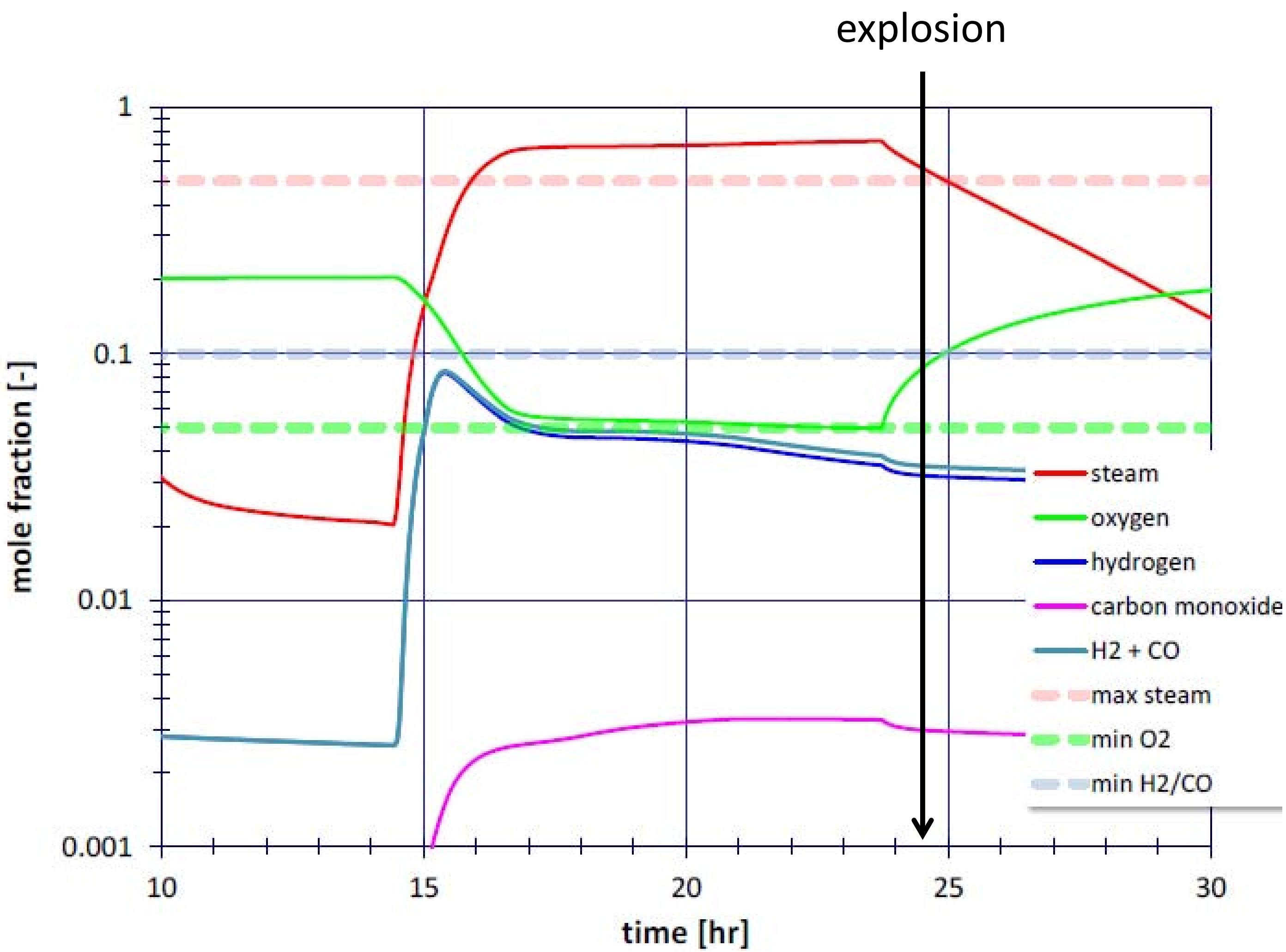
Suppression pool scrubs some FP from steam/H2

Vent Primary Containment to Reduce Pressure

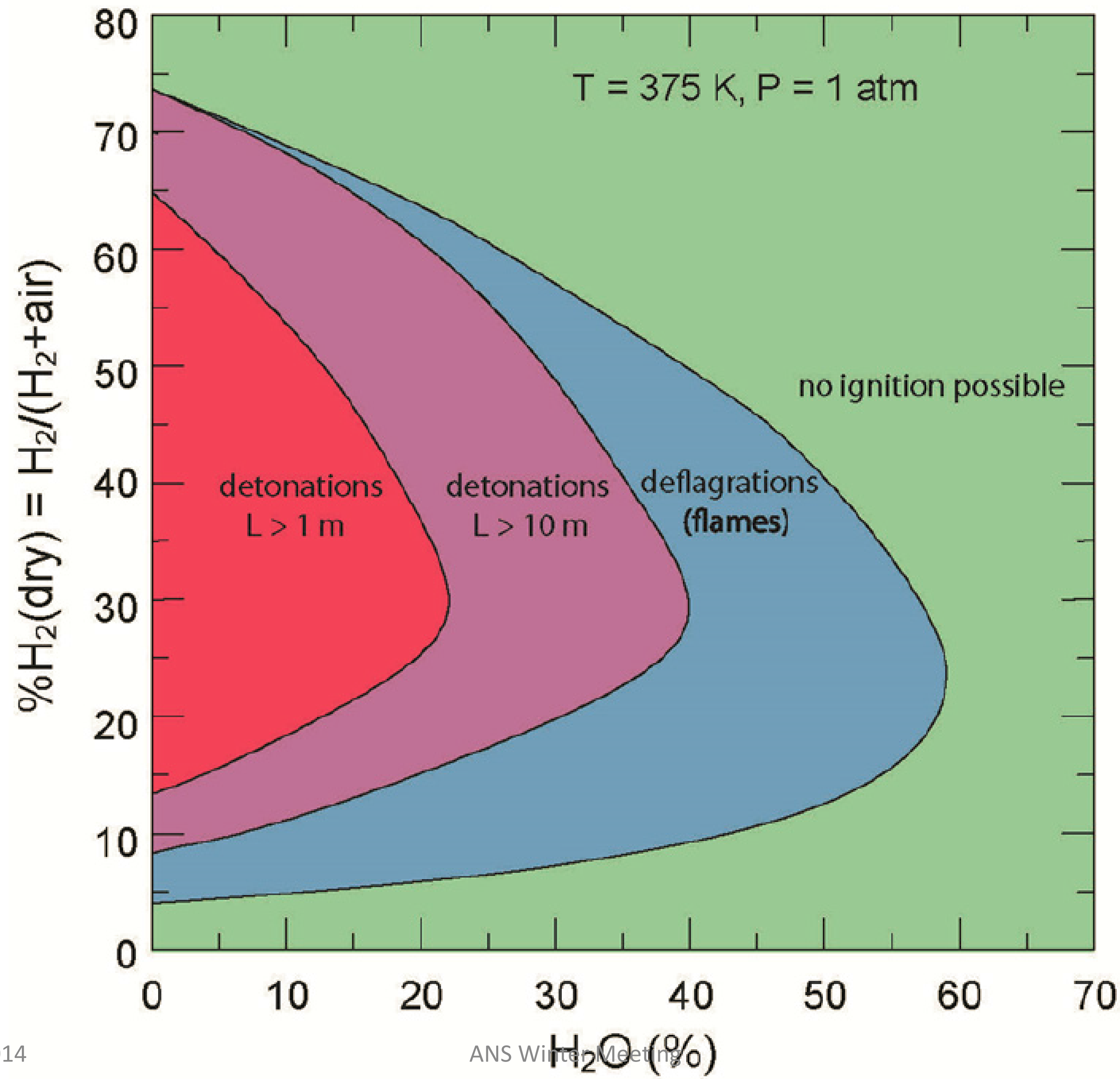


Vent primary containment. Some gas enters reactor building. Exact path unclear but H2 fills refueling bay region, mixes with air and explodes.

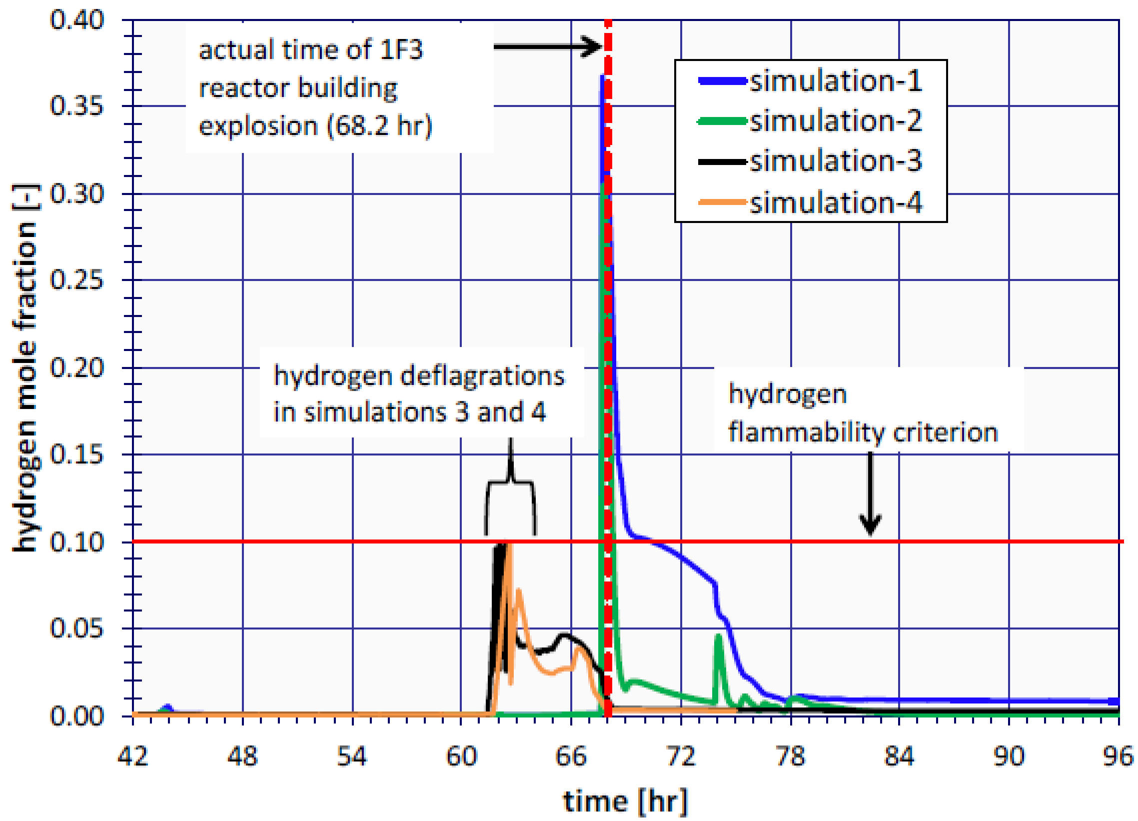
Gas composition in 1F1 Building



Sandia 2012-6173 MELCOR simulations


T = 375 K, P = 1 atm
no ignition possible
detonations
L > 1 m
detonations
L > 10 m
deflagrations
(flames)
%H2(dry) = H2/(H2+air)
H2O (%)
0
10
20
30
40
50
60
70
80

Gas Composition in 1F3



Origin of flammable gas for explosion	Timing (hours)	Gas transport from containment to reactor building
In-vessel H_2	35 – 44	Trapped in piping for 24+ hours (SGTS system), leaks to building
	57 – 68	**Ruptured S/C vent, S/C vent flows to building [*Simulation-1 and simulation-2*]**
		S/C penetration leakage, S/C vent flows to environment [*Simulation-3 and simulation-4*]
Ex-vessel H_2 and CO	60 – 68	Indeterminate: SGTS leak, vent leak, penetration leakage

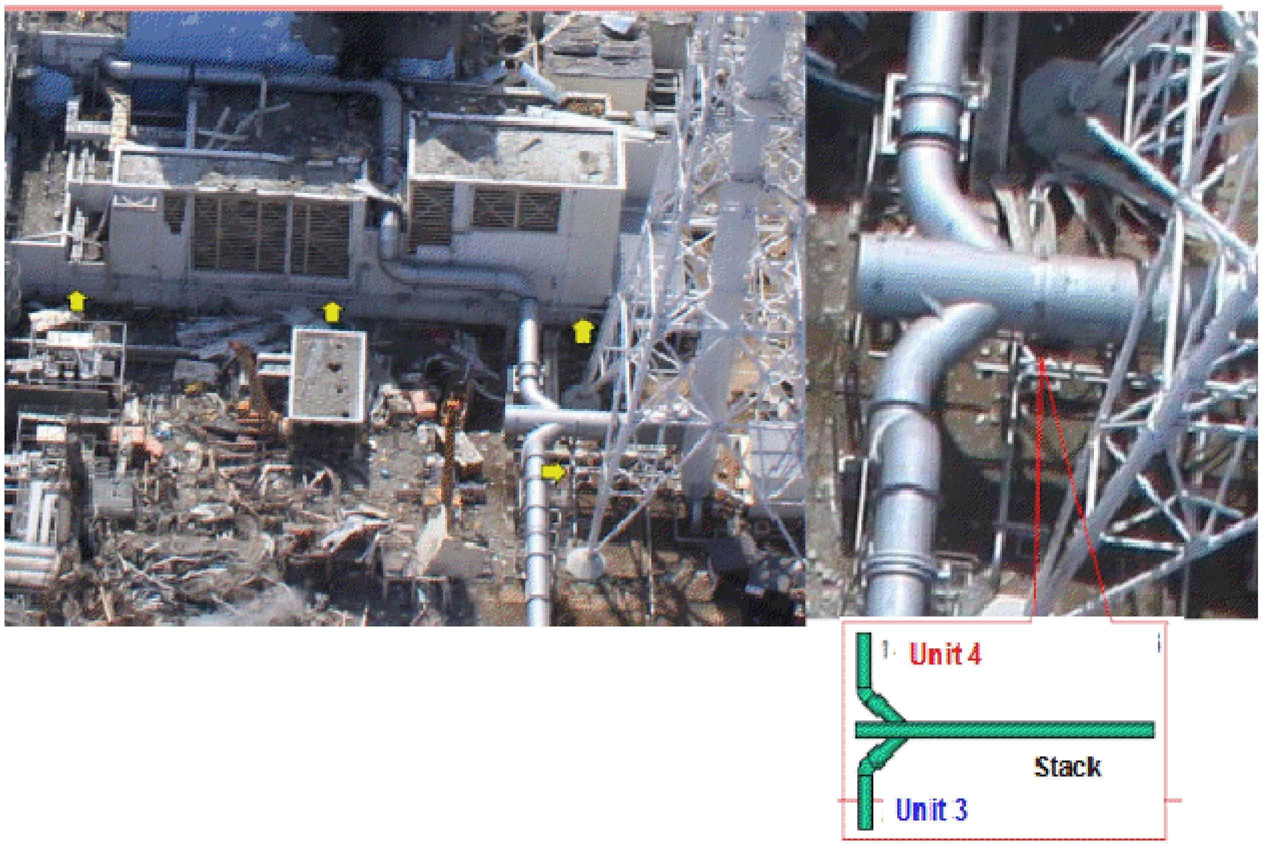
Sandia MELCOR simulations 2012 ANS meeting

H2 Explosion in 1F4

March 17, 2011 Tepco image of damage to Unit 4.

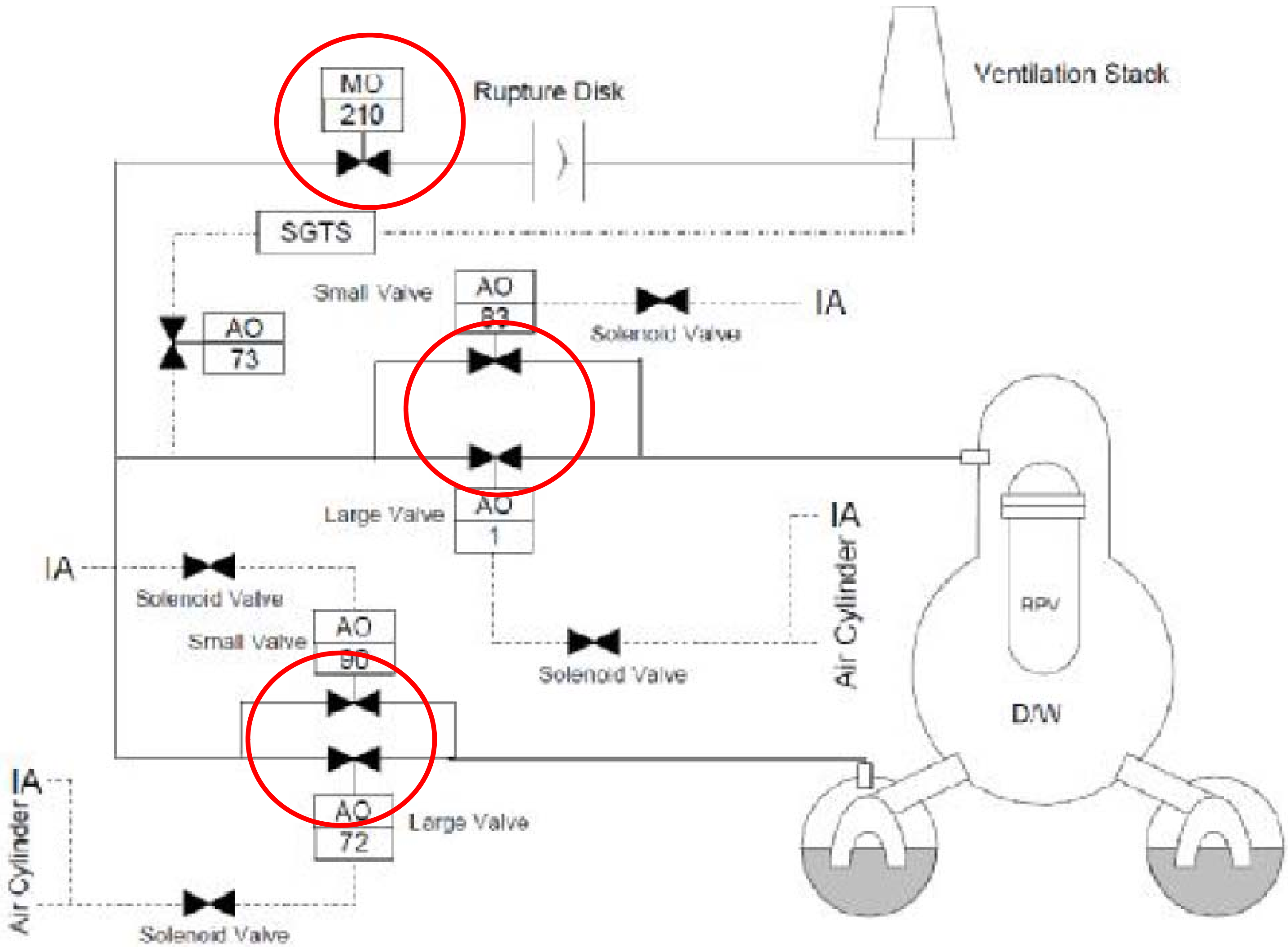
Multi-unit interactions

1F3-1F4 Stack Connection role in H2 entering 1F4



Tepco May 16

Venting and Intrinsic Safety



Hydrogen Issues Arising from 1F Events

- What is optimum strategy for depressurization and low pressure injection with improvised or ad hoc measures?
- Is mitigation needed in BWR reactor buildings?
- Will igniters and PARS work under SBO severe accident conditions?
- Are multi-unit interactions a generic safety issue?
- Will filtered vents be operable under SBO conditions?
- Forensics
  - What happened at 1F?
  - What type of explosions occurred?
  - What can we learn from damage and debris?
  - What are lessons learned for accident management and accident modeling