U.S. Perspectives Based on TMI-2 Defueling Activities

6th International Forum on the
Decommissioning of the Fukushima Daiichi Nuclear Power Station
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Three Mile Island Unit 2 (TMI-2) Accident on March 28, 1979

- **Design and Other Considerations:**
  - Plant contained two Babcock &Wilcox Pressurized Water Reactors, each rated at 2,772 MWt
  - Two loop nuclear steam supply system housed in a large dry containment
  - “Titanic” mentality about design safety existed
- **Event Synopsis:**
  - Loss of steam generator feedwater during maintenance on condensate polishing demineralizer system
  - Pressurizer pilot operated relief valve failed to close leading to undetected small break loss of coolant accident
  - Subsequent operator actions led to severe accident
    - Approximately 26% of core region voided; 20,000 kg of material relocated to reactor pressure vessel (RPV) lower head
    - Hydrogen release led to ignition in containment
  - Limited radioactive material release: 15 Ci (560 E9 Bq) of Iodine-131; International Nuclear Event Scale (INES) Level 5 [Accidents at Fukushima Daiichi rated as INES Level 7]
  - 144,000 persons within 15 miles voluntarily evacuated for ~1 week

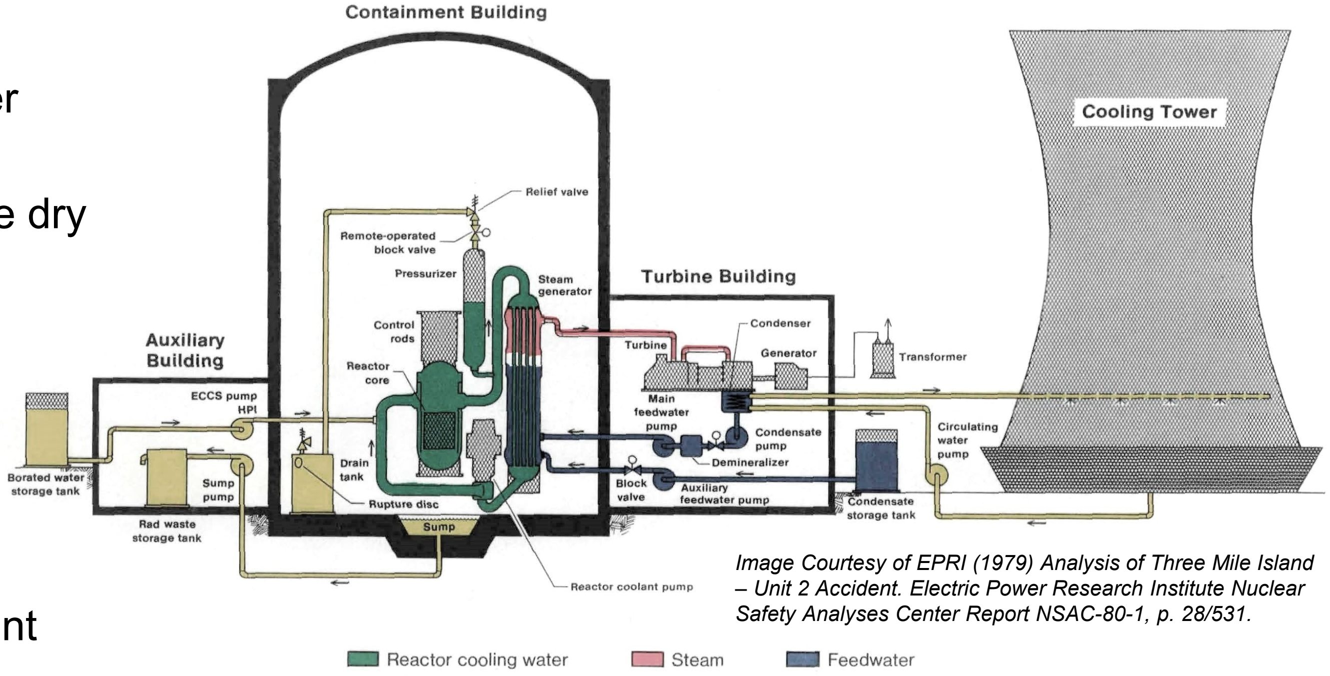
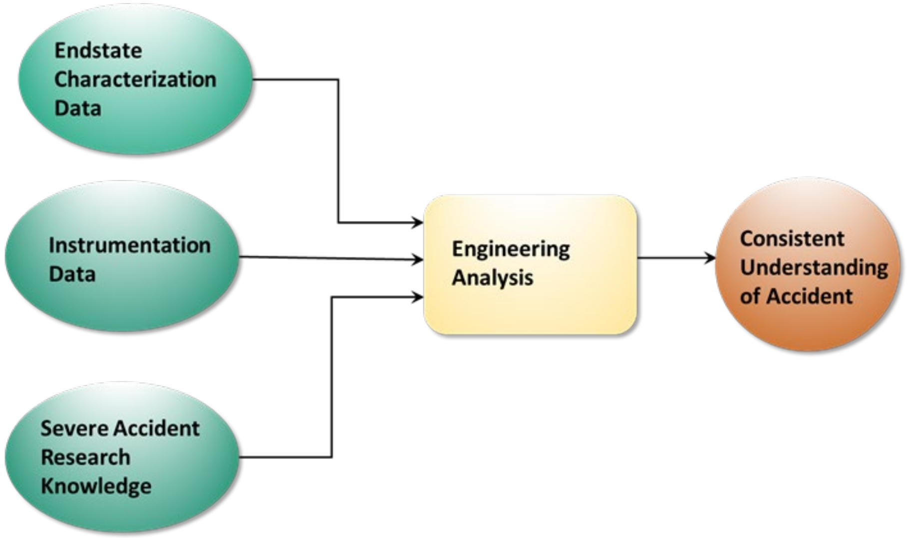


Image Courtesy of EPRI (1979) Analysis of Three Mile Island – Unit 2 Accident. Electric Power Research Institute Nuclear Safety Analyses Center Report NSAC-80-1, p. 28/531.

TMI-2 Approach to Identify and Prioritize Cleanup Information Needs

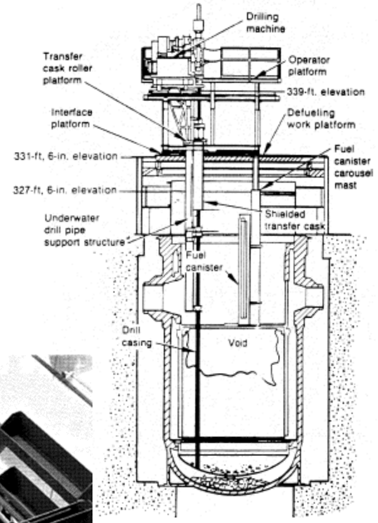


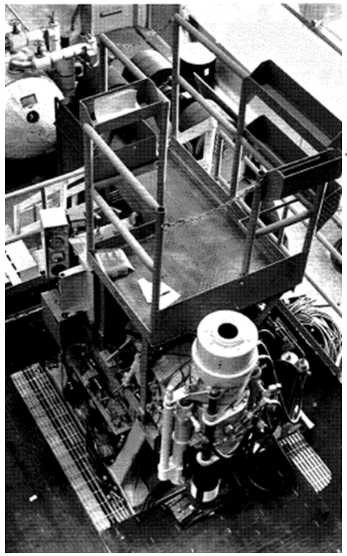
- **Process relies on instrumentation data, post-accident examinations, existing severe accident knowledge, and engineering analyses**
- **Efforts initially focused on stabilizing the plant before focusing on cleanup**

- **Key to prioritize activities, emphasizing those that:**
  - **Minimize future radiation releases and site hazards,**
  - **Ensure safe and efficient cleanup, and**
  - ***As resources allow*, reduce uncertainties related to accident progression and reactor safety enhancement.**
- **Most high priority information *desired* for reactor safety insights *required* for cleanup**

Various Debris Retrieval Methods Employed

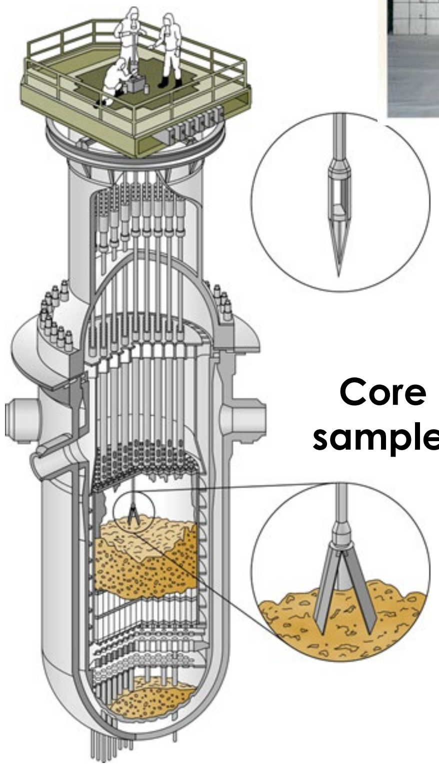
Core bore machine (adapted mining drill)





- Six major regions: core cavity, lower core support assembly (LCSA), behind and in the core baffle plate, lower reactor vessel head, and ‘elsewhere’ in the plant
- Different location geometries and debris types required different retrieval methods:
  - Core Bore Machine (solidified molten core, LSCA cutting)
  - Cutting (Plasma Arc, Hydraulic Shears and Saws)
  - Bulk Removal (Air Lift)
  - Mini-submarine (in pressurizer)
  - Manual Controlled Equipment (Grippers, Buckets)
- Difficulties (resolution)
  - In-situ repairs (mockups and testing, spares and repair tools)
  - Different debris/structure properties (prototypic testing)
  - Water clarity (hydrogen peroxide)
  - Heterogeneity (distribution and mass of samples)

Intact TMI-2 vessel and containment simplified cleanup

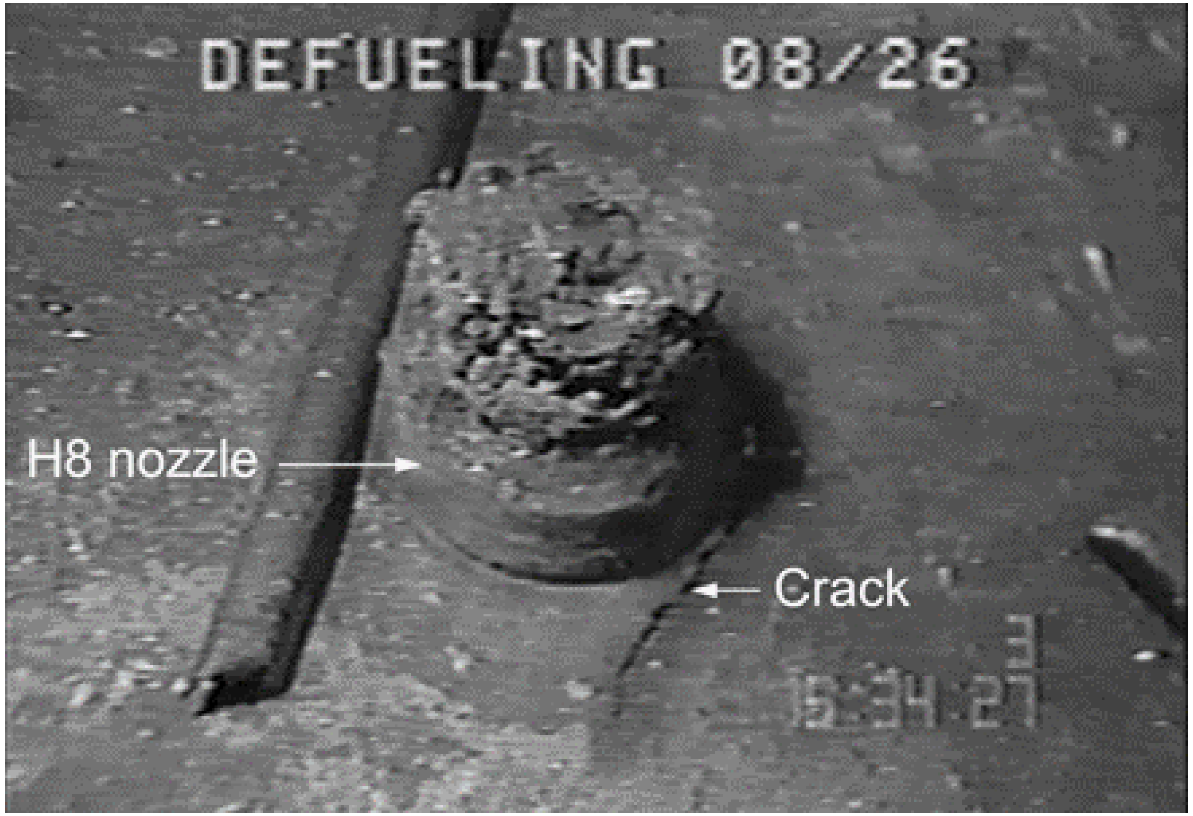


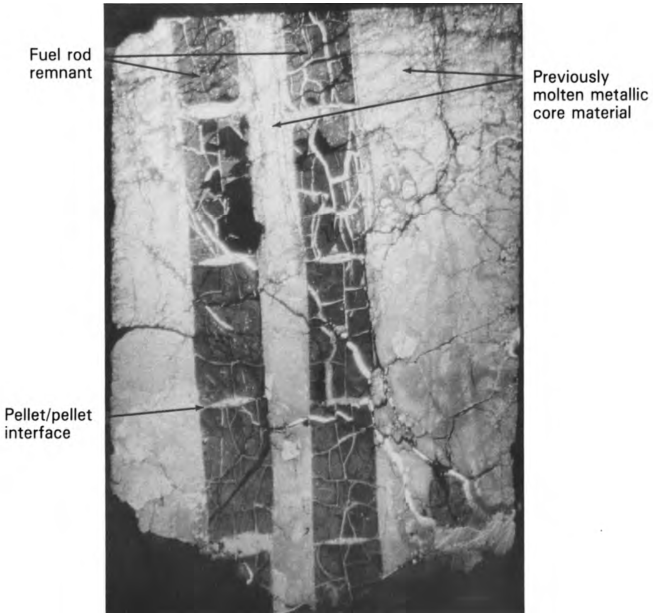
Manual scooper

Core grab sample tool

Graphics courtesy of Energy*Solutions* and INL

Examinations Provided Insights for Cleanup and Reactor Safety

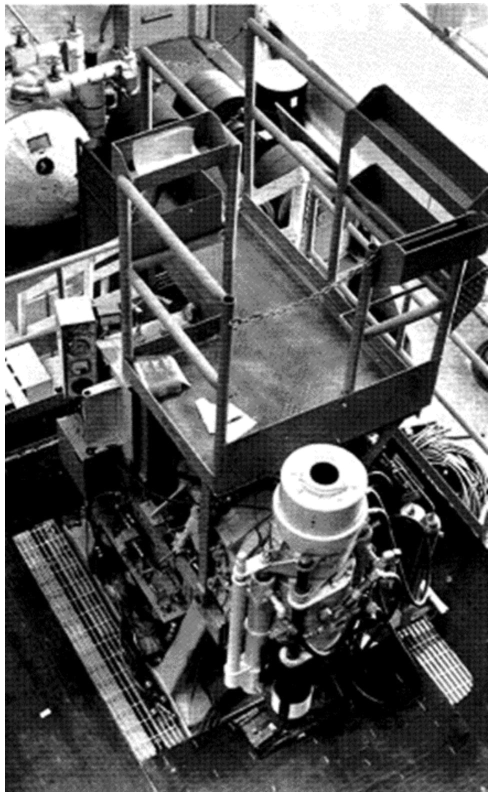




K-9 Core Bore Image Showing Material Interaction and Cladding Dissolution

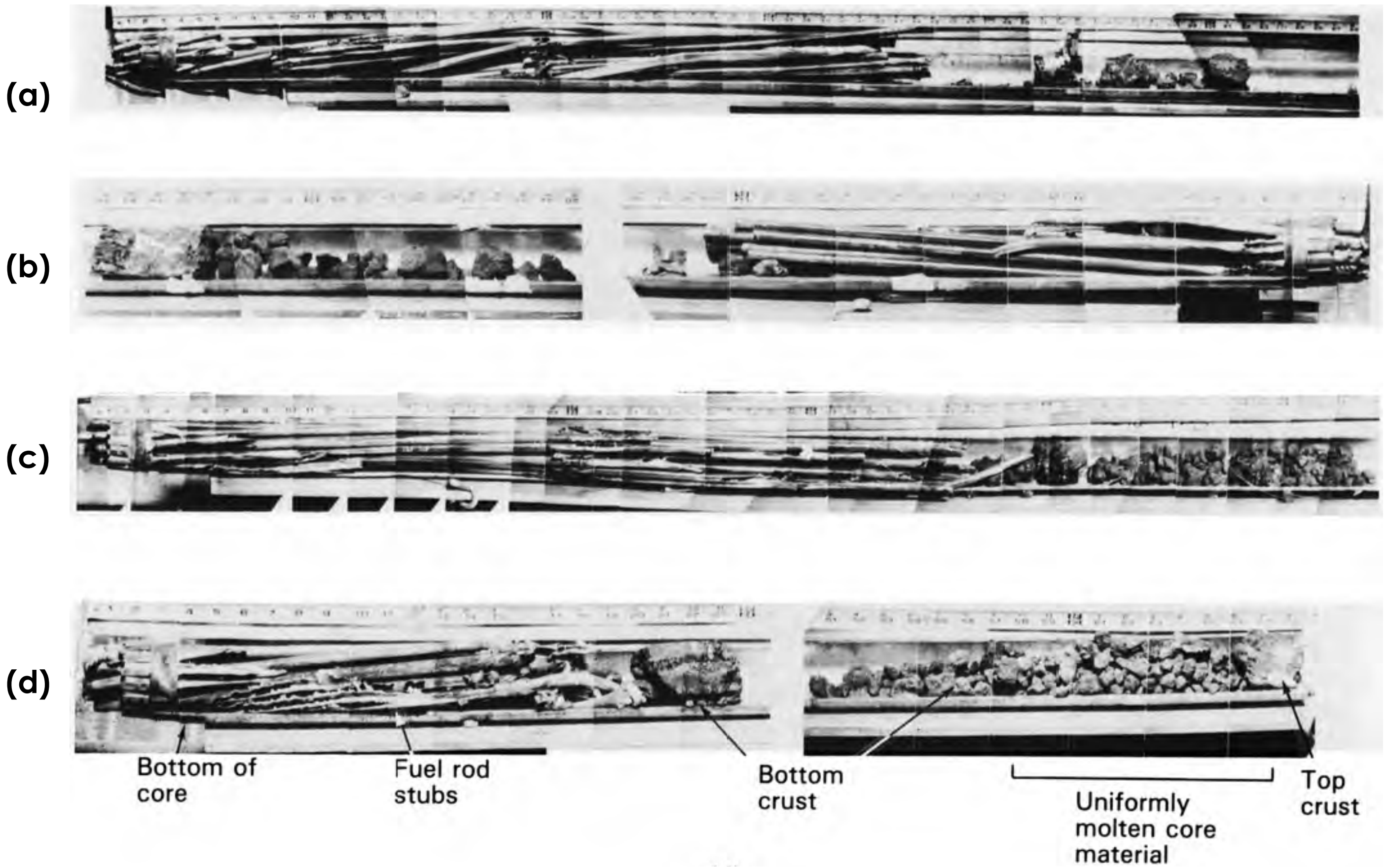
Graphics courtesy of INL and Energy*Solutions*

Core Bore Machine Provided Insights for Reactor Safety and Facilitated Subsequent Defueling



Core bore machine (adapted mining drill)

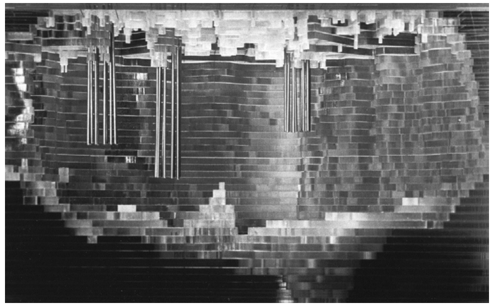
Graphics courtesy of INL and Energy*Solutions*



Mosaic photographs of core bore samples for (a) peripheral core position D8, (b) central position G8, (c) peripheral position G12, and (d) central position K9.

- Defueling paused for core bore sample retrieval
- Acquired 9 full length core samples of debris and remaining fuel structure
- *Primary purpose:* benchmark severe accident codes [elemental composition, oxidation state, material interactions, peak temperatures, and retained fission products]
- *Secondary purposes:* support defueling planning and provide access to lower core support structure
- When defueling resumed, core bore machine repurposed to destroy hard layer and eventually core support structure

TMI-2 Examination Perspectives

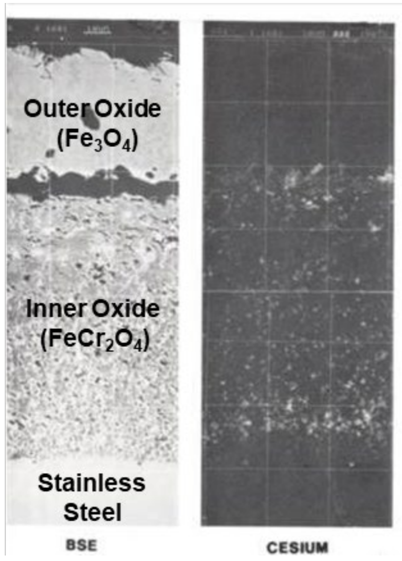


Graphics courtesy of Energy*Solutions* and INL

Desired Information	Methods	Planned Use/Comments
On-Site (In-situ)		
Debris location, topography, fuel and structure damage (distortion, slumping, melting, fragmentation, oxidation, asymmetries, etc.)	visual images (photos, videos, etc.)	Provided insights about core damage and debris location, melt progression and insights for selection of subsequent samples. Documented conditions of samples prior to removal. **Retrospective Comment:** Most useful information for defueling planning and design and model development / confirmation; required for cleanup
Debris location and topography	ultrasonic topography system	Backup to visual images, provided insights about debris location; used throughout defueling efforts. **Retrospective Comment:** Useful information for gross model development/confirmation. Confirmatory data for design and qualification of equipment for debris removal, transport, and storage.

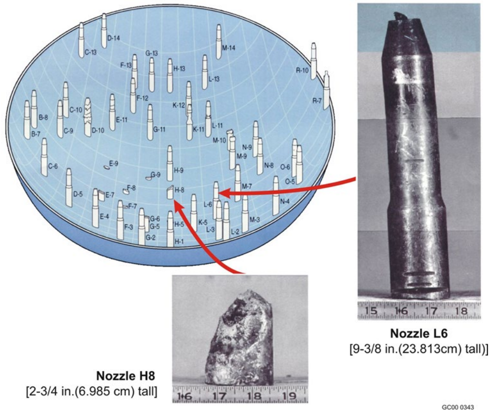
For additional information regarding TMI-2 examination requests, see EGG-TMI-6169 *at:* *https://inldigitallibrary.inl.gov/TMI/EGG-TMI-6169-r1.pdf#search=EGG%2DTMI%2D6169*

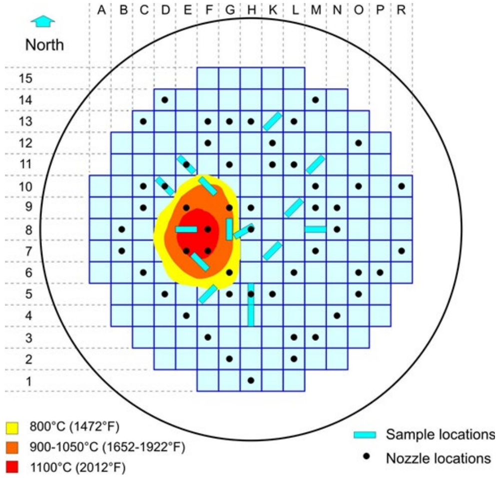
TMI-2 Examination Perspectives (Cont'd)



Graphics courtesy of INL and Energy*Solutions*

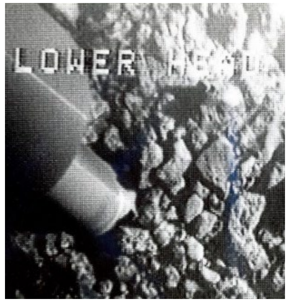
Desired Information	Methods	Planned Use/Comments
Laboratory		
Reactor coolant system structures and component information [peak temperatures, temperature history, and inventory, distribution, form, and size (if particulates) of deposited fission products)]	chemical, radiochemical, and metallurgical exams, and laboratory techniques for measuring physical properties of deposits	Data to benchmark code predictions for temperature and fission product transport and deposition. New models developed, as needed. **Retrospective Comment:** Fission product distribution and temperature information used for gross model calibration.





TMI-2 Examination Perspectives (Cont'd)

Broken Fuel Rods

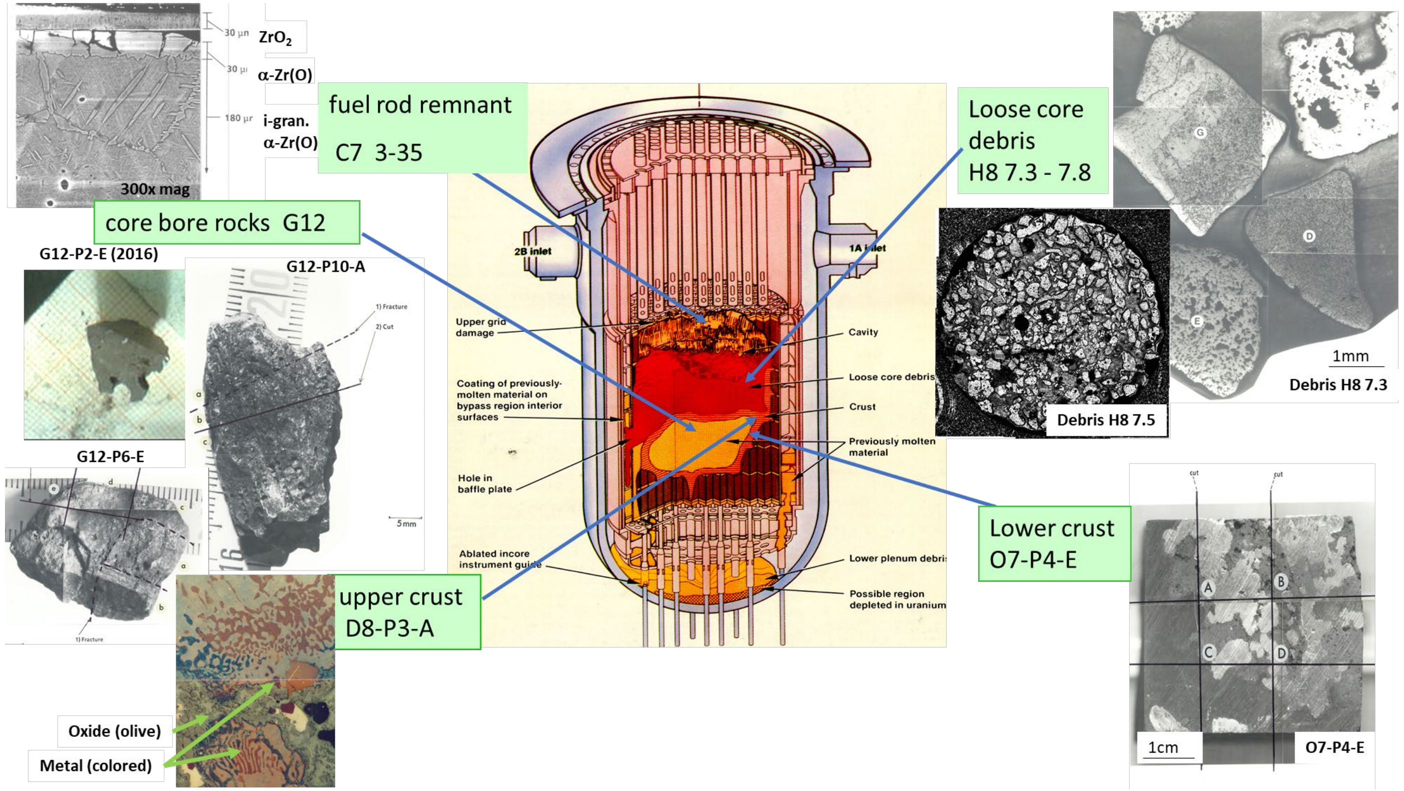


Lower Head Look

Graphics courtesy of Energy*Solutions*

Desired Information		Methods	Planned Use/Comments
Laboratory			
Corium, vessel, and nozzle samples	Loose Debris – composition, fission product retention/release, physical form (size, porosity, permeability), peak temperature, liquefaction temperature, cooling rate	chemical, isotopic, elemental, radiochemical, gamma scanning, metallographic exams and various laboratory methods (pushrod dilatometry, laser flash diffusivity, etc.) to obtain mechanical (hardness, tensile strength, compressive strength) and thermal properties (density, thermal conductivity, thermal expansion coefficient, specific heat capacity, liquidus temperature)	Data to develop and benchmark code predictions for temperature and fission product transport and deposition. New models developed, as needed. Insights regrading reactor pressure vessel integrity and potential failure modes. **Retrospective Comment:** Location-dependent composition data and fission product deposition data useful for gross model calibration but properties vary with oxidation and porosity. Easier to obtain with unirradiated materials (confirming irradiation effects, as needed). Peak temperature information only useful for gross calibration of model results. Confirmatory data for design and qualification of equipment for removal, transport, and storage. Additional data/photos to characterize debris/structure interface on lower head would have been useful.
	Fuel rod segments – characterize fuel rods at boundary or transition zone between the melted and rubble debris; fission product retention/release in intact pellets, oxidized fuel, liquefied fuel, fuel/cladding interactions, residual cladding integrity, peak fuel and cladding temperatures.		
	Core stratification samples (bore samples containing several fuel and one control rod) – composition (ratio of fuel to non-fuel), materials interactions (damage, materials interactions), fission product retention/release, coolability information (porosity, permeability), fission product retention/release)		
	Components (spacer grids, in-core instrumentation, end fittings, vessel steel) - characterize peak temperatures and materials interactions		
	Debris relocated to the vessel lower head (grab samples from hard layer of debris after breakup) – composition, fission product retention/release, fission product retention/release		

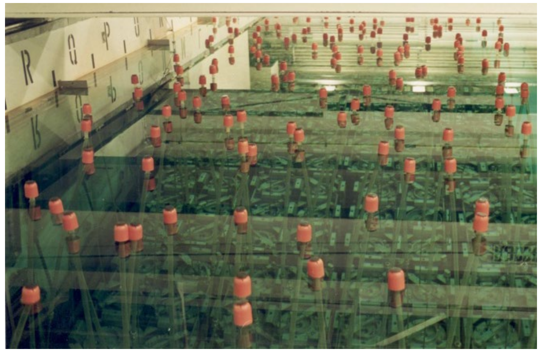
International Participation Important Aspect of Developing Accident Progression Consensus Insights



Graphics courtesy of JRC and INL

- International programs included sample examinations, stand-alone testing, and systems analysis code calculations.
- Exams completed by laboratories in European Union Joint Research Centre, Canada, France, Federal Republic of Germany, Sweden, Japan, Switzerland, and United Kingdom
  - Included debris ‘grab’ samples and fuel rod segments
  - Focused on peak temperatures, elemental composition, chemical form, oxidation state, materials interaction, morphology, fission product retention, and cooling rates / atmospheres
- Examination data, stand-alone test information, analysis code results, and discussions led to important consensus accident progression insights:
  - Mass and composition of relocated material within each RPV region
  - Fission product retention
  - Coolability
  - Oxidation state
  - Hydrogen generation potential

Examinations Supported Defueling, Transport, and Storage Activities

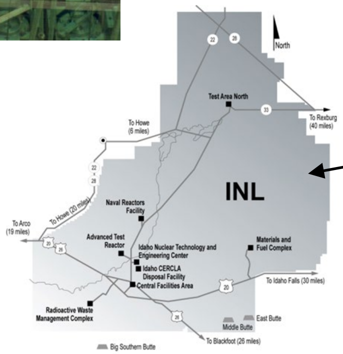


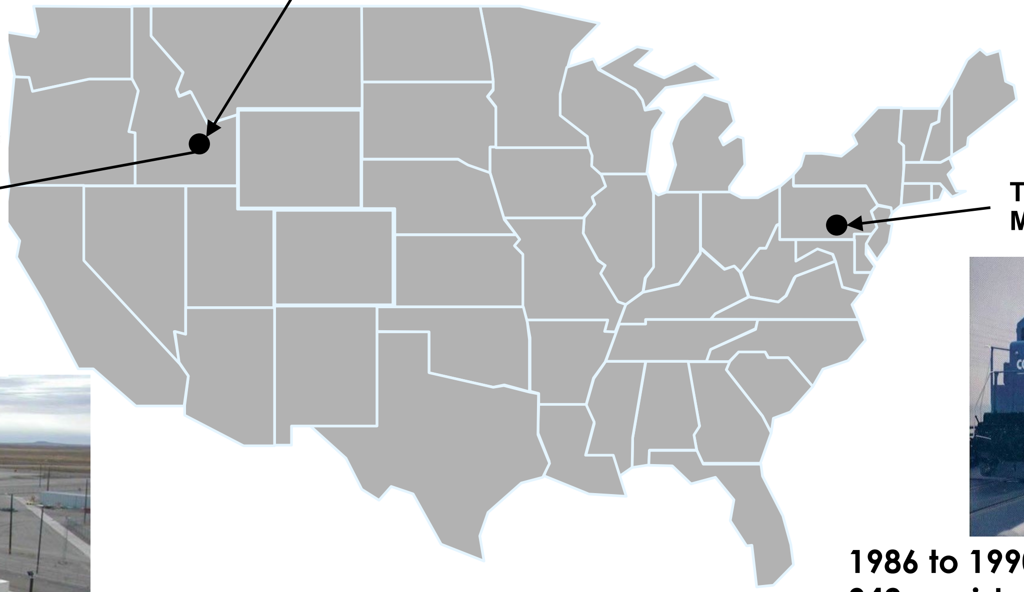
1986 to 2001
Wet Storage in INL TAN Facility Spent Fuel Storage Pool

7 canisters per Rail Transport Cask up to 3 casks per shipment

Fuel & Debris Storage
Idaho National Laboratory (INL)

~2200 miles / 3450 km





Three Mile Island
Middletown, Pennsylvania

2000 – 2001
Removed from pool, dewatered, dried, and placed in dry storage at INL INTEC Facility (25 miles/40 km)

1986 to 1990
342 canisters of fuel and debris in 49 shipments by Rail Transport Cask to INL

Graphics courtesy of
INL and Energy*Solutions*

Types of TMI-2 and Daiichi Defueling Challenges Similar

Graphics courtesy of
TEPCO Holdings and
Energy*Solutions*

- Incomplete knowledge:
  - Location of fuel-containing materials
  - Material properties to design removal equipment and shipping cannisters
  - Locations of highest contamination
- Possible defueling safety concerns:
  - Decay heat
  - Recriticality
  - Combustion/pyrophoric reactions
  - Radiation release (dust generation)
  - Containment or vessel structural failures (load drop, seismic events)
  - Other (industrial occupational safety, fire protection, etc.)
- Stakeholder communication

Closing Remarks

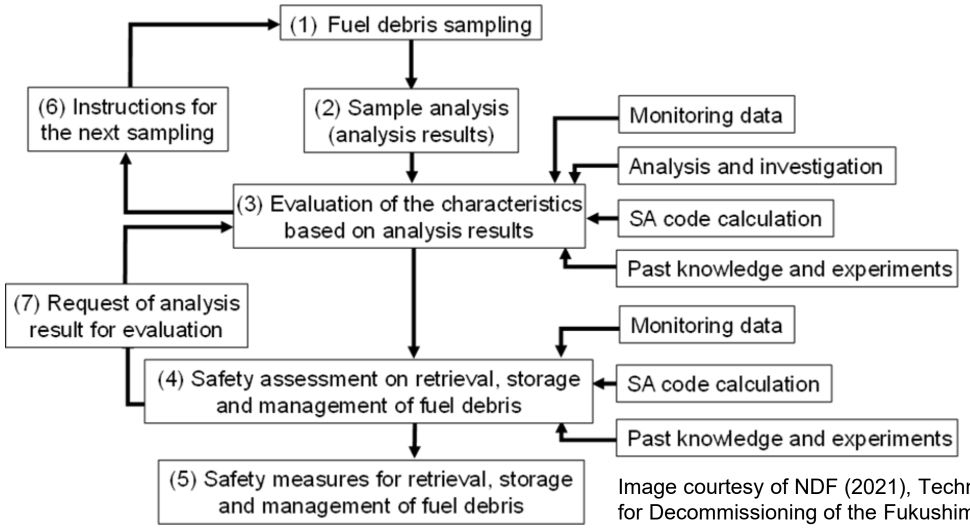


Image courtesy of NDF (2021), Technical Strategic Plan 2021 for Decommissioning of the Fukushima Daiichi Nuclear Power Station of Tokyo Electric Power Company Holdings, Inc.

- **At the time, TMI-2 accident and cleanup effort challenges unprecedented. Challenges met using flexible ‘step-by-step” approach:**
  - Broad stakeholder input for information requests
  - Specialized technology development (adapting existing methods)
  - Endstate diagrams and 3D models useful for communication (updated as new data obtained)
  - Severe accident systems analysis code development
  - Domestic and international programs
  - Transparent public communications

- **Japan applying systematic ‘step-by-step’ approach to address more complex Daiichi D&D:**
  - Broad stakeholder input for information request identification and prioritization (Japan MEXT /US DOE MOU)
  - Advanced technology development and testing with mockups (some technologies have normal operation and maintenance applications)
  - 2D and 3D visualization methods for communication (updated as new data obtained)
  - Severe accident systems analysis code enhancements (facilitate subsequent D&D)
  - Domestic and international programs (promotes common understanding of accident progression)
  - Transparent public communications (e.g., websites facilitating stakeholder interactions, public meetings, etc.)