SAND2010-0793C

THREE MILE ISLAND UNIT 2 (TMI-2)

THE REACTOR

THE ACCIDENT

THE CONSEQUENCES

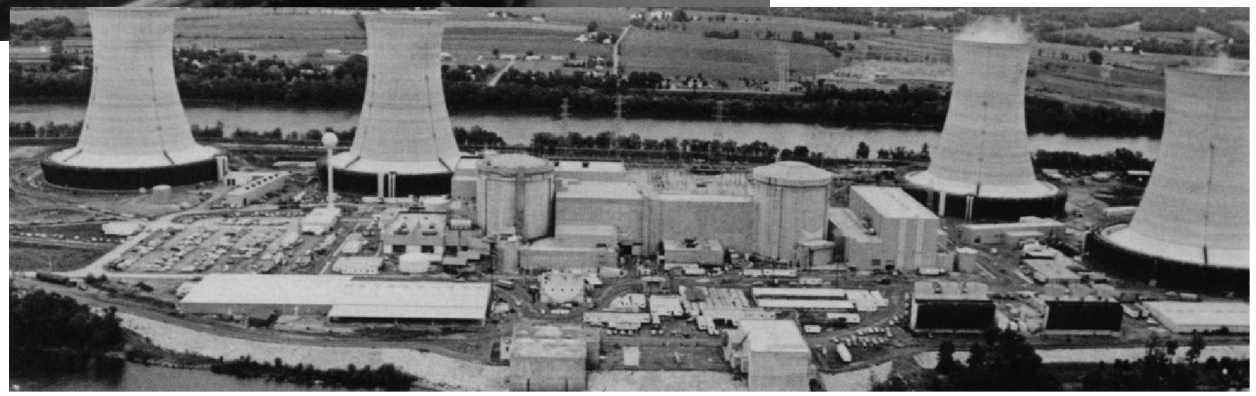
OBJECTIVES

2. Describe the role in the reactor accident at Three Mile Island, Unit 2 [TMI-2] of each of the following:
   - Pilot-operated relief valve, high-pressure injection system, and reactor coolant pumps
   - Post-shutdown decay-heat load, zirconium-water reactions, and hydrogen evolution

OBJECTIVES

4. Compare the TMI-2 and Chernobyl-4 reactor accidents in terms of:
   - Nature and extent of core damage
   - Release of noble gases, iodine, cesium, and particulates
   - Final station configuration after recovery

Three Mile Island Nuclear Station



ACCIDENT AT THREE MILE ISLAND UNIT 2

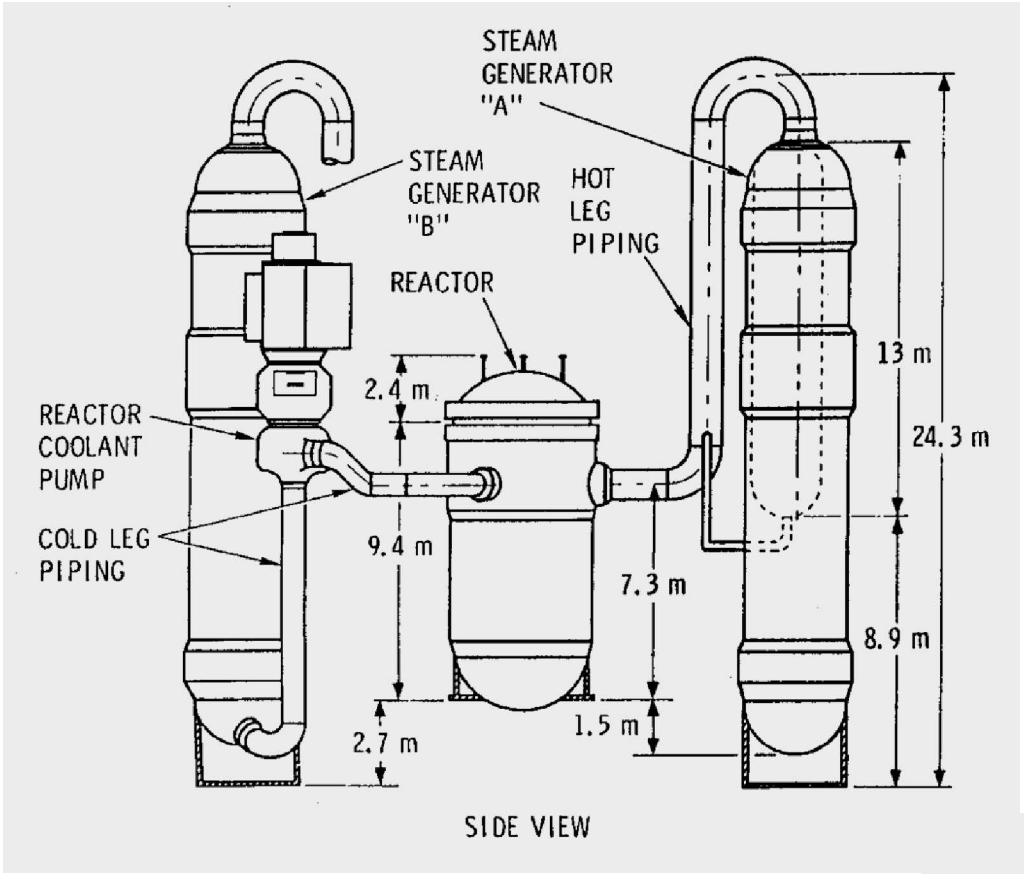
- THREE MILE ISLAND [TMI] NUCLEAR STATION
  - Owned & Operated by Metropolitan Edison & General Public Utilities (GPU)
  - Located Near Middletown, PA; 10 mi SE of Harrisburg, the State Capital
  - Babcock & Wilcox (B&W) PWR Units
    - Unit 1 - 792 MWe
    - Unit 2 - 880 MWe

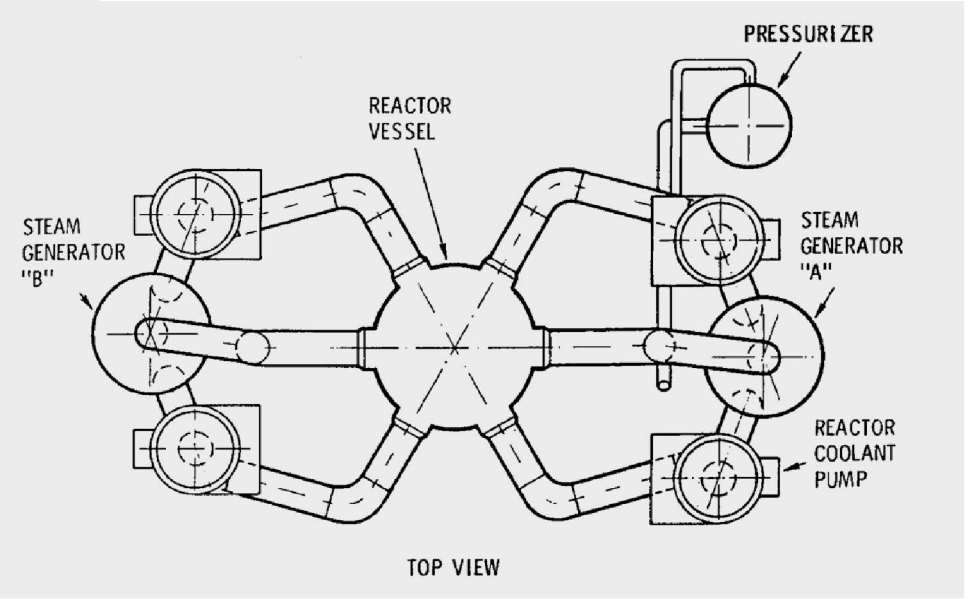
TMI-2

- REACTOR
  - Babcock & Wilcox (B&W) PWR Primary System
    - Reactor Vessel
    - Two Once-Through Steam Generators
    - Four Coolant Pumps
    - Pressurizer
    - Hot-Leg Piping to Steam Generator
    - Cold-Leg Piping (Dual) from Steam Generator

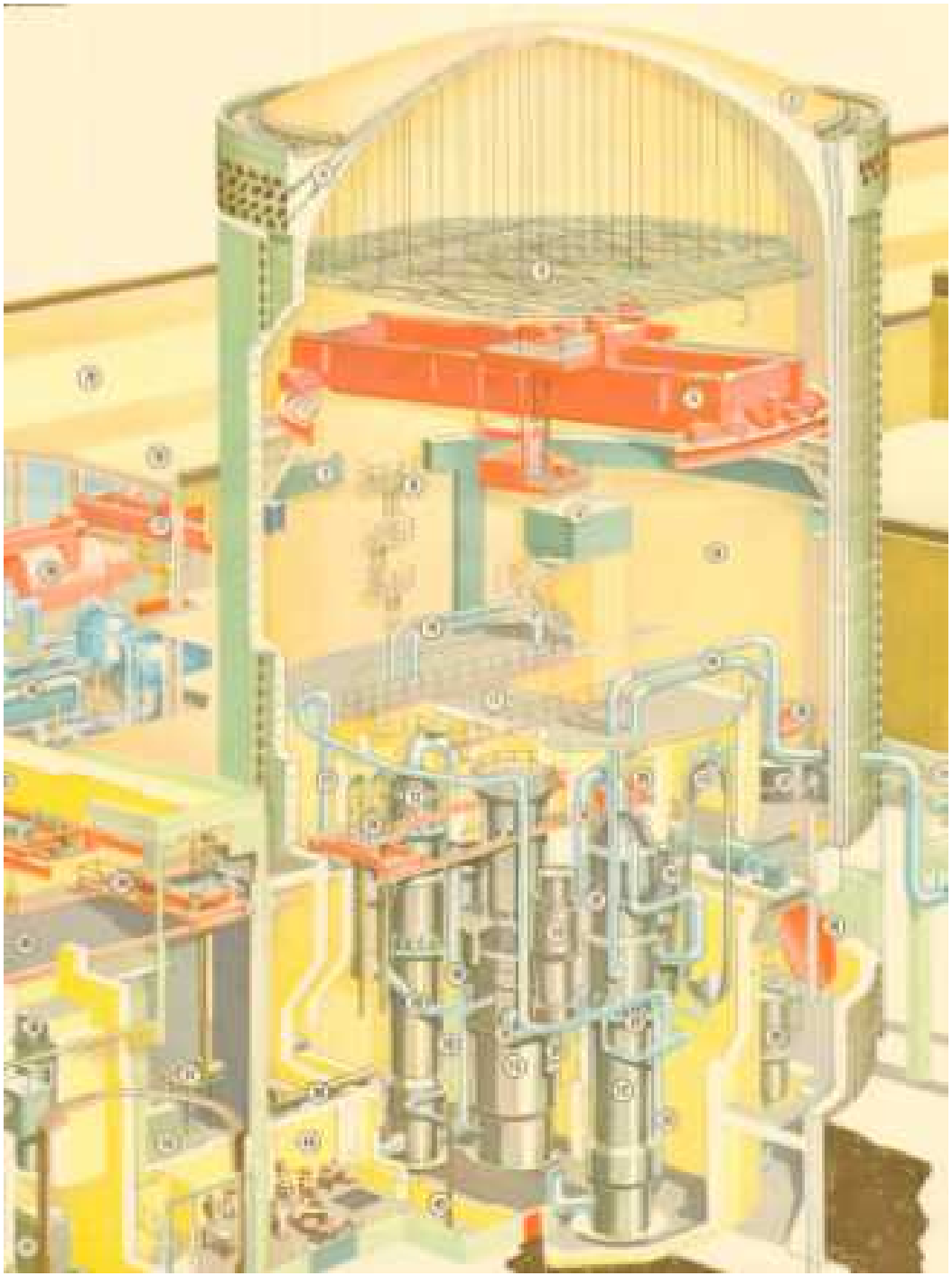
TMI-2 Reactor Coolant System

TMI-2 Reactor Coolant System





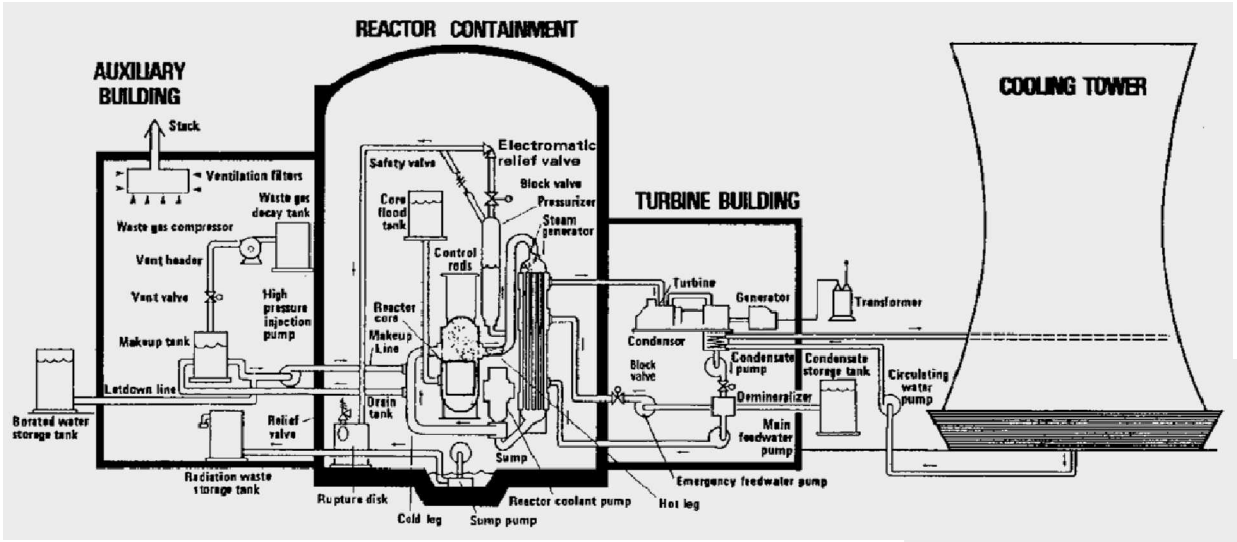
Babcock & Wilcox (B&W) PWR



TMI-2

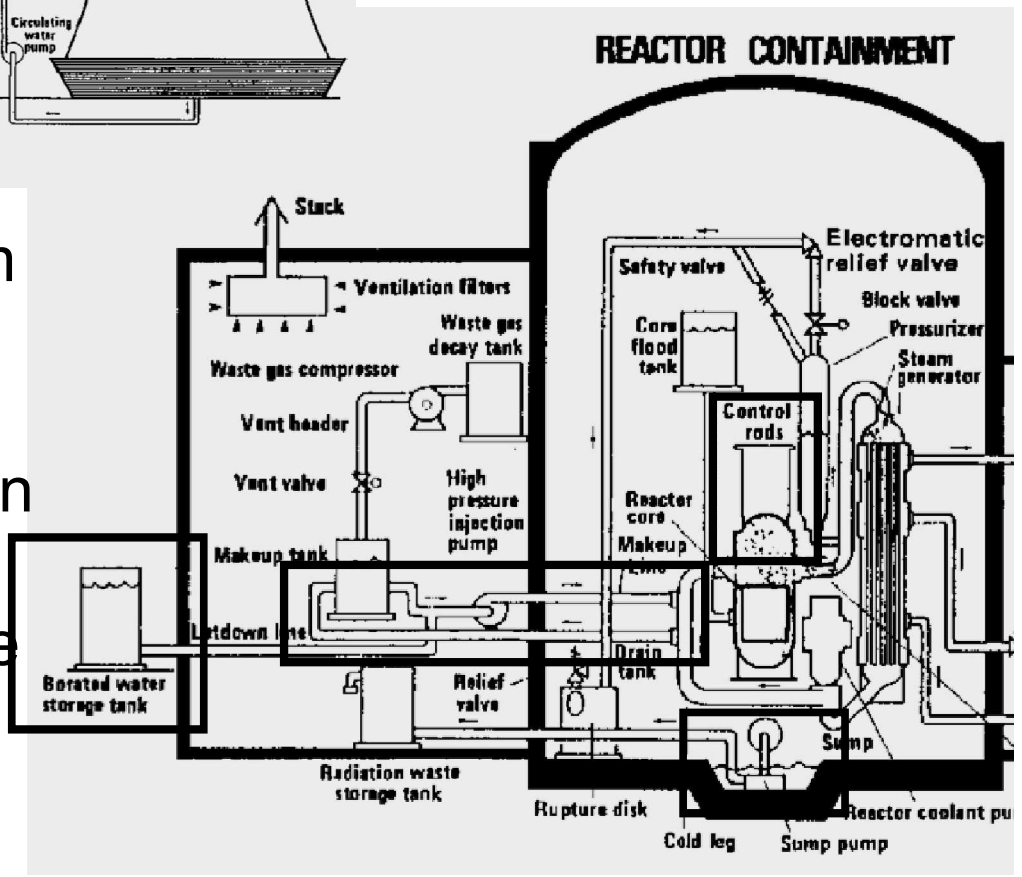
- REACTOR SCHEMATIC LAYOUT
  - One of Two Coolant Loops
  - Engineered-Safety-System Features
    - Control Rods
    - High-Pressure Injection [HPI]
    - Borated Water Storage Tank
    - ECCS-Recirculation Sump
  - Other Components

TMI-2 Station Schematic



Engineered-Safety-System Features

- Control Rods
- High-Pressure Injection [HPI]
- Borated Water Storage Tank
- ECCS-Recirculation Sump



THREE MILE ISLAND UNIT 2 (TMI-2)

THE REACTOR

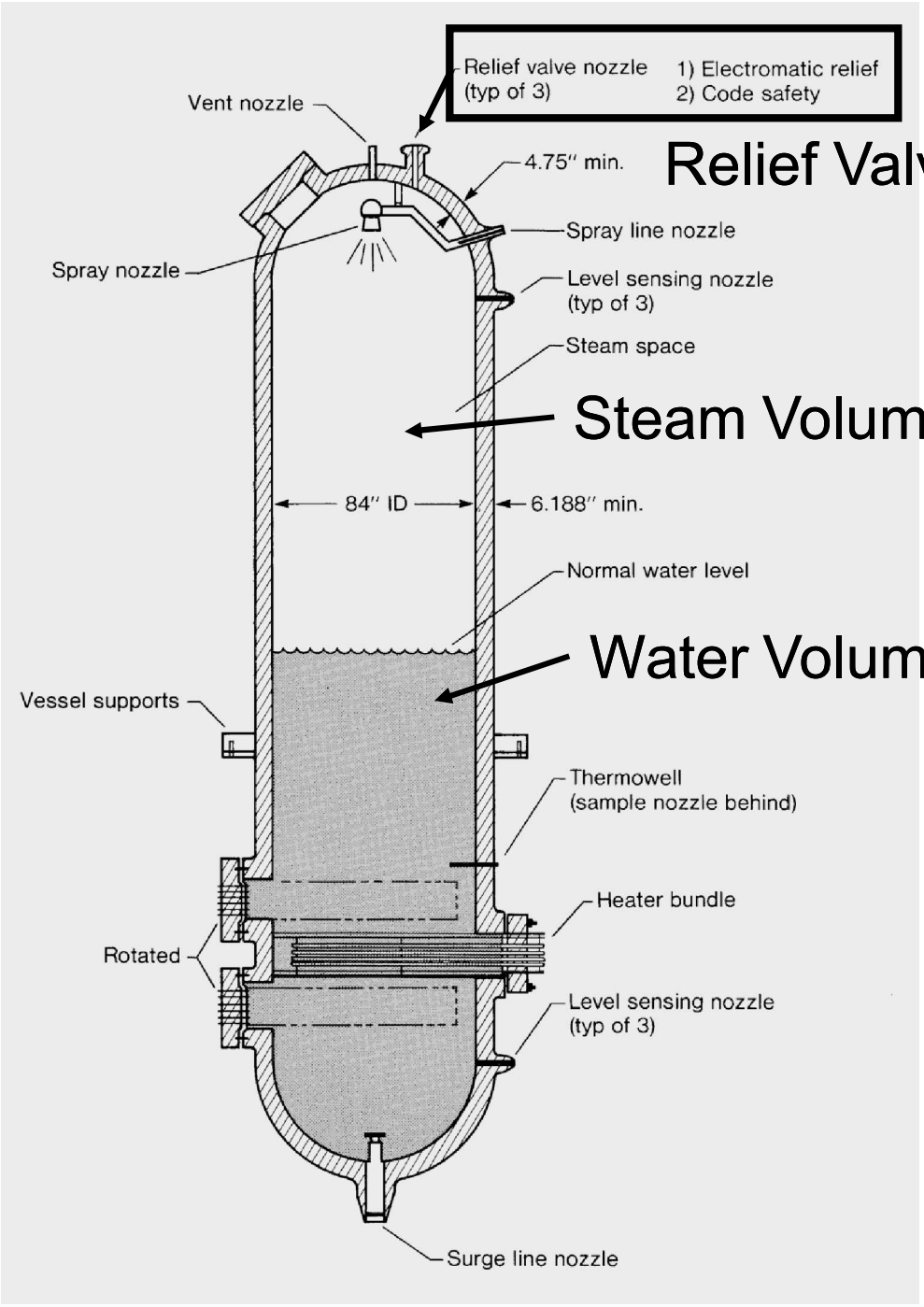
THE ACCIDENT

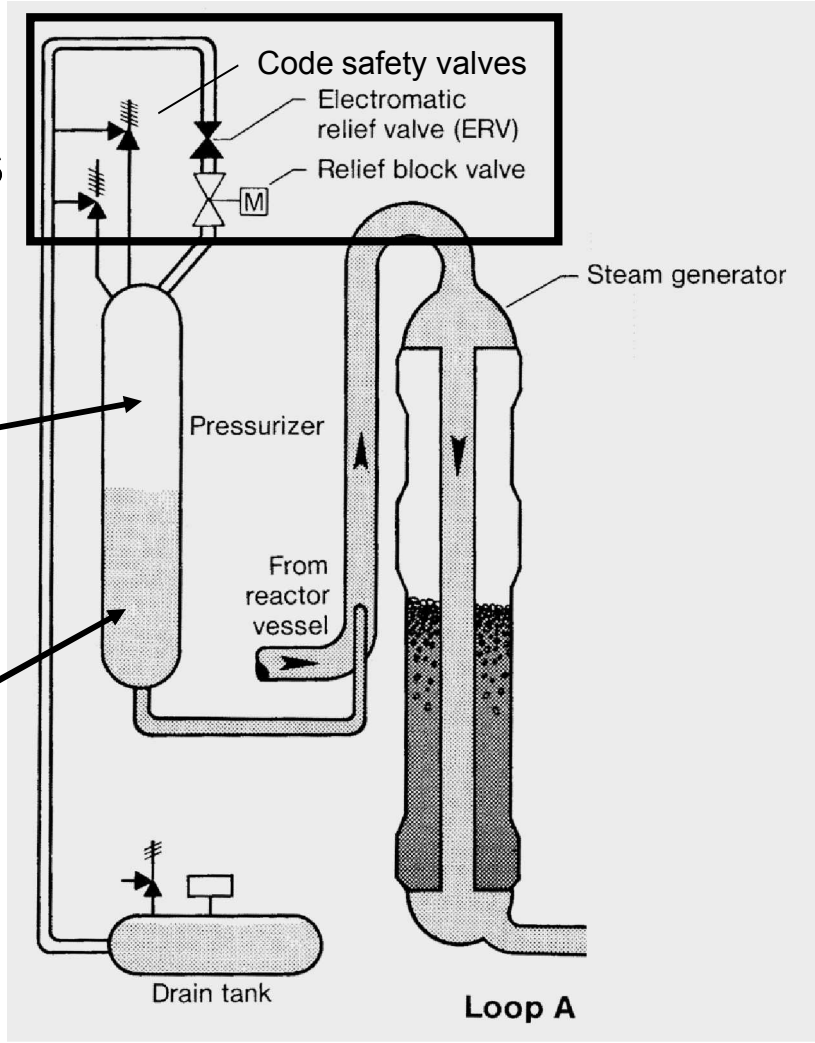
THE CONSEQUENCES

TMI-2 Control Room

TMI-2 ACCIDENT

- SEQUENCE OF EVENTS
  - Before 4:00 a.m. on March 28, 1979
    - 97 % Power
    - Problems Assumed Minor
      - Small Loss of Coolant Through Pressurizer Valve to Drain Tank
        - » One *Electromatic* (Pressure) Relief Valve [ERV]; Also Referred to as a Pilot-Operated Relief Valve [PORV]
        - » Two Passive “Code” Safety Valves





TMI-2 Pressurizer

TMI-2 ACCIDENT

- SEQUENCE OF EVENTS
  - Before 4:00 a.m. on March 28, 1979
    - 97 % Power
    - Problems Assumed Minor
      - Small Loss of Coolant Through Pressurizer Valve to Drain Tank
      - Emergency Feedwater Valves Closed (Unintentional and Unknown to Operators)
      - Feedwater Demineralizer Blockage

TMI-2 ACCIDENT

- SEQUENCE OF EVENTS

  4:00:36 a.m. March 28, 1979

  – INITIATOR: Unable to Clear Demineralizer Blockage →Loss of Condensate (Feedwater) Flow to Steam Generators →Degradation of Reactor Heat Removal Capability

TMI-2 ACCIDENT

- SEQUENCE OF EVENTS

  4:00:36 a.m. March 28, 1979

  – INITIATOR: Unable to Clear Demineralizer Blockage
  – Main Feedwater Pump Tripped Off-Line
  – Turbine Tripped Off-Line
  – Emergency Feedwater Pump Auto-Started
  – Pressurizer Pilot-Operated Relief Valve (PORV) Opened to Reduce Pressure
  – Reactor Tripped on Overpressure Signal

  - - - Normal System Response (First 8 sec) - - -

  Chain-Reaction Shutdown

  Decay-Heat Source Remains

TMI-2 ACCIDENT

- SEQUENCE OF EVENTS
  - Emergency Feedwater Blockage
    - Prevented Steam-Generator Function
    - Distraction Until Valves Re-Opened
    - Overall Effect on Accident Progression Uncertain
  - PORV Indicated “Closed” (Solenoid Was De-Energized)
    → PORV Actually Was Stuck Open
    → Small-Break Loss of Coolant Accident (SBLOCA) in Progress

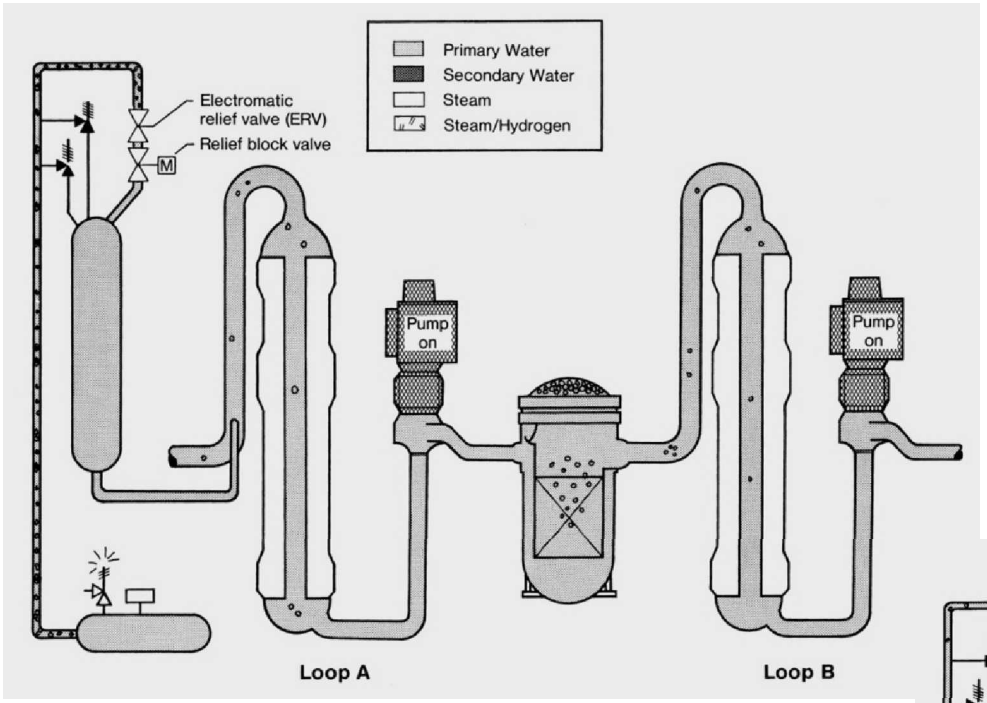
TMI-2 ACCIDENT

- SEQUENCE OF EVENTS
  - Pressurizer Drain Tank Filled
    - Pressure Shown by Meter on Back-Facing Panel
      - Reading Nominal Before Tank Filled
      - No Chart Recorder for Trending
    - Drain-Tank Rupture Disk “Popped”
      - Reading Nominal Again
      - No Lasting Positive Indication of Pressurizer Coolant Loss

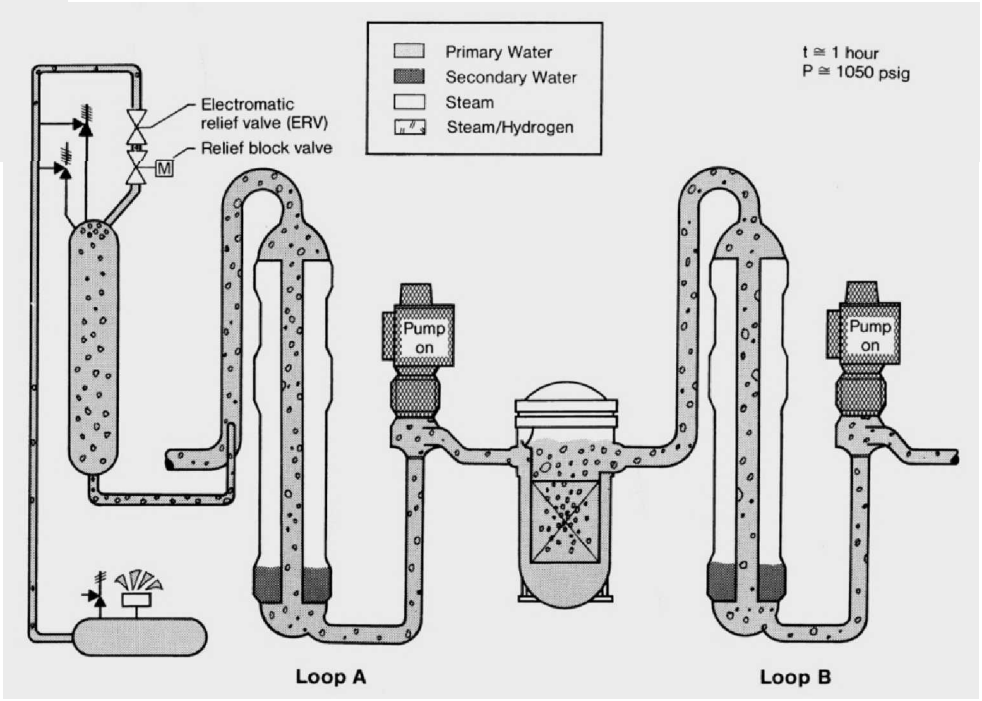
TMI-2 ACCIDENT

- SEQUENCE OF EVENTS
  - High-Pressure Injection (HPI)
    - Auto-Started
    - Operator Throttled HPI Manually
      - Responded to Pressurizer Filling w/ Water ("Going Solid")
      - However, Simultaneously, Coolant Was Being Lost from Reactor Coolant System As-a-Whole
      - System Configuration Led to Ambiguous Indications & Inappropriate Action

TMI-2 Reactor Coolant System



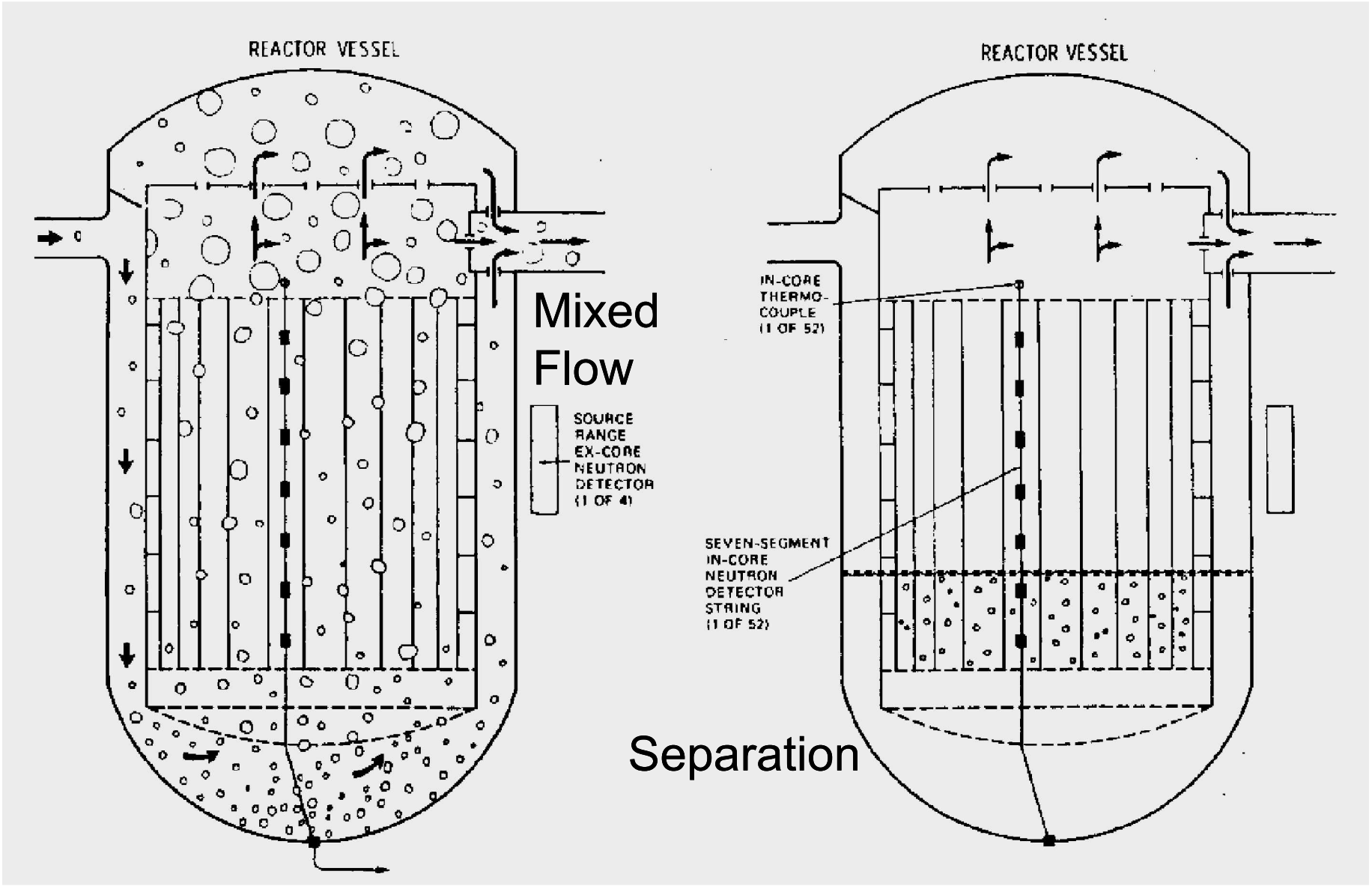
Piping Configuration Allows RCS to Empty While Pressurizer Appears to be Filling



TMI-2 ACCIDENT

- SEQUENCE OF EVENTS
  - Coolant Pump Vibration
    - Two-Phase Coolant Flow
    - Pump Seal Destruction Would Cause LOCA
    - Pumps Shutdown
    - Water & Steam Separated

Voiding Effects

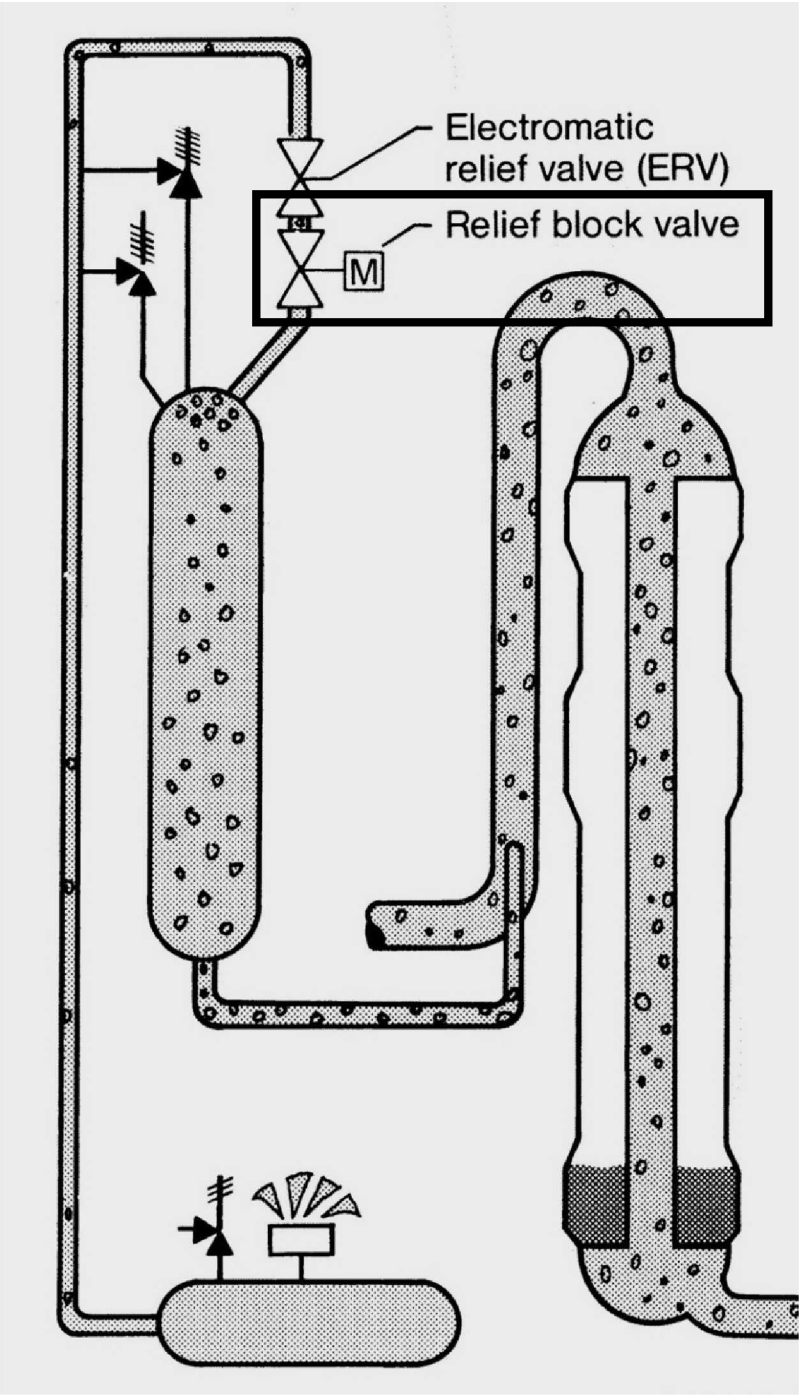


TMI-2 ACCIDENT

- SEQUENCE OF EVENTS
  - Coolant Pump Vibration
  - Core Uncovered w/ Subsequent Heat-Up
    - Zr-Steam Reactions
    - Hydrogen Evolution
  - Cooling Restoration
    - Pressurizer Relief Block Valve Closed
    - Hydrogen & Steam Blockage Remained

TMI-2 PORV

Block Valve



TMI-2 ACCIDENT

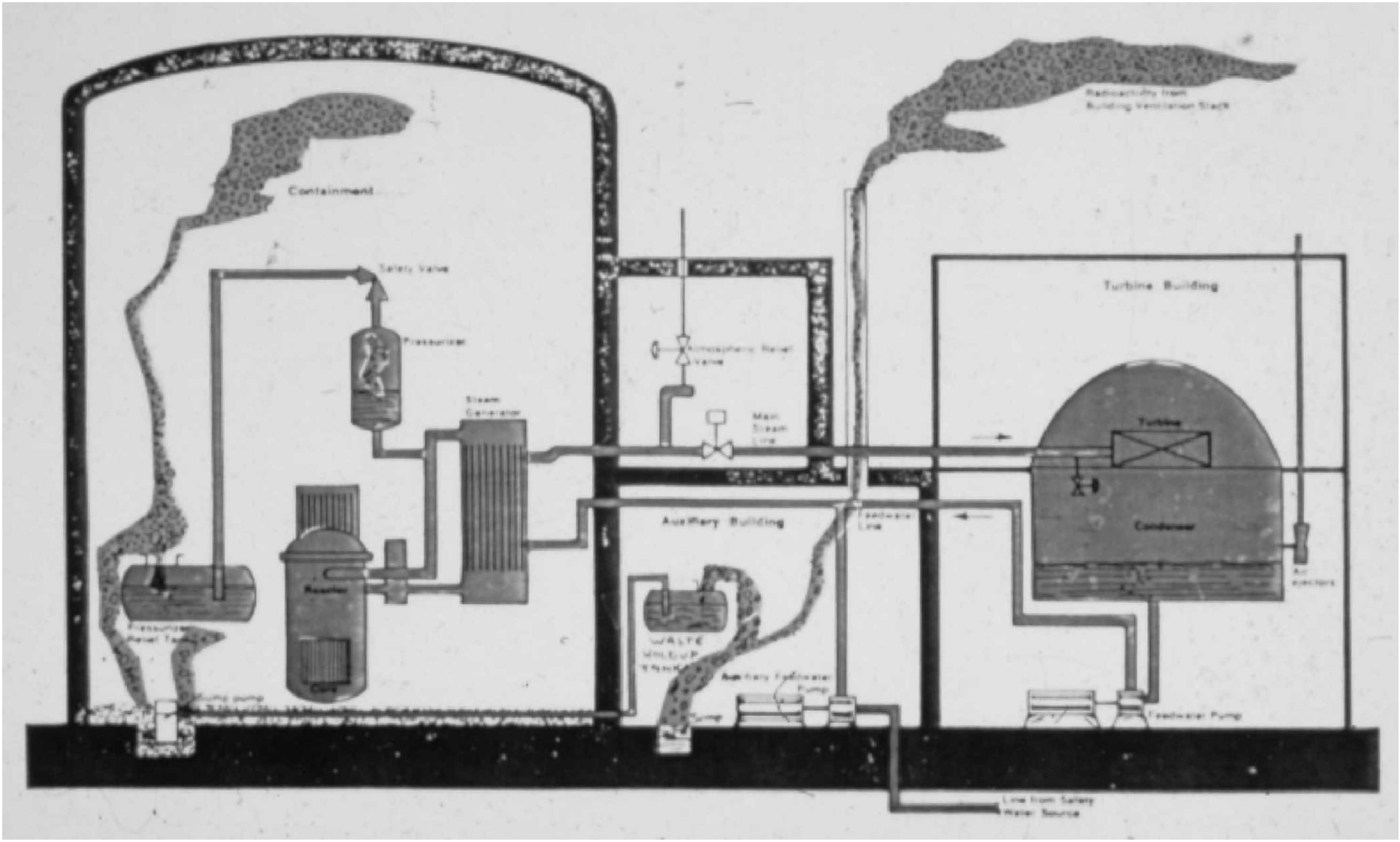
- SEQUENCE OF EVENTS
  - Cooling Restoration
    - Pressurizer Relief Block Valve Closed
    - Hydrogen & Steam Blockage Remained
    - Minimal Natural & Forced Circulation to Steam Generators
    - “Feed-and-Bleed” Through PORV
      - Cycle Low-Pressure Coolant Injection Pumps
      - Cycle PORV Open-and-Closed
    - Restart of Coolant Pump Restored Cooling
  - ~9:00 a.m. [+5 hrs] – Coolable Geometry

ACCIDENT TECHNICALLY OVER !!

TMI-2 ACCIDENT

- RADIOACTIVITY
  - Drain Tank Rupture Disk “Popped”
    - Radioactive Water Collected in Sump
  - Automatic Transfer from Sump to Auxiliary Building
    - Very High Radioactivity Transfer w.r.t. Typical
    - No Isolation (Set-Point @ 4 psi for Large LOCA)
  - Fission Gas Release from Auxiliary Building
    - Noble Gases 5%
    - Iodine 10^{-5}%
  - Emergency Declarations

Radioactivity Release Pathways



TMI-2 ACCIDENT

- HYDROGEN
  - Normal Operation: Excess Hydrogen to Limit Oxidation of Cladding & Structures
  - Accident: Generated in Zr-Steam Reactions
    - Entered Containment Building via PORV and Drain Tank
    - Burned w/ Resulting 28-psi Pressure Spike
  - “Hydrogen Bubble” in Vessel Head
    - Concern for Hydrogen Explosion Rupture of Vessel
    - Public May Have Thought “Hydrogen Bomb”
    - Concluded to be Chemically Not Credible

TMI-2 ACCIDENT

- REACTOR CORE STATUS - INITIAL EVALUATION
  - Clad Damage Assessment Based on:
    - Neutron-Detector Response
    - Hydrogen Generation History
    - Fission-Product Releases
  - Coolant Restoration Presumed to Have Caused Damage by Quenching Hot Fuel
  - Some Melting of Ag-In-Cd & Other Materials Expected
  - No Indication of Global Fuel Melting

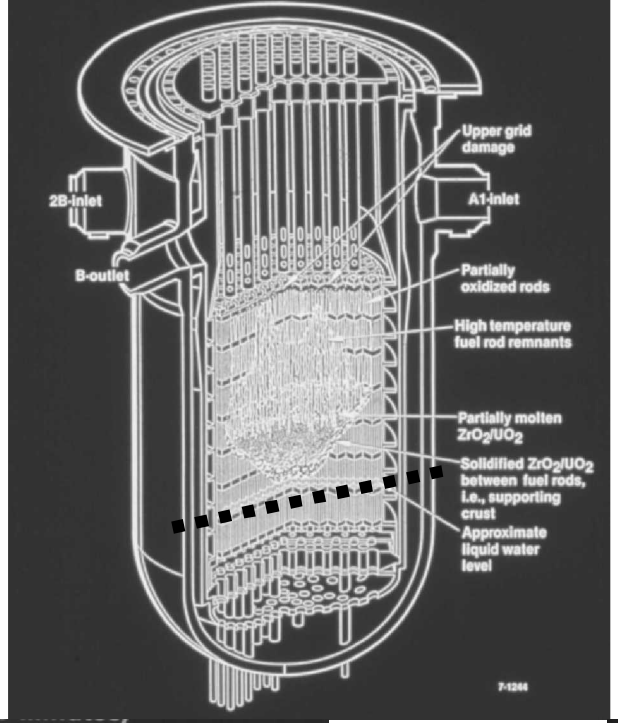
TMI-2 ACCIDENT

- REACTOR CORE STATUS
  - Evolutionary Knowledge Over Recovery & Cleanup
    - “Quick Look” Camera
    - Reactor Vessel Head Removal
    - Core Boring
    - Defueling
    - Lower Plenum Removal
    - Completion of Defueling

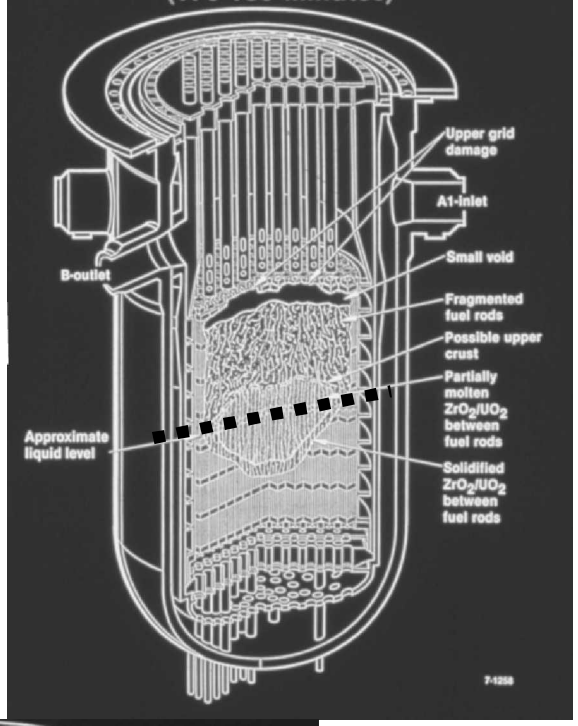
TMI-2 ACCIDENT

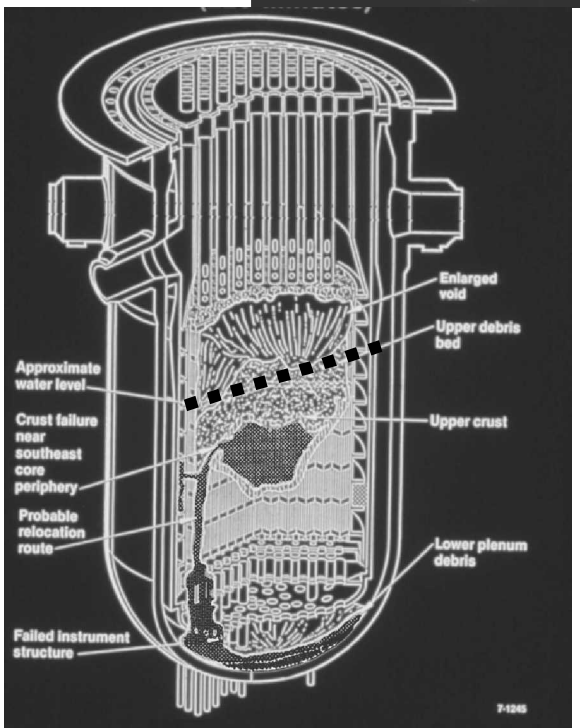
- REACTOR CORE STATUS - FINAL HYPOTHESIZED SCENARIO
  - Damage Sequence
    - Coolant Pumps Turned Off → Heat-Up
    - Blocked PORV → No Steam Flow
    - Coolant Restoration → Quenching & Collapse
    - Insulation → Melting
    - Molten Mass Formation / Extrusion
    - Molten Fuel in Bottom of Vessel

After Pumps Off

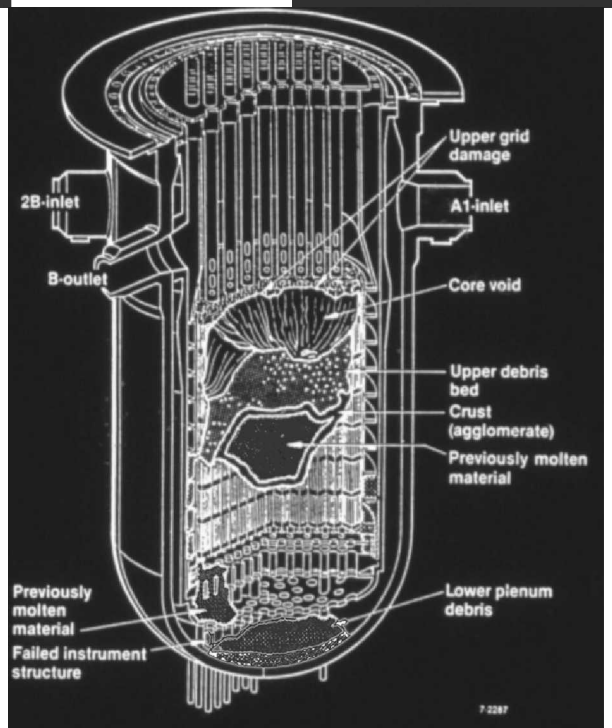


After Pumps On





Melt & Melt-Through



1987 End State Configuration

TMI-2 ACCIDENT

- RADIOLOGICAL CONSEQUENCES
  - Ad Hoc Interagency Dose Assessment Group
    - Findings
      - 2,000,000 Persons $\rightarrow$ 3300 Person-Rem
      - Average Population Dose 1.5 mrem
      - Maximum “Fence-Post” Dose 83 mrem (Estimated Actual Maximum Dose 37 mrem)
      - One Excess Cancer (Over 325,000 Bkgd)
      - Food Sampling - All Below FDA Limits

TMI-2 ACCIDENT

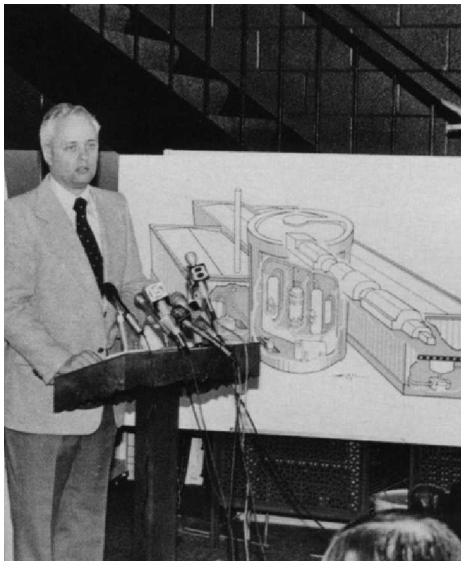
- POST-ACCIDENT RESPONSE
  - Emergency Response
    - Initial Emergency Declarations
    - Helicopter Sampling
      - During Planned Release of Radioactive Gases
        - » One-Time
        - » Purged Tanks for Other Near-Term Uses
      - Assumed by Samplers to be Typical of On-Going Releases
      - Severity Significantly Overestimated
        → Led to Consideration of Evacuation

TMI-2 ACCIDENT

- POST-ACCIDENT RESPONSE
  - Emergency Response
    - Initial Emergency Declarations
    - Helicopter Sampling
    - Evacuation Recommendation on Day 2
      - Shelter w/in 10 Miles
      - Close Schools
      - Evacuate Pre-School Children & Pregnant Women

      Overall: 144,000 Persons/50,000 Households
    - Talk of "Hydrogen Bubble"
    - Evacuation Called Off on Day 10

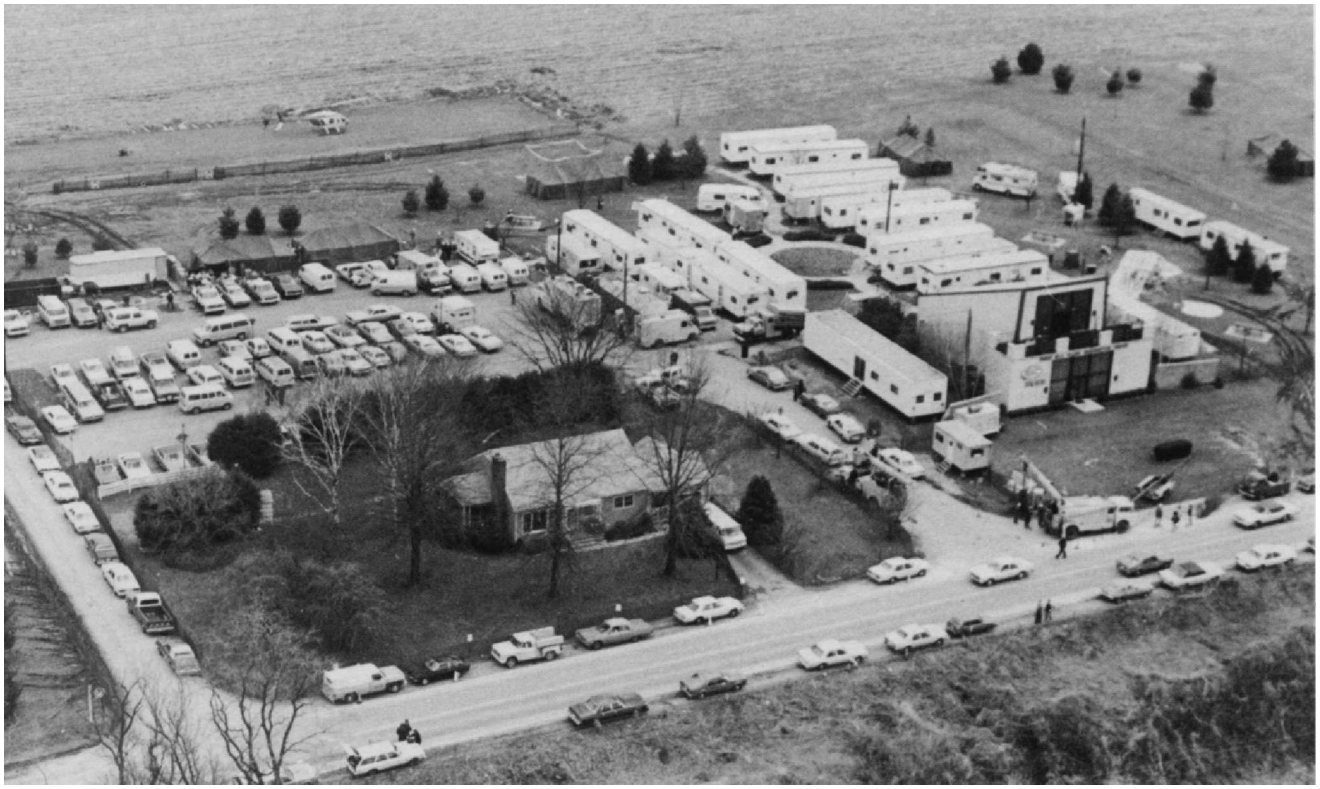
Dignitaries, Briefings & Media



TMI-2 ACCIDENT

- POST-ACCIDENT RESPONSE
  - Plant Recovery
    - Stabilization - Core Cooling
    - Begin Auxiliary Building Decontamination
    - Technical Support - 1400 Personnel Worldwide

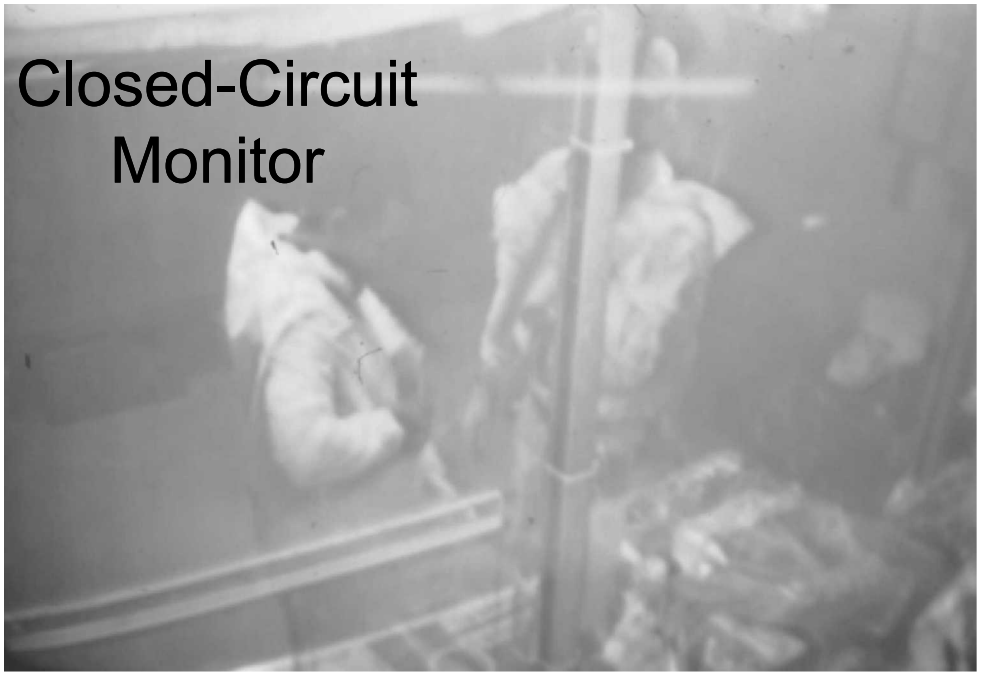
Technical Support

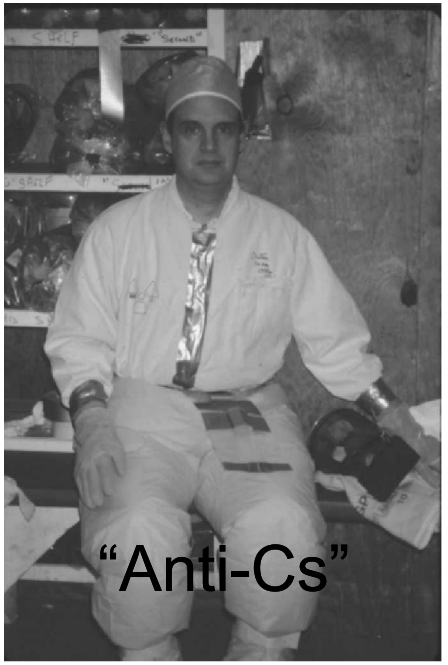


POST-ACCIDENT RESPONSE

- DECONTAMINATION
  - Auxiliary Building & Containment Entrance
    - Hands-On Methods
    - Heavy-Duty Ion-Exchange System for Removal of Radioactive Species from Accident Water

Radiation Safety



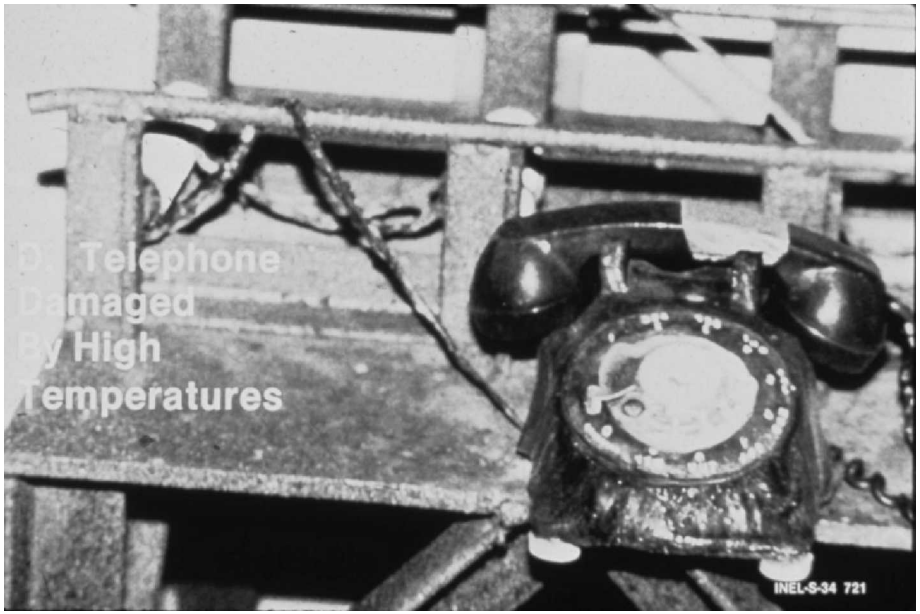


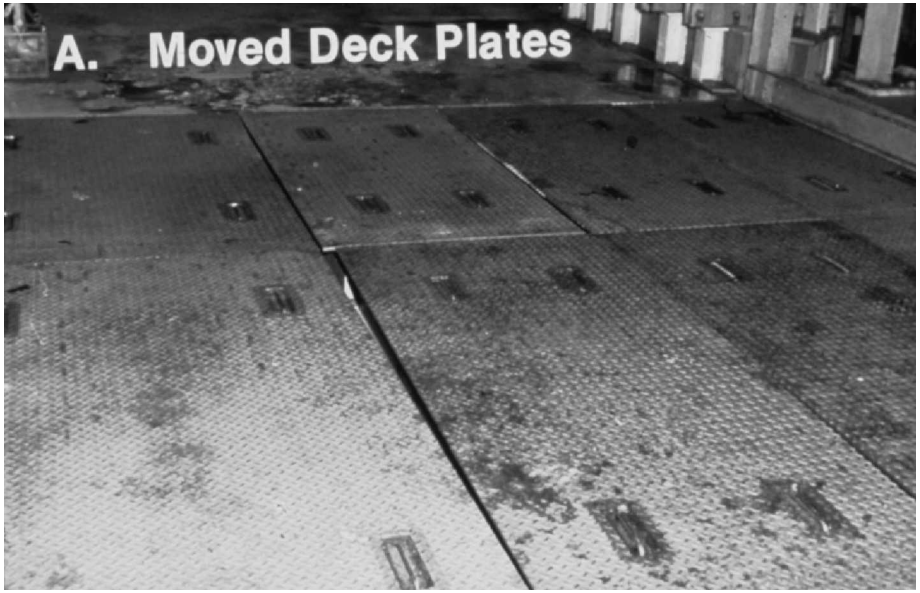
POST-ACCIDENT RESPONSE

- DECONTAMINATION
  - Auxiliary Building & Containment Entrance
  - Radioactive Noble Gases (Primarily ^{85}Kr) Vented from Containment Building
  - First Personnel Entries

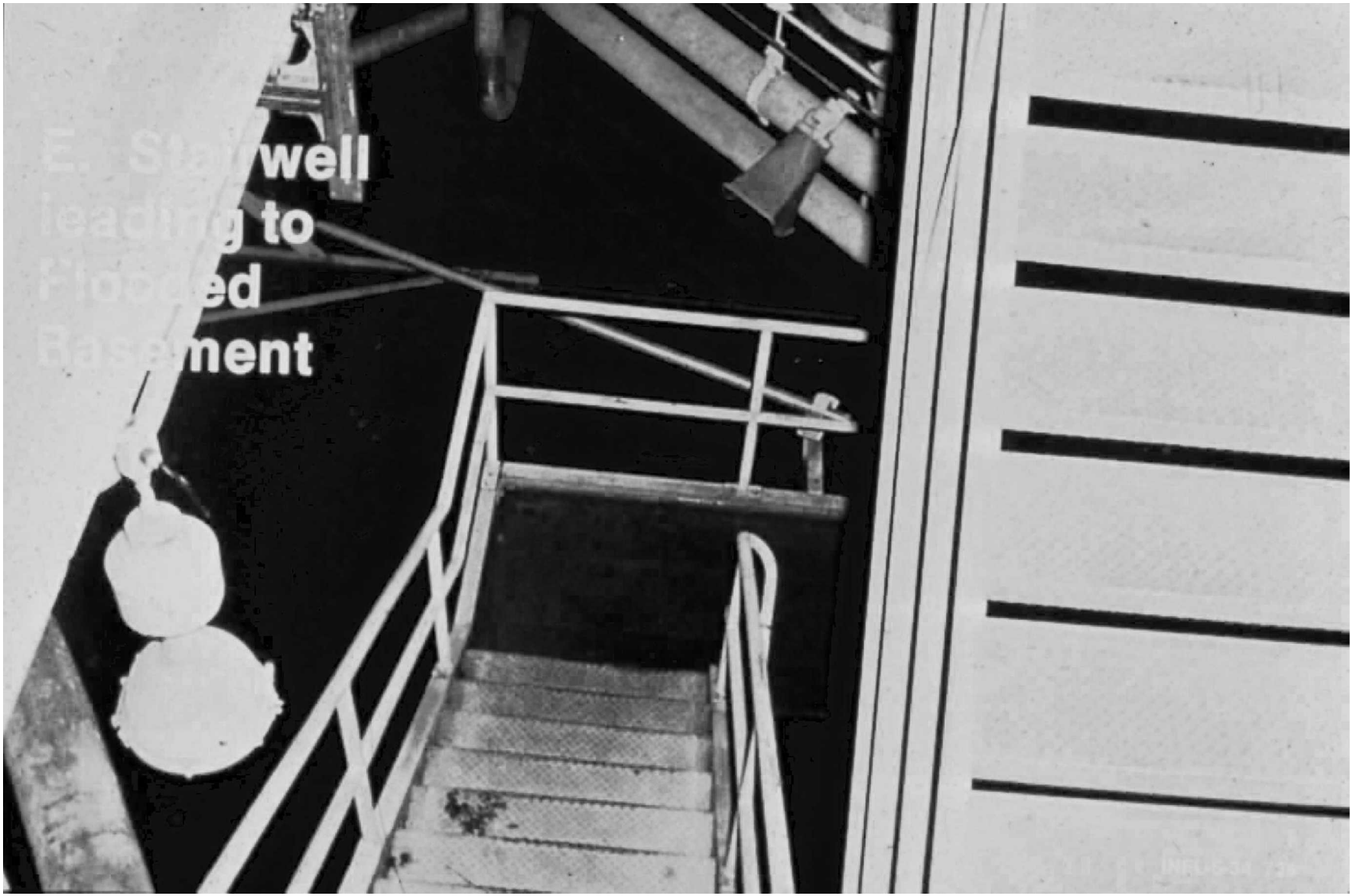
First Manned Entry

Damage from Hydrogen Burn





Stairwell to Flooded Basement



POST-ACCIDENT RESPONSE

- DECONTAMINATION
  - Auxiliary Building & Containment Entrance
  - Radioactive Noble Gases (Primarily ^{85}Kr) Vented from Containment Building
  - First Personnel Entries
  - Brute-Force $\rightarrow$ State-of-the-Art Methods

Containment Decontamination

Strippable Coatings

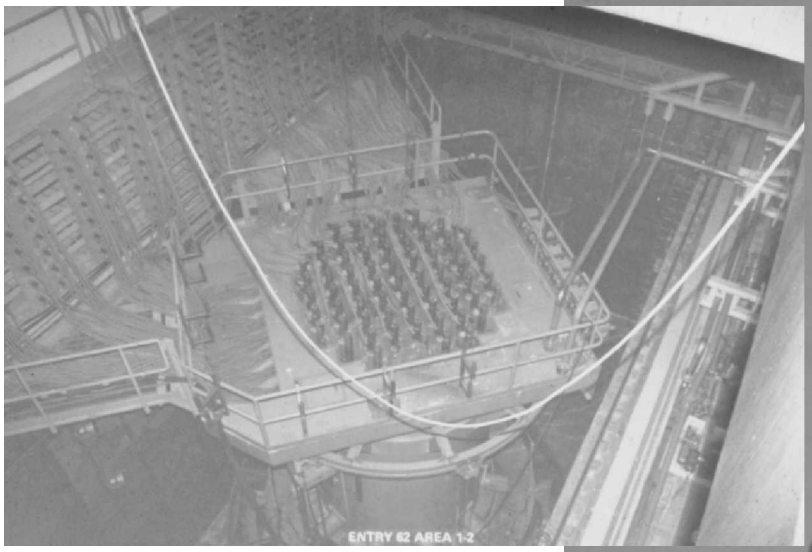
Scabbling

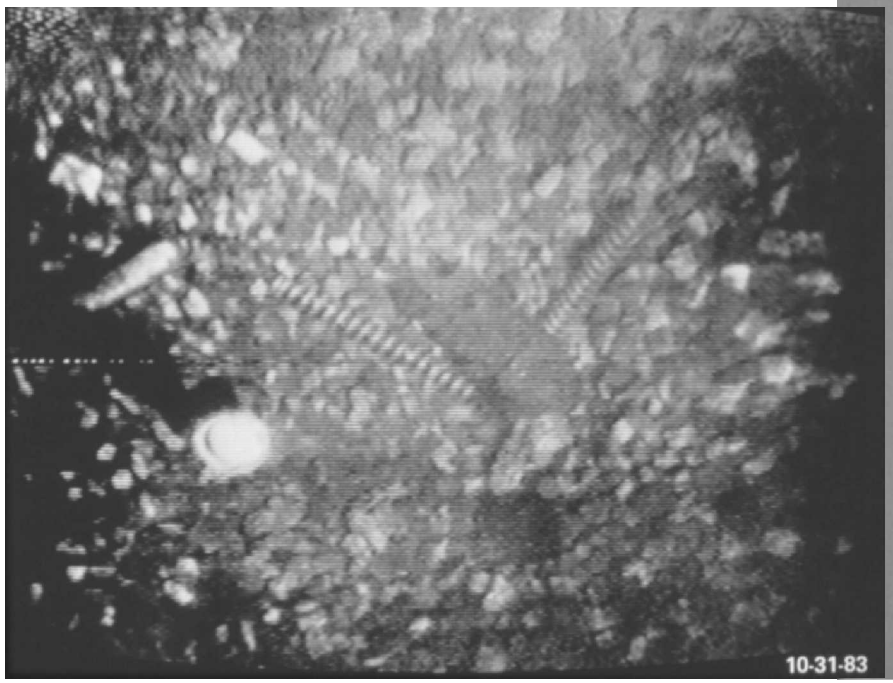
HydroLasing
Manual
Robotic

POST-ACCIDENT RESPONSE

- DEFUELING
  - "Quick Look"
  - Sampling & Mapping

Quick Look


ENTRY 62 AREA 1-2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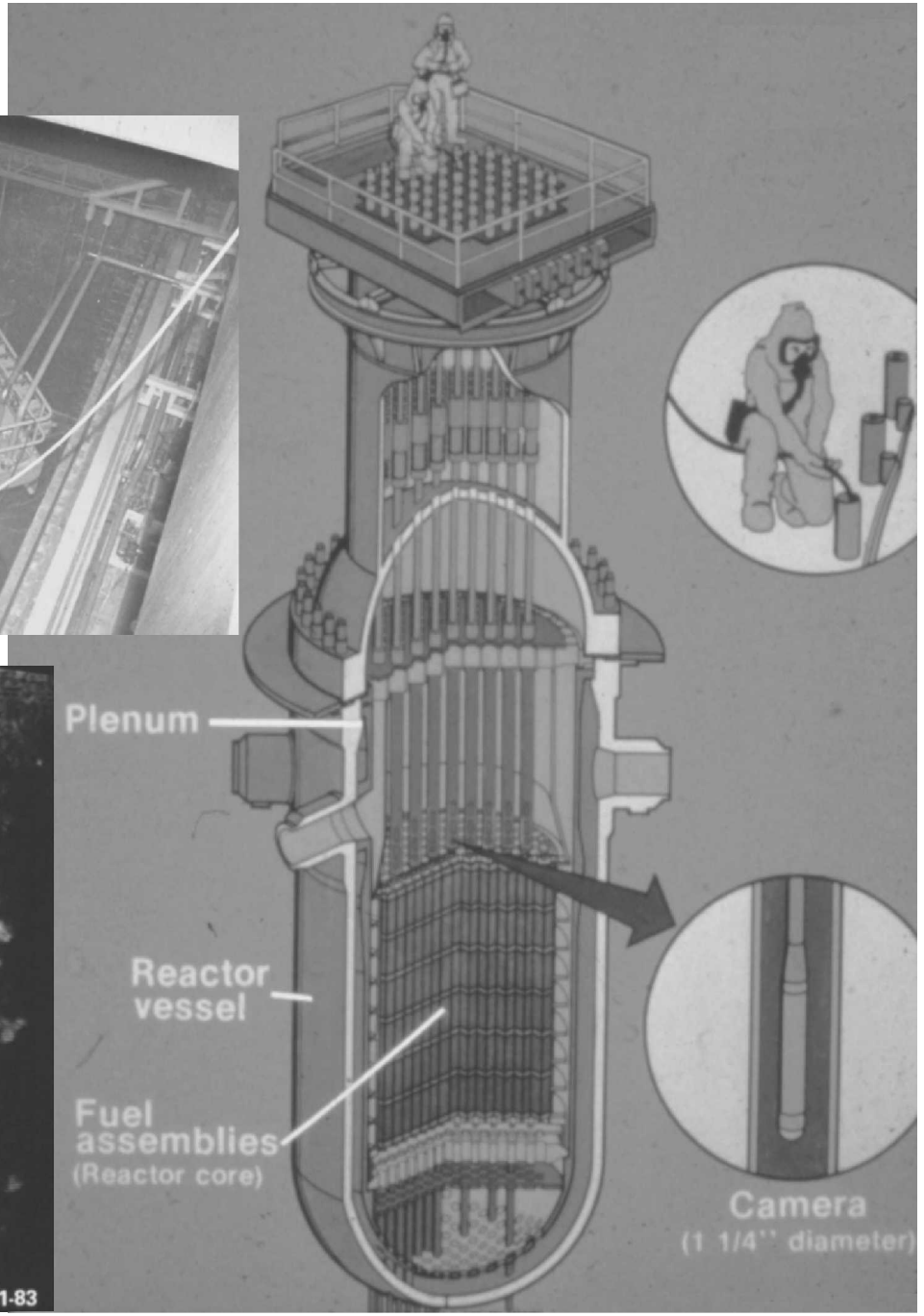
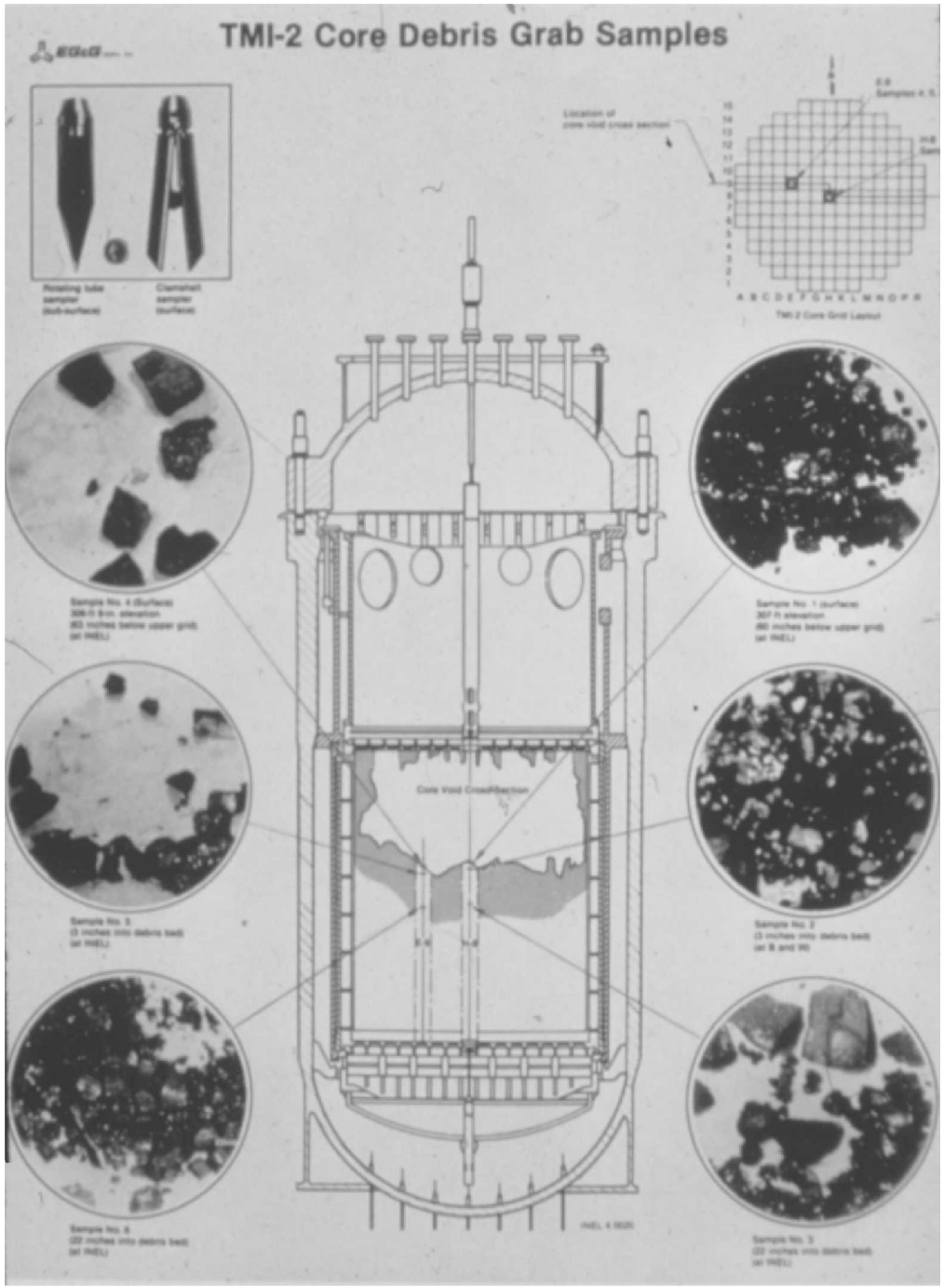
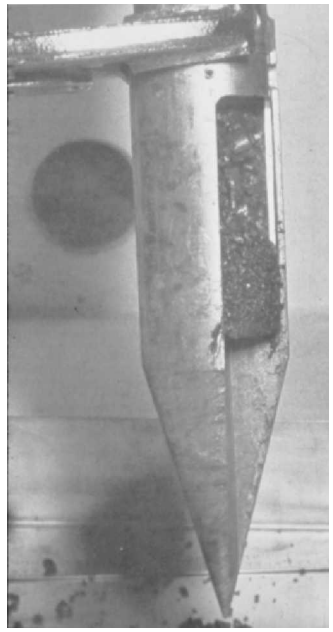

Plenum
Reactor vessel
Fuel assemblies
(Reactor core)
Camera
(1 1/4'' diameter)



Sampling & Mapping

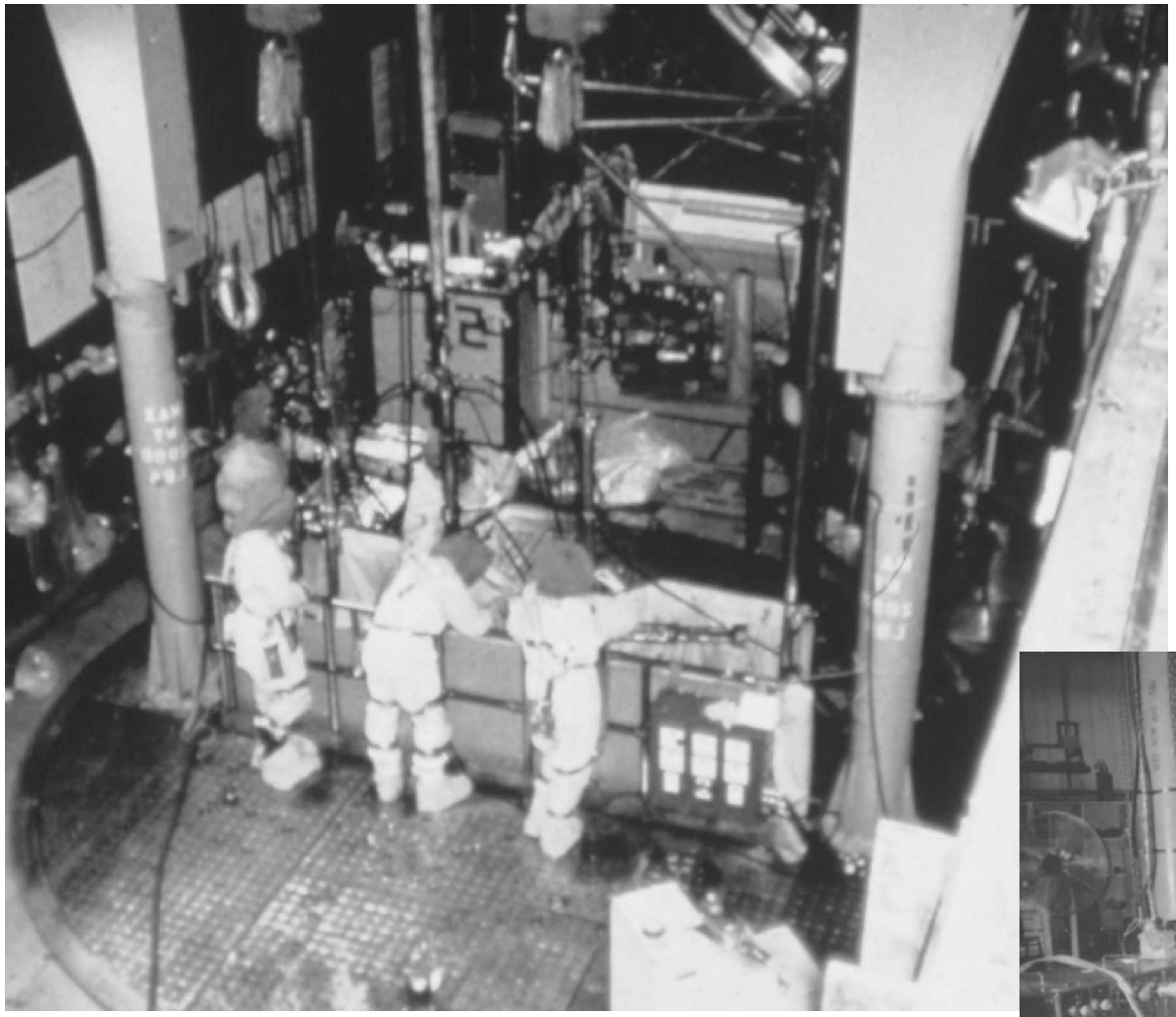


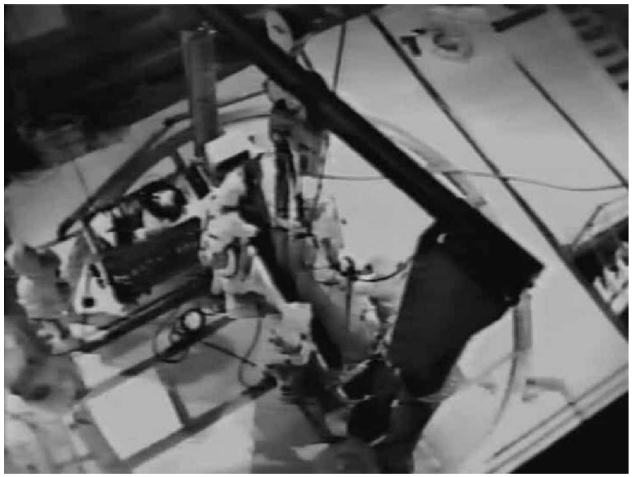
Fuel in Lower Head

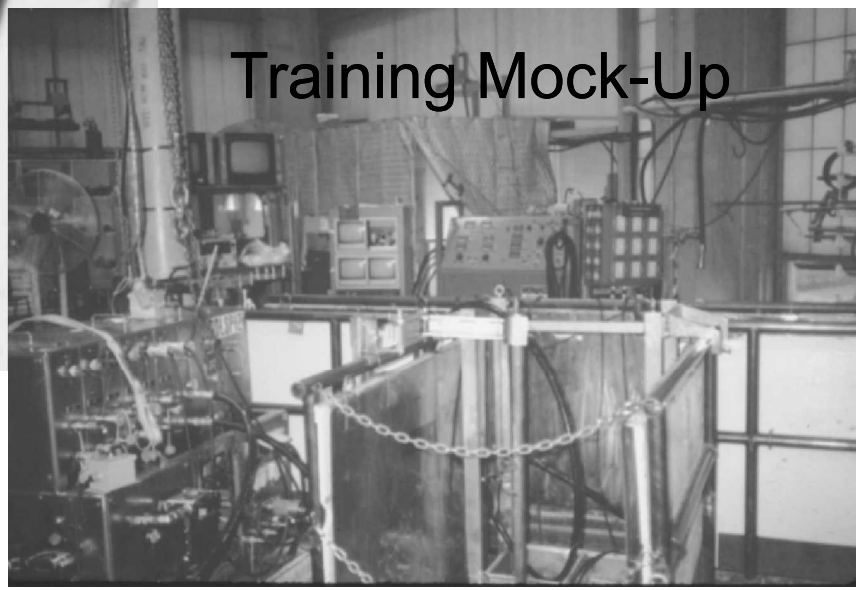
POST-ACCIDENT RESPONSE

- DEFUELING
  - "Quick Look"
  - Approach
    - Shielded Platform / TV Monitors
    - Long-Handled Tools
    - Vacuum System
    - Fuel Canisters
      - Vacuum
      - Filter
      - Manual (for Fuel Assembly)

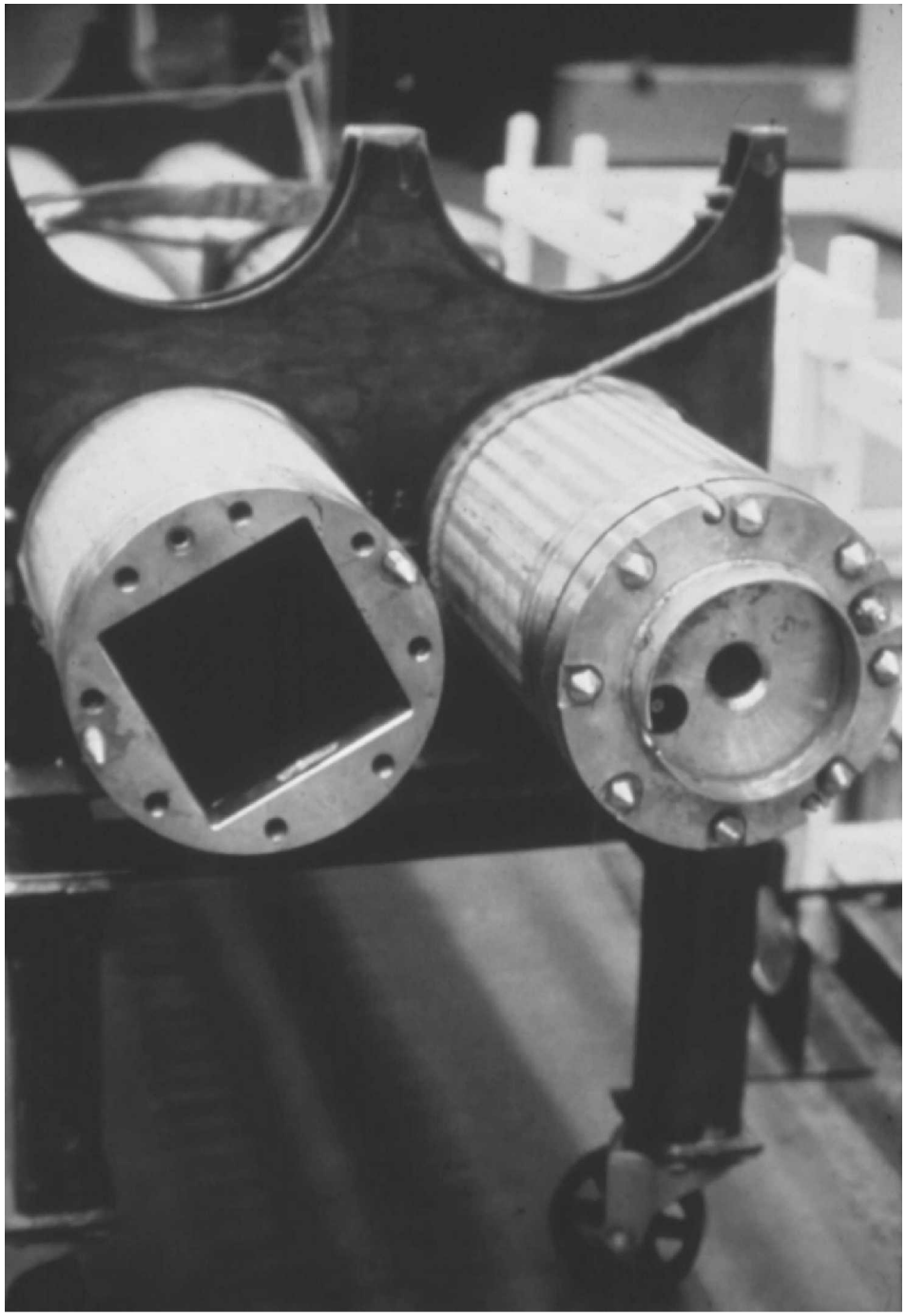
Rotating Defueling Platform







Fuel-Assembly & Vacuum Canisters



TMI-2 Fuel Canister Shipping Cask

THREE MILE ISLAND UNIT 2 (TMI-2)

THE REACTOR

THE ACCIDENT

THE CONSEQUENCES

TMI-2 ACCIDENT

- ECONOMIC & OTHER CONSEQUENCES
  - Direct Costs
    - Recovery - $1 Billion
    - Price-Anderson Payments - $14.3 M
    - 2000+ Unresolved Claims
  - Minimal Local Residual Impact
  - TMI-1 Restart Hearings & 6-1/2-Year Shutdown
  - Nuclear Industry
    - Backfit & License-Related Costs
    - No Reactor Orders Post-Accident Through 2008

TMI-2 ACCIDENT

- SUMMARY
  - Most Serious Accident in U.S. Commercial Nuclear Power History
  - Reactor Core Melted (Not Known at Time)
  - Large Releases to Containment Building
  - Only Minor Environmental Releases & Consequences
  - Profound Effects
    - Utility
    - Nuclear Industry
    - Regulatory Authorities

TMI-2 LESSONS LEARNED

1. The NRC
    1. Resident Inspectors
2. The Utility and Its Suppliers
    1. Human-Factored Control Rooms
3. Training of Operating Personnel
    1. Ops - Engineering – Training – Management
    2. Replica Simulators
4. Technical Assessment
    1. First-Principles Simluation/Modleing
5. Worker and Public Health and Safety
    1. Radiation Effects Studies
6. Emergency Planning and Response
    1. Off-Site EOC
    2. Full Scope Drills/Exercises
7. The Public Right to Information
    1. Professional Organization

INDUSTRY RESPONSE

- Institute for Nuclear Power Operations (INPO)
  - Membership: All U.S. Nuclear Utilities [Now + Operating Companies]
  - HQ: Atlanta, GA
  - Role: Industry “Self-Assessment” and “Self-Policing”
    - INPO Staff and Utility Peer Assessments
      - Operations & Maintenance
      - Training & Qualification
      - Radiological Protection
      - . . .
    - Reporting

INPO

Communitarian Regulation – A system that has a well-defined industrial morality that is backed by enough communal pressure to institutionalize responsibility among its members