Challenges for Removal of Damaged Fuel and Debris

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C. A. (Chuck) Negin
Project Enhancement Corporation
Germantown, Maryland, USA
“Challenges” can be addressed for many topics such as Managerial, Technical, Regulatory, Financial, Safety, etc.

This presentation’s focus is primarily technical, and is addressed in four major phases, each of which has different challenges:
1. Characterization In Situ
2. Removal
3. On site Management
4. Offsite Management

Mostly TMI-2 examples for illustration (EPRI NP-6931 and others)
## Fuel Damaging Events; Chronologically

<table>
<thead>
<tr>
<th>Plant (year)</th>
<th>INES Scale</th>
<th>Country</th>
<th>Primary cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRX (1952) water cooled, heavy water moderated</td>
<td>5</td>
<td>Canada</td>
<td>Design, operator error</td>
</tr>
<tr>
<td>Windscale (1957) gas cooled graphite pile</td>
<td>5</td>
<td>UK</td>
<td>Lack of information for operators</td>
</tr>
<tr>
<td>SL-1 (1961) small prototype PWR</td>
<td>4</td>
<td>USA</td>
<td>Design</td>
</tr>
<tr>
<td>Chapelcross (1967) Magnox carbon dioxide cooled, graphite moderated</td>
<td>4</td>
<td>UK</td>
<td>Design, operations</td>
</tr>
<tr>
<td>Fermi 1 (1968) sodium cooled</td>
<td>4</td>
<td>USA</td>
<td>Design</td>
</tr>
<tr>
<td>Agesta (1968) water cooled</td>
<td>4</td>
<td>Sweden</td>
<td>Design</td>
</tr>
<tr>
<td>St. Laurent (1968) gas cooled, graphite moderated</td>
<td>4</td>
<td>France</td>
<td>Procedure</td>
</tr>
<tr>
<td>Plant (year)</td>
<td>INES Scale</td>
<td>Country</td>
<td>Primary cause</td>
</tr>
<tr>
<td>-----------------------------------------------------------------------------</td>
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</tr>
<tr>
<td>Lucens (1969) experimental gas cooled, heavy water moderated</td>
<td>5</td>
<td>Switzerland</td>
<td>Channel flow blockage</td>
</tr>
<tr>
<td>Jaslovské Bohunice, A-1, (1977) gas cooled, heavy water moderated</td>
<td>4</td>
<td>Slovakia</td>
<td>Operator error, blocked fuel channel</td>
</tr>
<tr>
<td>Three Mile Island (1979) PWR, light water cooled</td>
<td>5</td>
<td>USA</td>
<td>Design, operator error, relief valve stuck open</td>
</tr>
<tr>
<td>Chernobyl (1986) RBMK, water cooled, graphite moderated</td>
<td>7</td>
<td>Ukraine</td>
<td>Design, violation of operating procedures</td>
</tr>
<tr>
<td>PAKS (2003), PWR</td>
<td>3</td>
<td>Hungary</td>
<td>Design, operational delay</td>
</tr>
<tr>
<td>Fukushima-Daiichi (2011), BWRs, light water cooled</td>
<td>7</td>
<td>Japan</td>
<td>Tsunami, Design</td>
</tr>
</tbody>
</table>
Major Phase 1: Characterization In Situ

- Visual information or visual depiction *of the actual conditions* as soon as possible
- Until this happens, decisions and detailed planning for fuel removal cannot proceed and have great uncertainty
- Challenges for in situ characterization related to
  - Gaining Access
  - Selection of equipment for the radiation, temperature, immersion
  - Placement for still and video cameras, sonar and laser scanning
  - Other information
  - Analysis of information gathered
- Remote Technology is essential, but challenging in itself
Chernobyl
Major Phase 2: Removal

TMI-2 History

- Five concepts for fuel removal before visual characterization; none used:
  - Dual Telescoping Tube, Manipulator
  - Manual Defueling Cylinder
  - Indirect Defueling Cylinder
  - Flexible Membrane
  - Dry
- Later, a remotely operated service arm, shredder, and vacuum transfer system was considered and rejected
- Used the core bore mining drill and manual methods
## Some Important TMI-2 Removal Decisions

<table>
<thead>
<tr>
<th>Decisions</th>
<th>Significance</th>
</tr>
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</table>
| Decision to not to install in-core shredding equipment in the vessel | • New application for the proposed technology, concern that failure would cause problems, relied mostly on manual manipulation with power assist  
• Allowed defueling to start earlier, knowing that overall schedule would not be minimized. This was preferred over a 3 year development before any fuel would be removed. |
| Decision to leave refueling canal dry          | • Less depth for manually operated tools  
• Shielded work platform 2m above the reactor pressure vessel flange  
• Reduced need for water processing  
• Dose rates were low within the refueling canal |
| Core Boring Machine                            | • Samples of the fuel and debris that was melted together  
• Breaking up the crust and molten mass when manual methods were unsuccessful |
TMI-2 Defueling Progress and Key Impacts

1982-1983
Defueling Options Evaluations

1982
First Video of Core

1983
First Sample

1983
Sonar Mapping & Improved Video

1984
Defueling Method Decision
Dry Canal & Mostly Manual

Mid-1984
Vessel Head Lift

1984
Vessel Defueling Progress

Oct-85 Apr-86 Nov-86 May-87 Dec-87 Jun-88 Jan-89 Aug-89


Vessel Defueling Progress

0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%

Oct-1985
Dec-1986
April-1987
Sept-1987
Dec-1987
May-1989
Core Former Disassembly
Feb-1990

Lower Grid Cutting
Lost Water Clarity
Each had their own specific challenges:
- Core Cavity
- Lower Support Grid
- Flow Distributor
- Behind and within the Core Baffle Plates
- Lower Head

Damage on the Underside of the Upper Grid
Boiling Water Reactor

- Some Important Differences:
  - Duration of extreme temperatures!
  - Mass of material above the core
  - Thinner vessel walls
  - Vessel melt through
  - Mass of material beneath the vessel
  - Greater vertical dimension
Accounting for Fissionable Material

- Standard accountability (at the gram level) was impossible
- NRC granted an exemption to the requirement
- Required a detailed survey conducted after defueling for what remained
- Computer code analyses conducted for fissionable nuclides: 1) existing prior to the accident, 2) remaining after the accident, and 3) radioactive decay
- Therefore the net balance is what was sent to Idaho

300,000 lbs = 136,000 kg
Residual Fuel

- When defueling was complete, there was about 1,000 kg of fuel remaining; the reactor pressure vessel has less than 900 kg
- In the reactor coolant system has less than 133 kg; greatest single location amount is \( \approx 36 \) kg on the B Steam Generator upper tube sheet
- Criticality ruled out by analysis

Assessment Required a Combination of:

- Video inspection for locations
- Gamma dose rate and spectroscopy
- Passive neutron solid state track recorders, activation, BF3 detectors
- Active neutron interrogation
- Alpha Detectors
- Sample Analysis
Remote Technology in the 1980s

- Much of what was done was innovation based on the immediate need.
- The wagon is one example. A toy remote controlled vehicle was used to survey a very radioactive equipment cubicle.
- Several robotic devices were created specifically for TMI-2; ROVER is one example. A miniature submarine in the pressurizer is another.
Characterization and Removal Remote Capability

Functions

1. Information & Data
   - In Place Samples
     - Characterize
       • Photos
       • Video
       • Gamma
       • Neutron
       • Toughness
       • Brittleness
       • Composition
       • Temperature
       • pH (?)
       • Salinity (?)
     - Retrieval
       • Cutting
       • Boring
       • Chipping
       • Grinding
       • Grabbing
       • Clamshells
       • Loading sample containers

2. In Place Force Operations
   - Size Reduce
     - Materials
       • Corium rocks
       • Crust
       • Once melted mass
       • Steel & Zircalloy
       • Fused combinations
     - Operations
       • Cutting
       • Crushing
       • Shearing
       • Boring
       • Coring
   - Positioning
     - Tools
       • Saws
       • Drills
       • Chisels
       • Borers
       • Millers
       • Plasma Arc

3. Movement Operations
   - Retrieve
     - Materials
       • Corium
       • Metal pieces
       • Particles
     - Operations
       • Grabbing
       • Lifting
       • Vacuuming
   - Remove
     - Fill Containers
       • Buckets
       • Baskets
       • Canisters
     - Canister Operations
       • Inserting
       • Rack position
       • Lid placement
       • Dewatering
       • Lifting out
The Challenge:
- Developing remote equipment for any one of the functions on the previous viewgraph can be considered a project;
- or part of a project that will develop equipment for multiple functions.
- The development cycle for each application can take weeks or months, depending on complexity and if components are available or component development is also needed.
Major Phase 3: Onsite Management

- Containers for removal
- Movement of containers on site
- Containers for storage and shipping
- Storage facility on site and transport
Three Canister Design – 341 Shipped

271 Fuel & Debris Canisters

10 Knockout Canisters (for vacuum tools)

60 Filter Canisters (water processing)
Storage and Handling

Canister Staging in Spent Fuel Pool

Transfer Cask Operations
Major Phase 4: Offsite Management

- Transport to offsite
- Storage offsite: wet or dry
- Processing or Disposal
Shipping

Loading the Shipping Cask

Shipping Cask
Packaging, Transport, & Storage at Idaho

1986 to 1990
341 canisters of fuel & debris in 46 shipments by rail cask to the Idaho National Laboratory

1990 to 2000
Wet Storage in Spent Fuel Storage Pool

2000 – 2001
Removed from pool, dewatered, dried, and placed in dry storage
Canister Dewatering

- 1 year required for design, fabrication, testing. About 6 months for drying operations of the 341 canisters.
- Water removed in the pool area. Drying conducted in two vacuum ovens by remote control in a shielded machine shop.
- Each oven held 4 canisters. Each cycle required 2 days for drying at a maximum temperature of ≈500º C.
- Since then, vacuum drying for non-TMI fuels has been conducted at < 100º C, with drying times of about a week.

Canister Dewatering Machine in the Pool Area

Loading a Canister into the Vacuum Dryer
Drying Campaign at INL
Conclusion

- There are significant differences among every fuel damaging event.
- Challenges and approaches may be the same in general, there will be significant differences in every situation.
- Until visual evidence of the physical form is available there will be great uncertainty for designing the tools, machines, and methods for removal.
- Damaged fuel removal is the most challenging aspect in most post-accident cleanups.
- Selection of fuel removal hardware must be such that its failure in use will not significantly impact continued removal operations.
- Planning and design must consider the entire fuel removal and disposition campaign from beginning to end.
- This integration must include worker health and safety, physical removal tools and equipment, containers, various measurements of removed materials and debris, interim on-site storage, and how the material is to be packaged and transported.