Challenges for Removal of Damaged Fuel and Debris

Presented at the
International Experts' Meeting Decommissioning and Remediation after a Nuclear Accident

28 January – 1 February 2013
Vienna, Austria

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Overview

- **“Challenges” can be addressed for many topics such as Managerial, Technical, Regulatory, Financial, Safety, etc.**
- **This presentation’s focus is primarily technical, and is a 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

Plant (year)	INES Scale	Country	Primary cause
NRX (1952) water cooled, heavy water moderated	5	Canada	Design, operator error
Windscale (1957) gas cooled graphite pile	5	UK	Lack of information for operators
SL-1 (1961) small prototype PWR	4	USA	Design
Chapelcross(1967) Magnox carbon dioxide cooled, graphite moderated	4	UK	Design, operations
Fermi 1 (1968) sodium cooled	4	USA	Design
Agesta (1968) water cooled	4	Sweden	Design
St. Laurent (1968) gas cooled, graphite moderated	4	France	Procedure

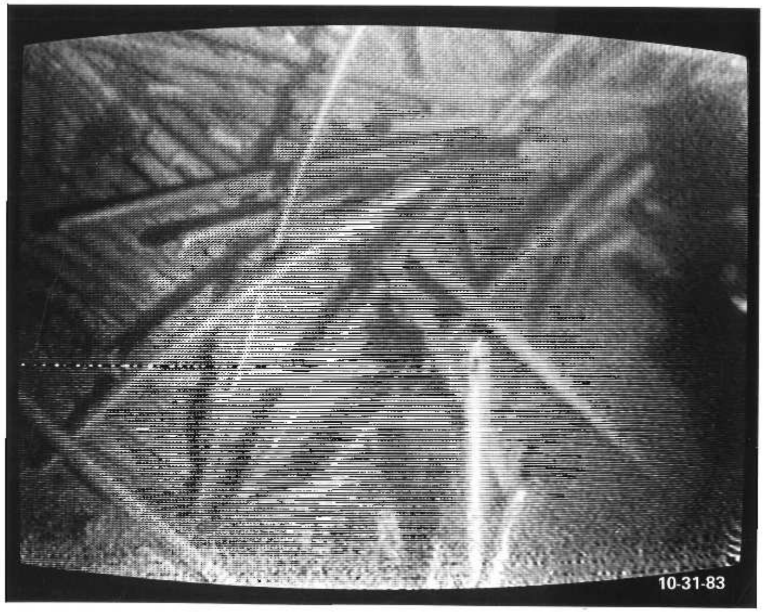
Fuel Damaging Events; Chronologically (cont.)

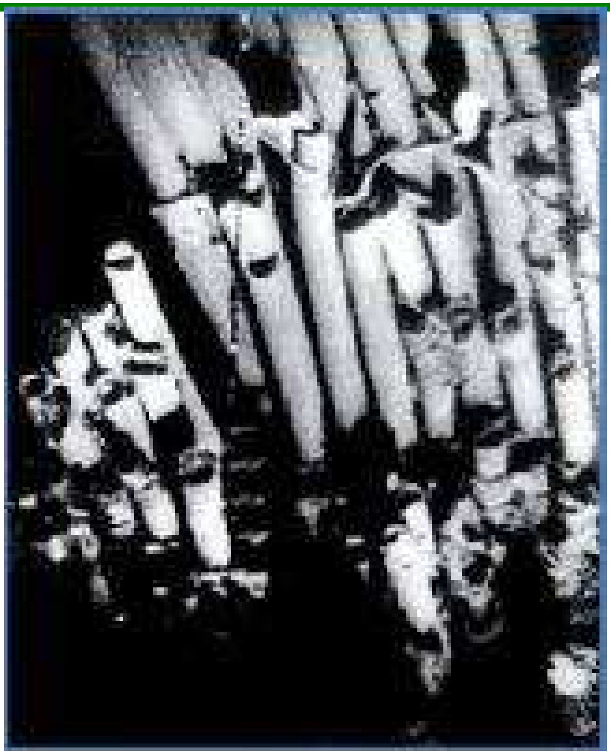
Plant (year)	INES Scale	Country	Primary cause
Lucens (1969) experimental gas cooled, heavy water moderated	5	Switzerland	Channel flow blockage
Jaslovské Bohunice, A-1, (1977) gas cooled, heavy water moderated	4	Slovakia	Operator error, blocked fuel channel
Three Mile Island (1979) PWR, light water cooled	5	USA	Design, operator error, relief valve stuck open
Chernobyl (1986) RBMK, water cooled, graphite moderated	7	Ukraine	Design, violation of operating procedures
PAKS (2003), PWR	3	Hungary	Design, operational delay
Fukushima-Daiichi (2011), BWRs, light water cooled	7	Japan	Tsunami, Design

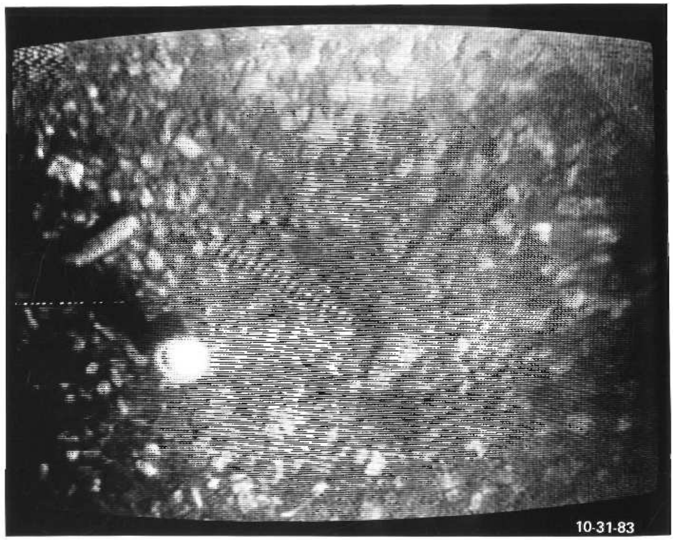
Major Phase 1: Characterization In Situ

- 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

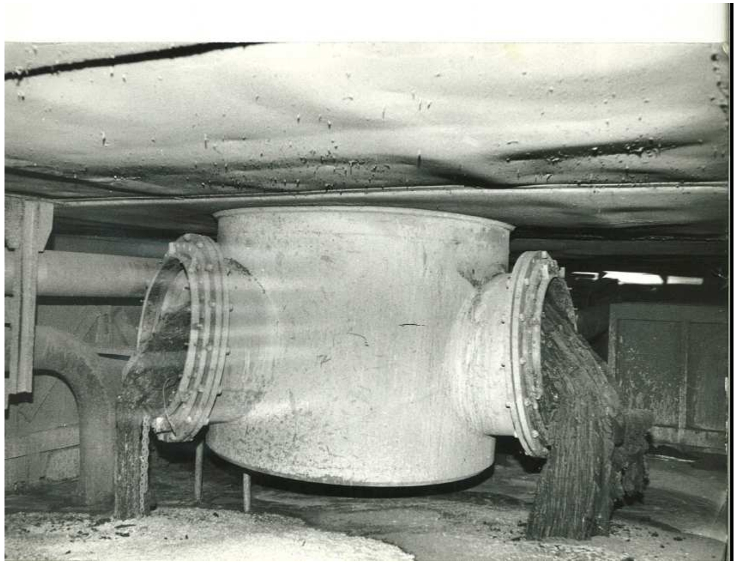
TMI-2







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

Decisions	**Significance**
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

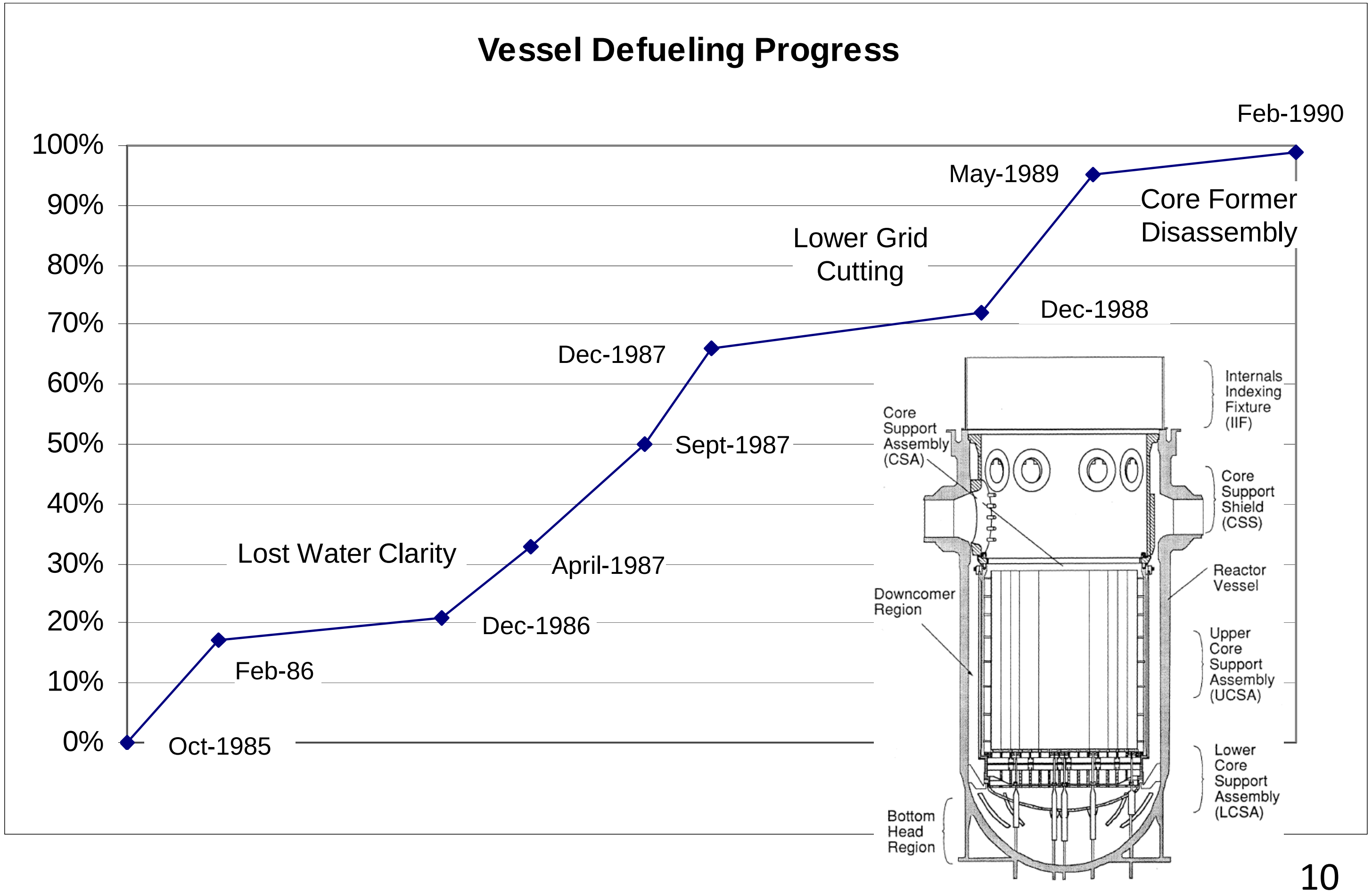
1982
First Video of Core

1983
First Sample

1983
Sonar Mapping &
Improved Video

1984
Defueling Method Decision
Dry Canal & Mostly Manual

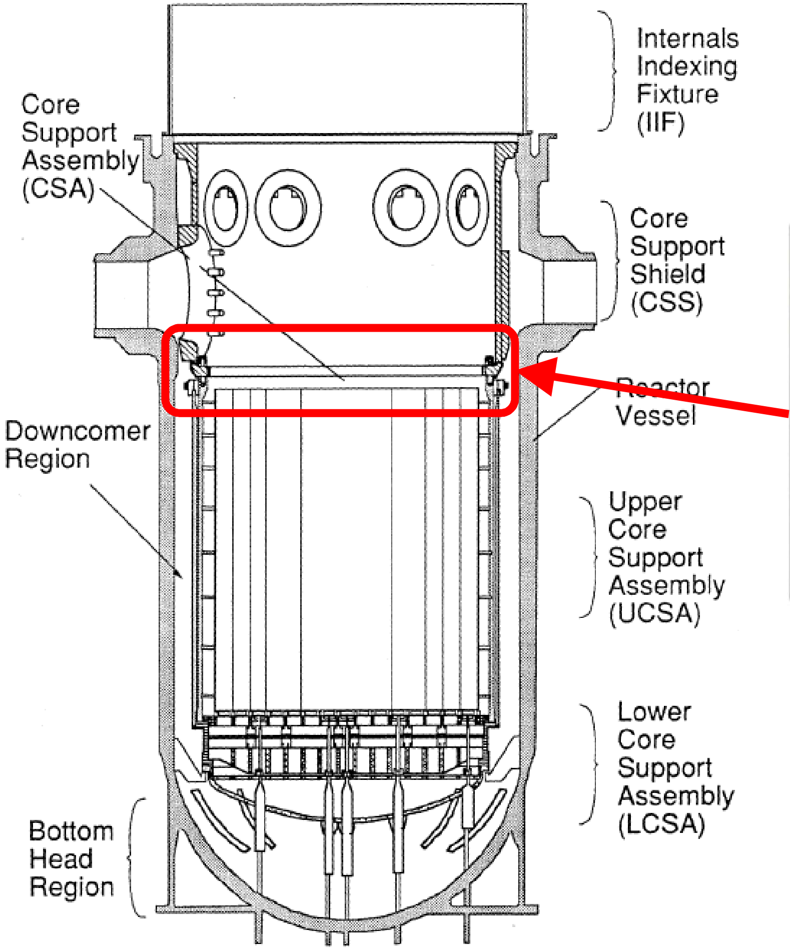
Mid-1984
Vessel Head Lift



Vessel Defueling Progress

TMI-2 Vessel Debris Removal

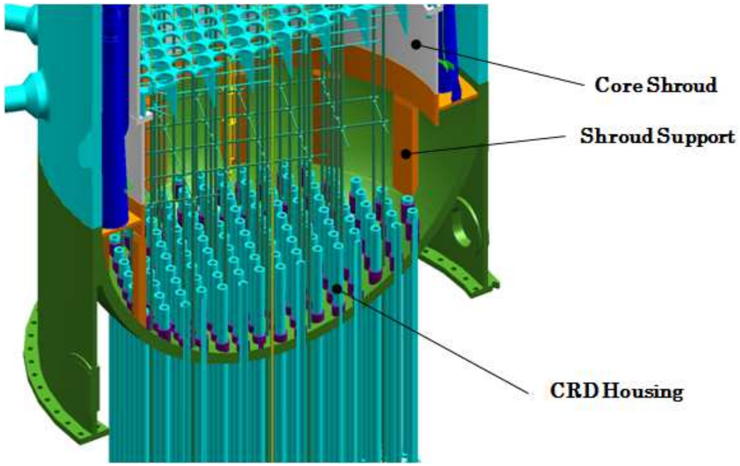
- Each had their own specific challenges:
  - Core Cavity
  - Lower Support Grid
  - Flow Distributor
  - Behind and within the Core Baffle Plates
  - Lower Head

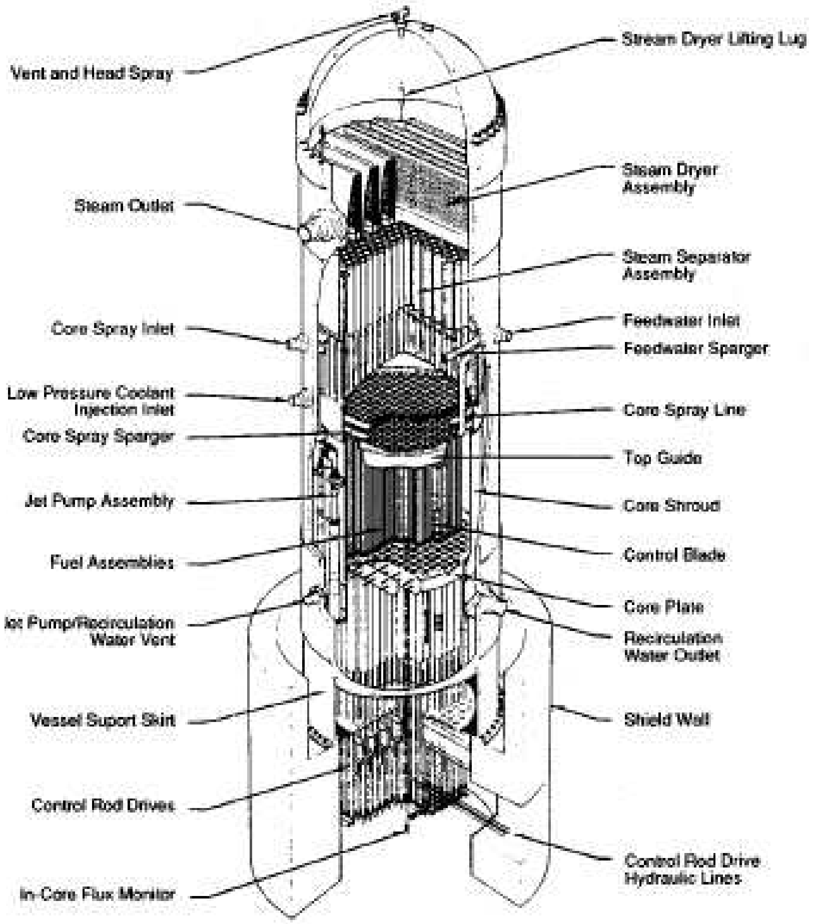


Damage on the Underside of the Upper Grid

Boiling Water Reactor

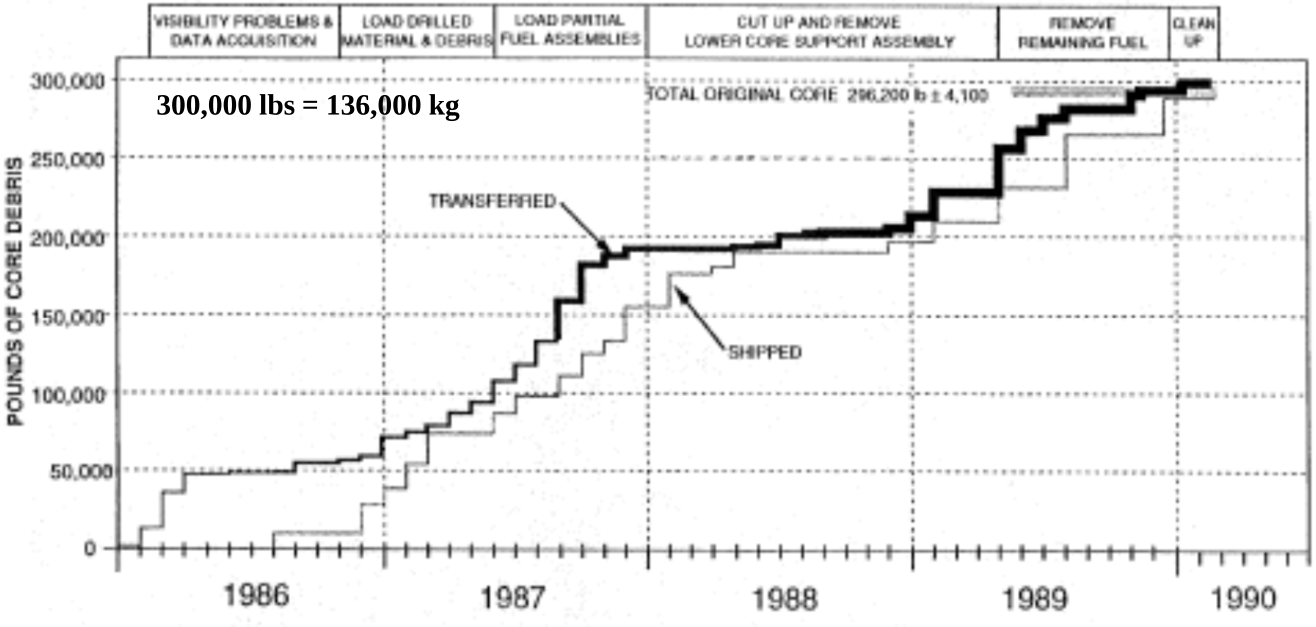
- Some Important Differences:
  - Duration of extreme temperatures!
  - Mass of material above the core
  - Thinner vessel walls
  - Vessel melt through
  - Mass of material beneath the vessel
  - Greater vertical dimension





9 Typical BWR reactor arrangement. (*Source:* Courtesy of General Electric Company.)

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

TMI-2 Final Verification

- 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 ≈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

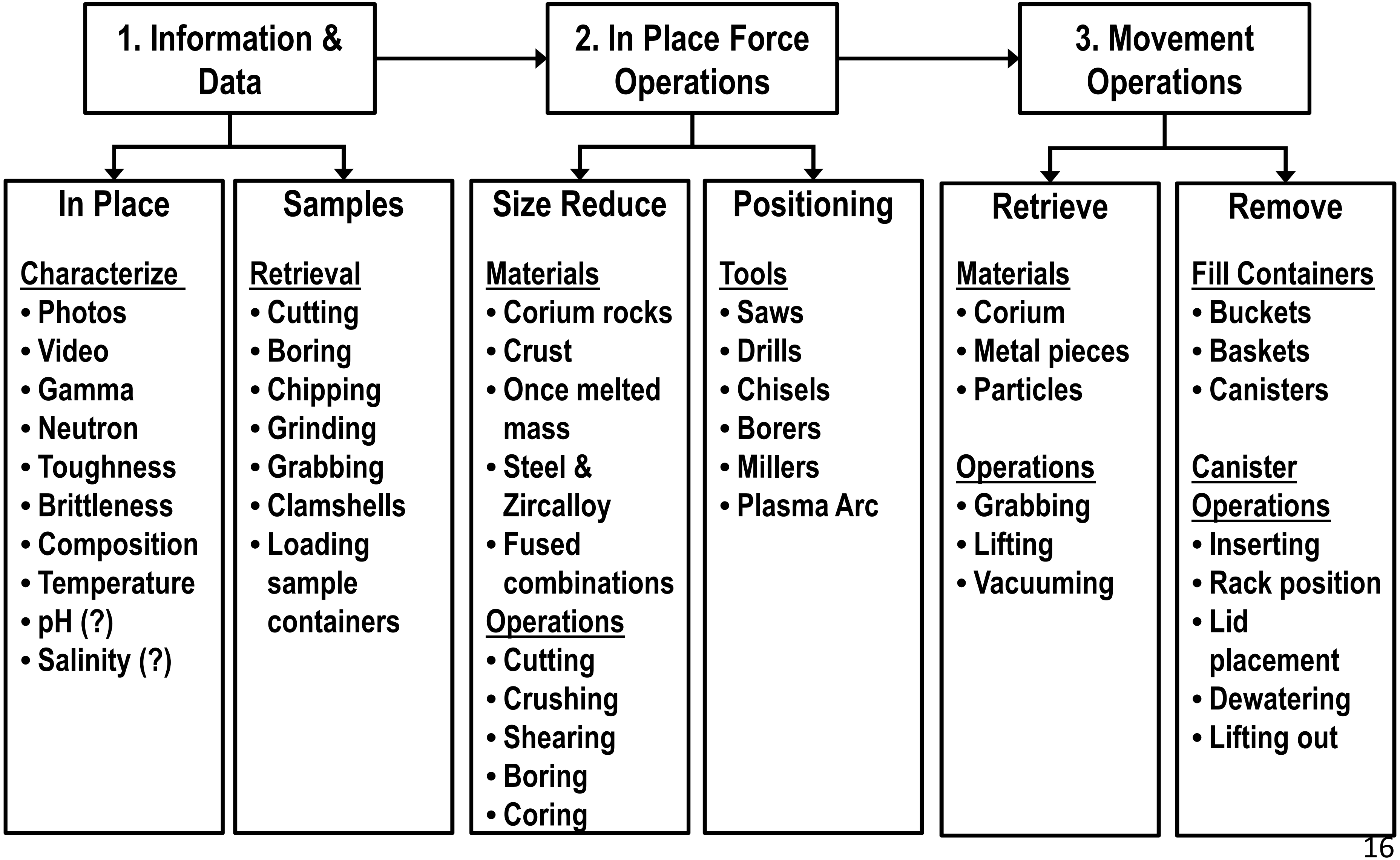
- Much of what was done was innovation based on the immediate need
- The wagon is one example. A toy remote controlled vehicle was used to survey a very radioactive equipment cubicle.
- Several robotic devices were created specifically for TMI-2; ROVER is one example. A miniature submarine in the pressurizer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

Mini Submarine

Low Tech but Effective

ROVER

Characterization and Removal Remote Capability Functions



1. Information & Data

In Place

Characterize
- Photos
- Video
- Gamma
- Neutron
- Toughness
- Brittleness
- Composition
- Temperature
- pH (?)
- Salinity (?)

Samples

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

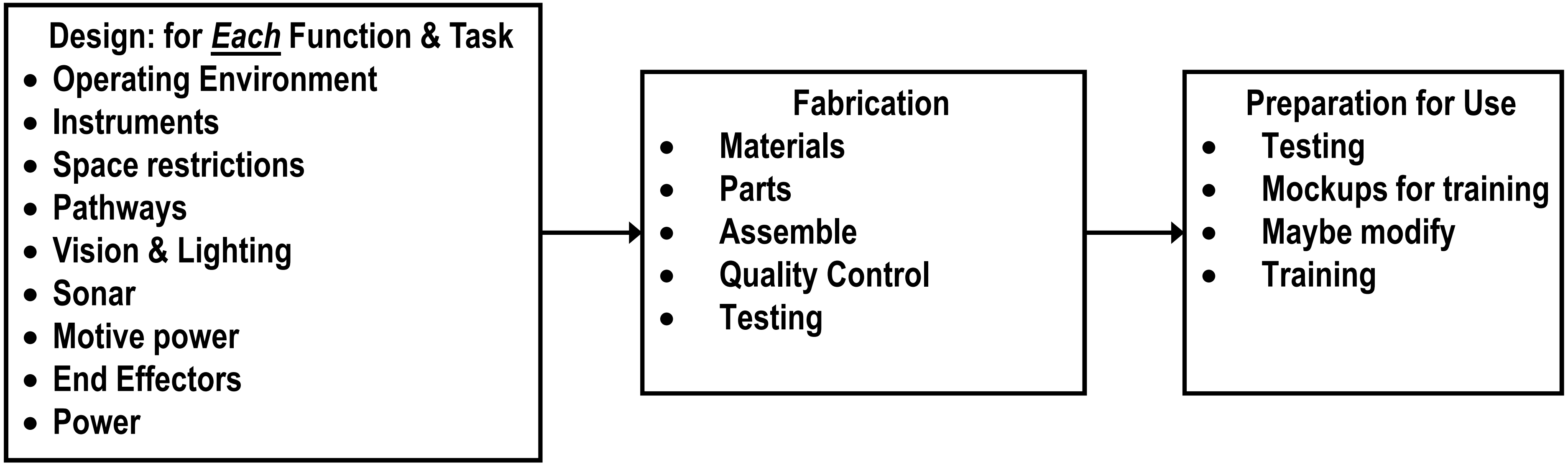
Operations
- Grabbing
- Lifting
- Vacuuming

Remove

Fill Containers
- Buckets
- Baskets
- Canisters

Canister Operations
- Inserting
- Rack position
- Lid placement
- Dewatering
- Lifting out

Development and Application Cycle



Design: for *Each* Function & Task

- Operating Environment
- Instruments
- Space restrictions
- Pathways
- Vision & Lighting
- Sonar
- Motive power
- End Effectors
- Power

Fabrication

- Materials
- Parts
- Assemble
- Quality Control
- Testing

Preparation for Use

- Testing
- Mockups for training
- Maybe modify
- Training

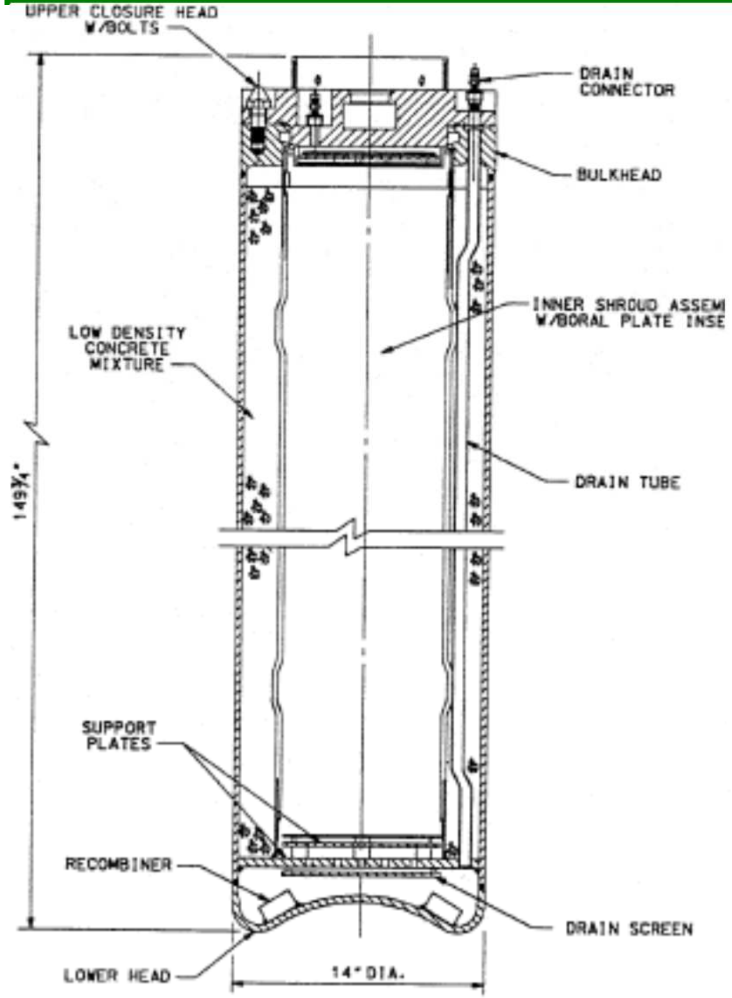
The Challenge:

- 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.

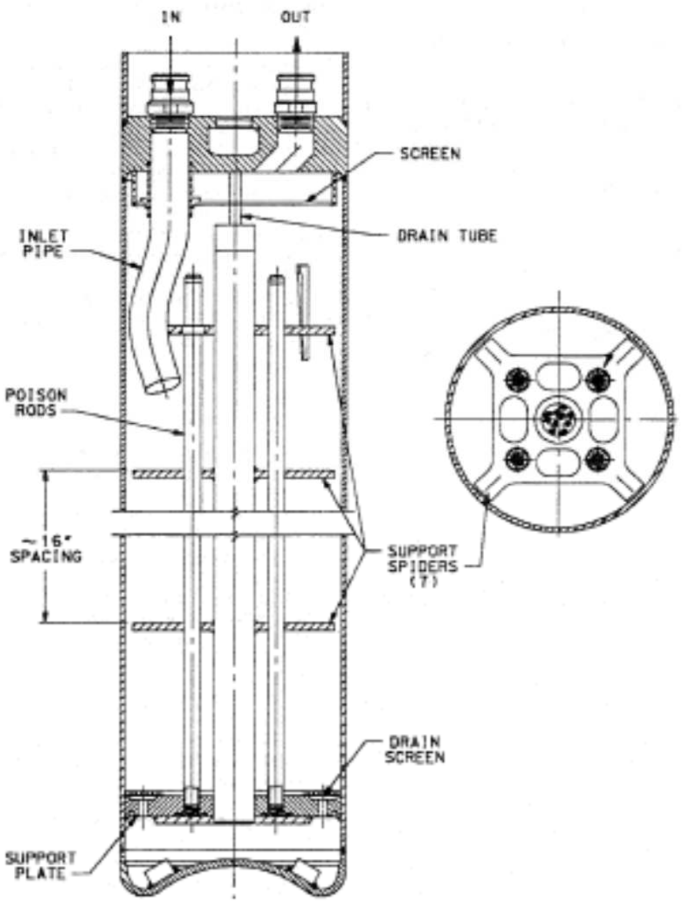
Major Phase 3: Onsite Management

- Containers for removal
- Movement of containers on site
- Containers for storage and shipping
- Storage facility on site and transport

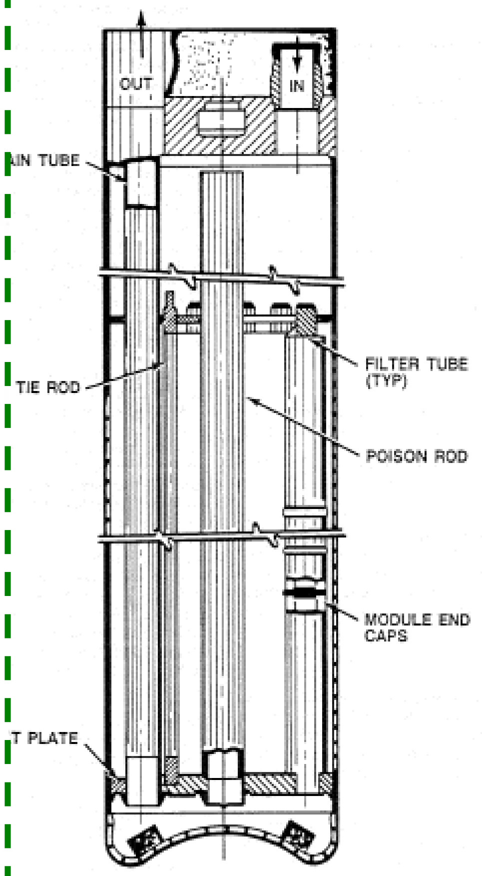
Three Canister Design – 341 Shipped



271 Fuel & Debris Canisters



10 Knockout Canisters
(for vacuum tools)



60 Filter Canisters
(water processing)

Storage and Handling

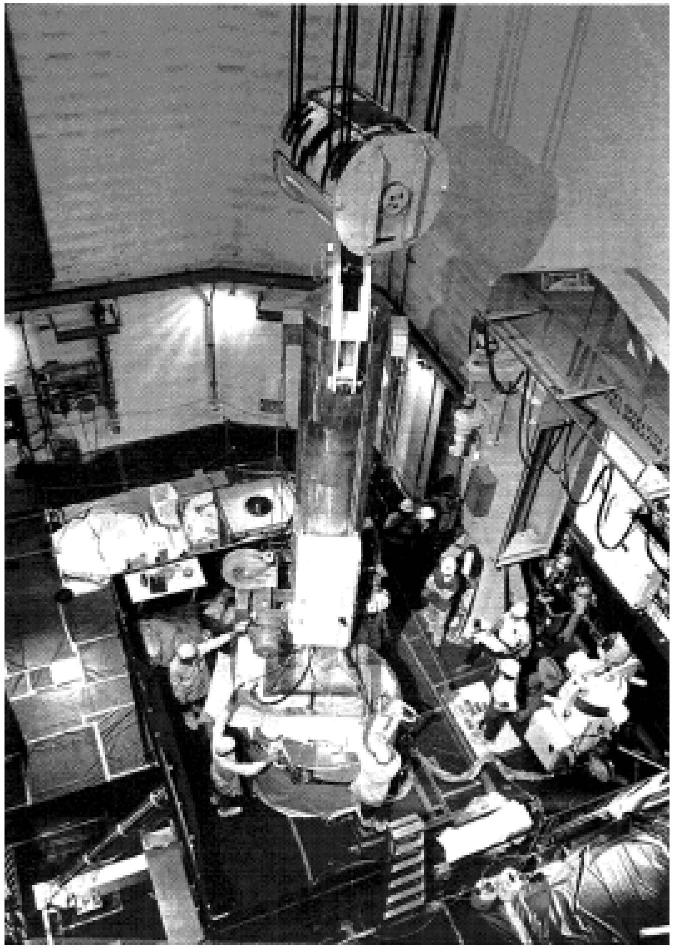
Canister Staging in Spent Fuel Pool

Transfer Cask Operations

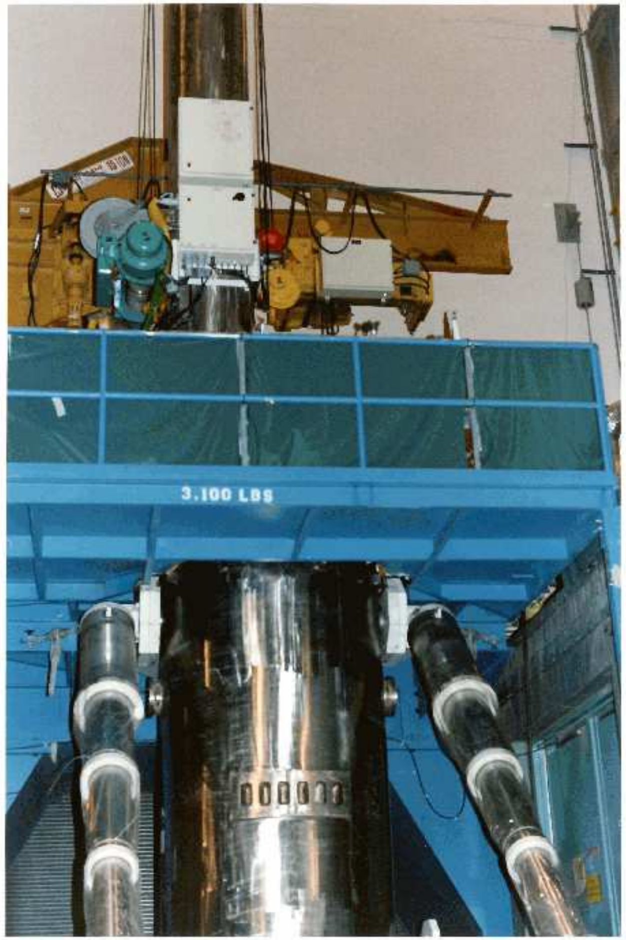
Major Phase 4: Offsite Management

- 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

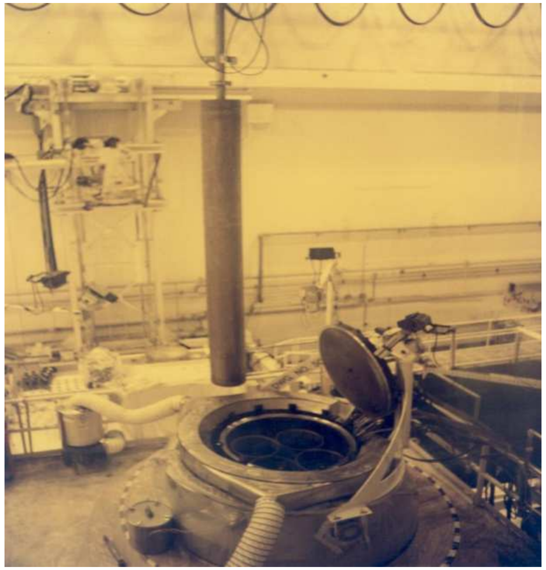
1990 to 2000
Wet Storage in Spent Fuel Storage Pool

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

Canister Dewatering

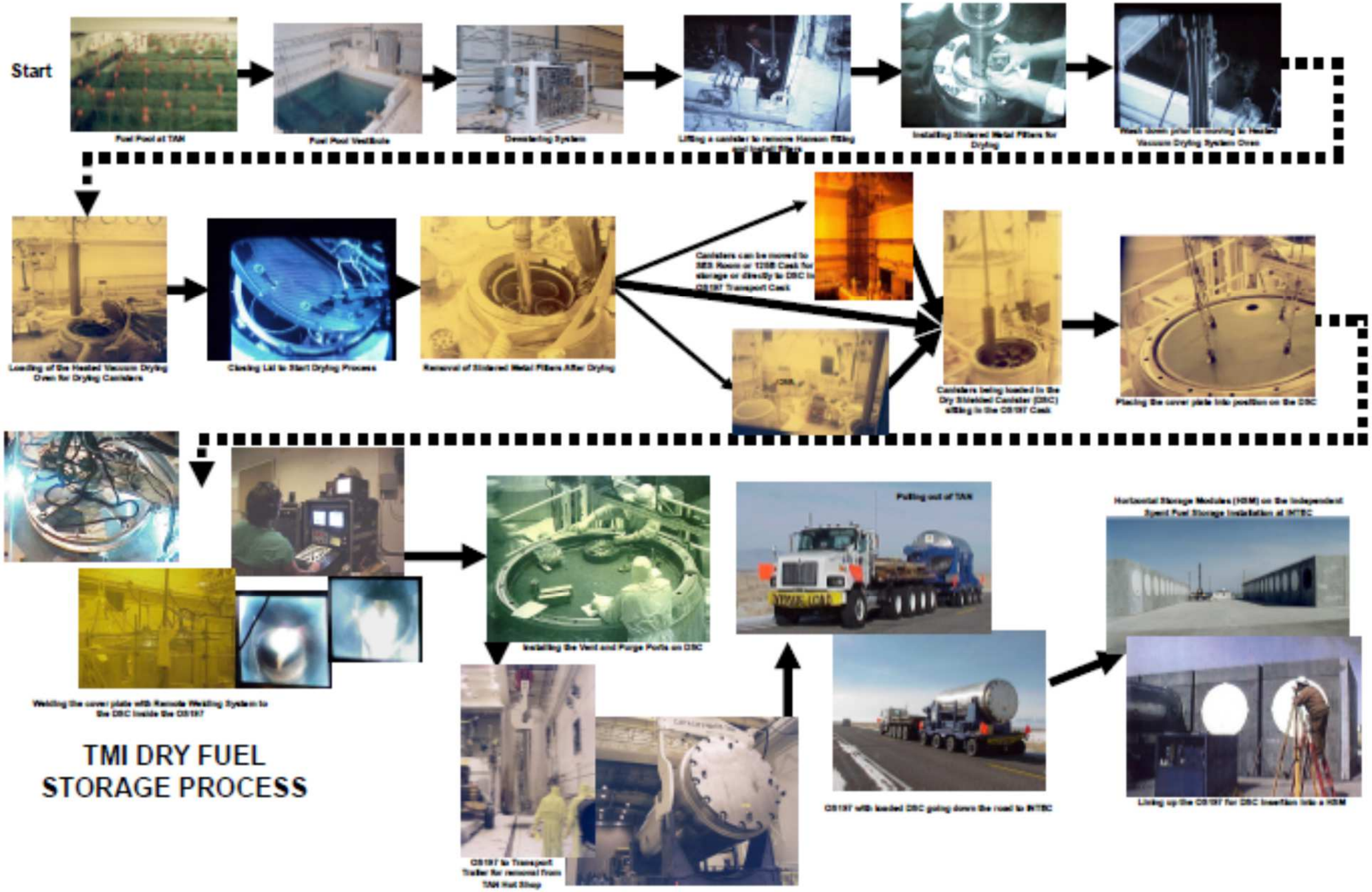
- 1 year required for design, fabrication, testing. About 6 months for drying operations of the 341 canisters.
- Water removed in the pool area. Drying conducted in two vacuum ovens by remote control in a shielded machine shop
- Each oven held 4 canisters. Each cycle required 2 days for drying at a maximum 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.