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

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Explosion Hazards in Waste Storage and Treatment Facilities

Hanford WA Pu-239 from 1945 to 1989

$2 \times 10^8$ \& radioactive waste in leaking tanks

WTP convert to glass, 36 tonne/day in 2014

Radiolysis and chemical reaction create H2, N2O, O2.
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

\[ P_s \rightarrow P_{CJ} \rightarrow P_i \]

\[
\begin{array}{c|c|c|c|c}
\text{products} & \text{Taylor wave} & \text{detonation} & \text{reactants} \\
\hline
u_i = 0 & u_z & U_{CJ} & u_j = 0 \\
\end{array}
\]
Plastic Deformation Validation

LS-Dyna Simulation

Graphs showing residual plastic strain vs distance from end for 2 bar and 3 bar conditions.
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

Explosion
Aerosol dispersion
Vapor space

Liquid Waste

Shock or detonation
Incident Wave

Reflected Wave

Reflected Wave

Reflect

Refraction \( U > C \)

Irregular Refraction \( U < C \)

\[ M = 2.3 \]

\[ M = 2.3 \]

0.5 ms

\[ M = 1.5 \]
\[ M = 1.5 \]
\[ M = 1.35 \]
\[ M = 1.45 \]

\[ 0.5 \text{ mm} \]
\[ 0.3 \text{ mm} \]
\[ 0.5 \text{ mm} \]

Teodorczyk and Shepherd 1994-5

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DDT over water layer

H2-N2O 15 mm gas layer above 35 mm water layer
Explosion Hazards In Nuclear Power
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...”
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

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Containment Size

• Mark I primary is 300,000 ft³
• 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.

<table>
<thead>
<tr>
<th>Unit</th>
<th>ZR (tonne)</th>
<th>H2 (tonne)</th>
<th>H2 (m^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>44</td>
<td>2</td>
<td>23804</td>
</tr>
<tr>
<td>2 or 3</td>
<td>60</td>
<td>3</td>
<td>32612</td>
</tr>
</tbody>
</table>
Where Can the H2 go?

- Reactor
- Pressure vessel
- Secondary containment
- Refueling bay
- Dry well
- Above suppression pool

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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. 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
Gas Composition in 1F3

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