Molten-Fuel Moderator-Interaction Studies at Chalk River Laboratories

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Outline

- Overview of the Molten Fuel Moderator Interaction Program
  - Background
  - Qualification of CANDU Thermite
  - Planned MFMI experiments
- Damage Propagation Experiments
  - Small-Scale Burst Test
  - Stern Lab Tests
  - TUBRUPT Validation
- Planned ACR Experiments
- Summary

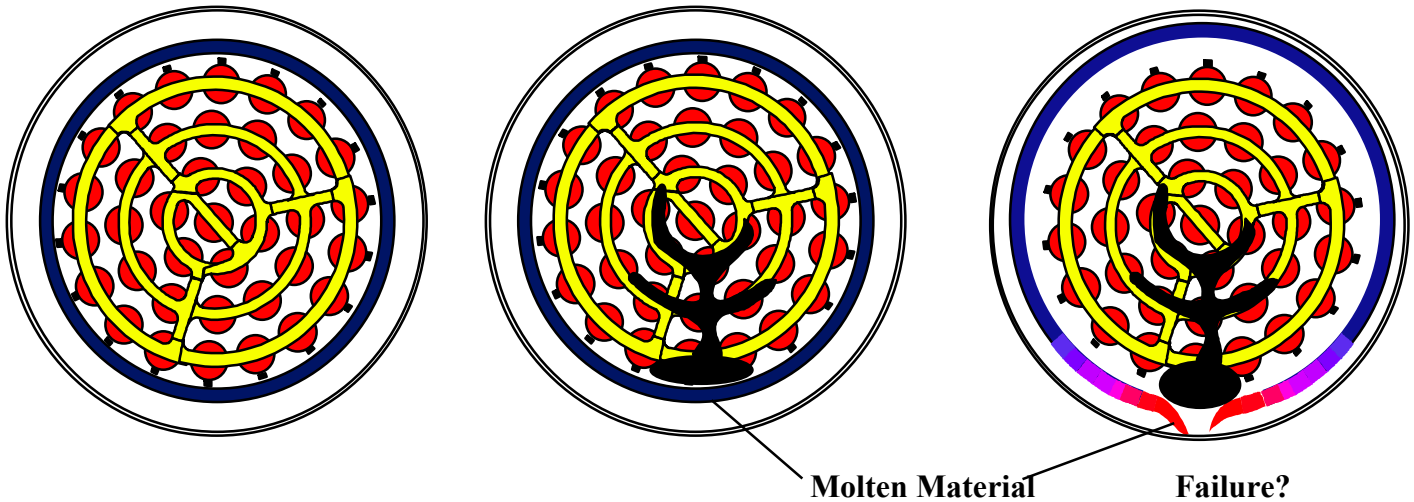
Limited Core Damage Accidents

- In a Limited Core Damage Accident (LCDA) the fuel does not melt but may experience clad melting
- The term molten material in this presentation refers to molten cladding
- The following two postulated scenarios are considered within an LCDA in this presentation:
  - Stagnation Feeder Break and
  - Severe Channel Flow Blockage

Potential LCDAs

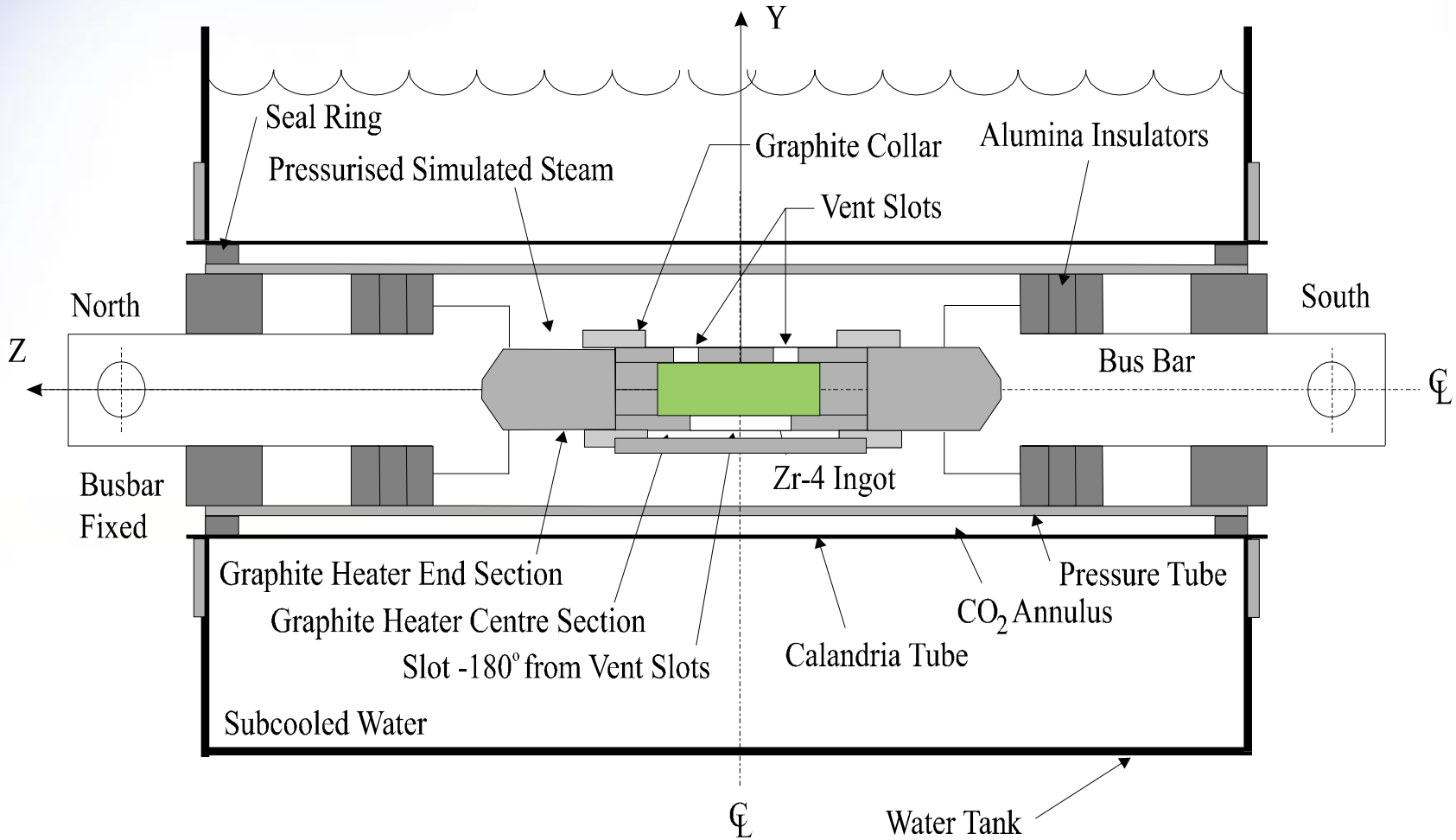
- Stagnation Feeder Break
  - Feeder break just right size to degrade flow in a channel
  - Power / coolant mismatch in channel
  - Heat-up of fuel channel, leads to pressure tube rupture
- Single Channel Flow Blockage
  - Blockage in inlet feeder or PT that drastically reduces flow
  - Power / coolant mismatch in channel
  - For flow area reduction >95%, fuel heats up and leads to fuel channel rupture

Fuel Channel Failure Mechanism for Severe Flow Blockage Scenarios

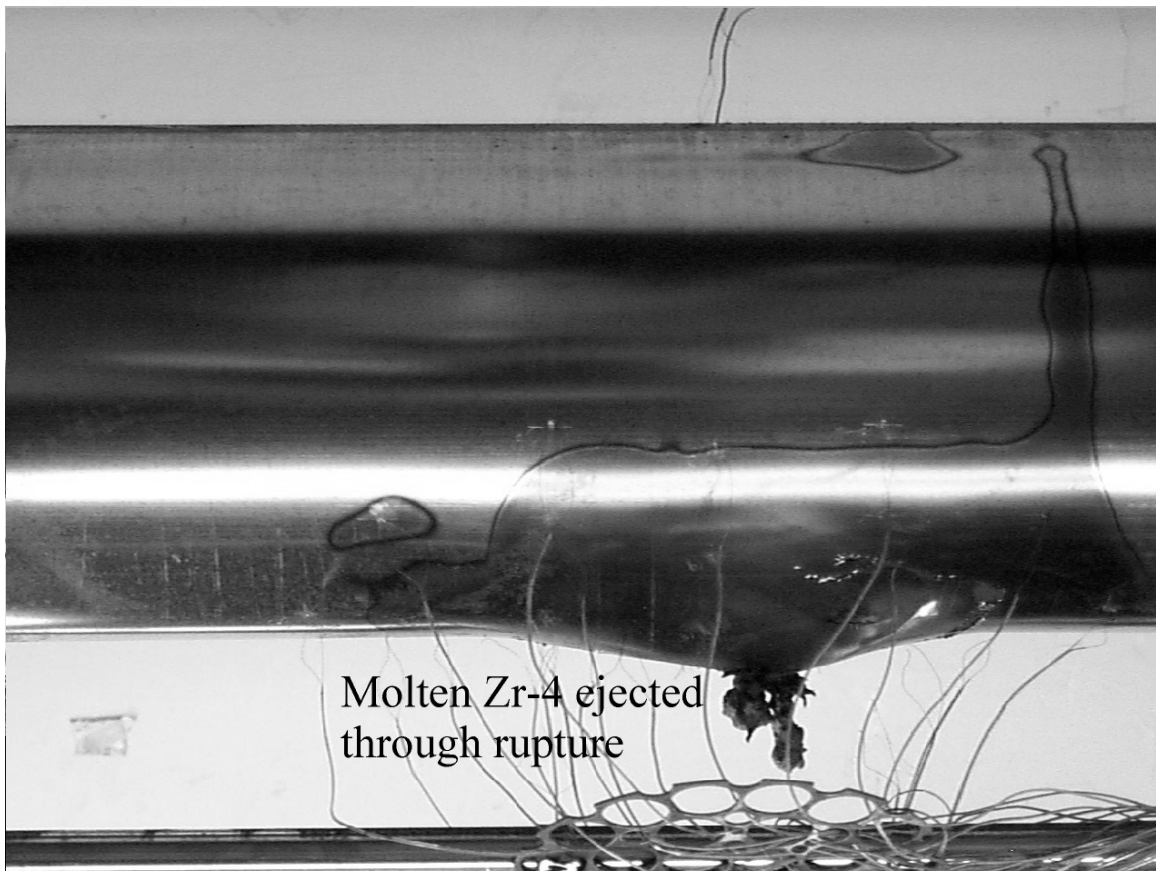


- Small quantities of molten material from an overheated bundle have been shown to be sufficient to rupture a fuel channel at high system pressure

Test Apparatus for FBCR10



Post-Test Photo (FBCR10)



Conclusions of Flow Blockage Channel Rupture Program

- Molten Material Contact Prior to PT/CT Contact (FBCR1-9)
  - Relatively small quantities (~50 g) of molten material are sufficient to create localized hot spots which fail the PT prior to ballooning into CT contact.
- Molten Material Contact After PT/CT Contact (FBCR10-15)
  - The amount of molten material required to fail the channel is ~ 200 g.
  - It is estimated that with high internal pressures (~10 MPa) and close to 200 g of molten material, the pressure tube will fail in less than 2 s.

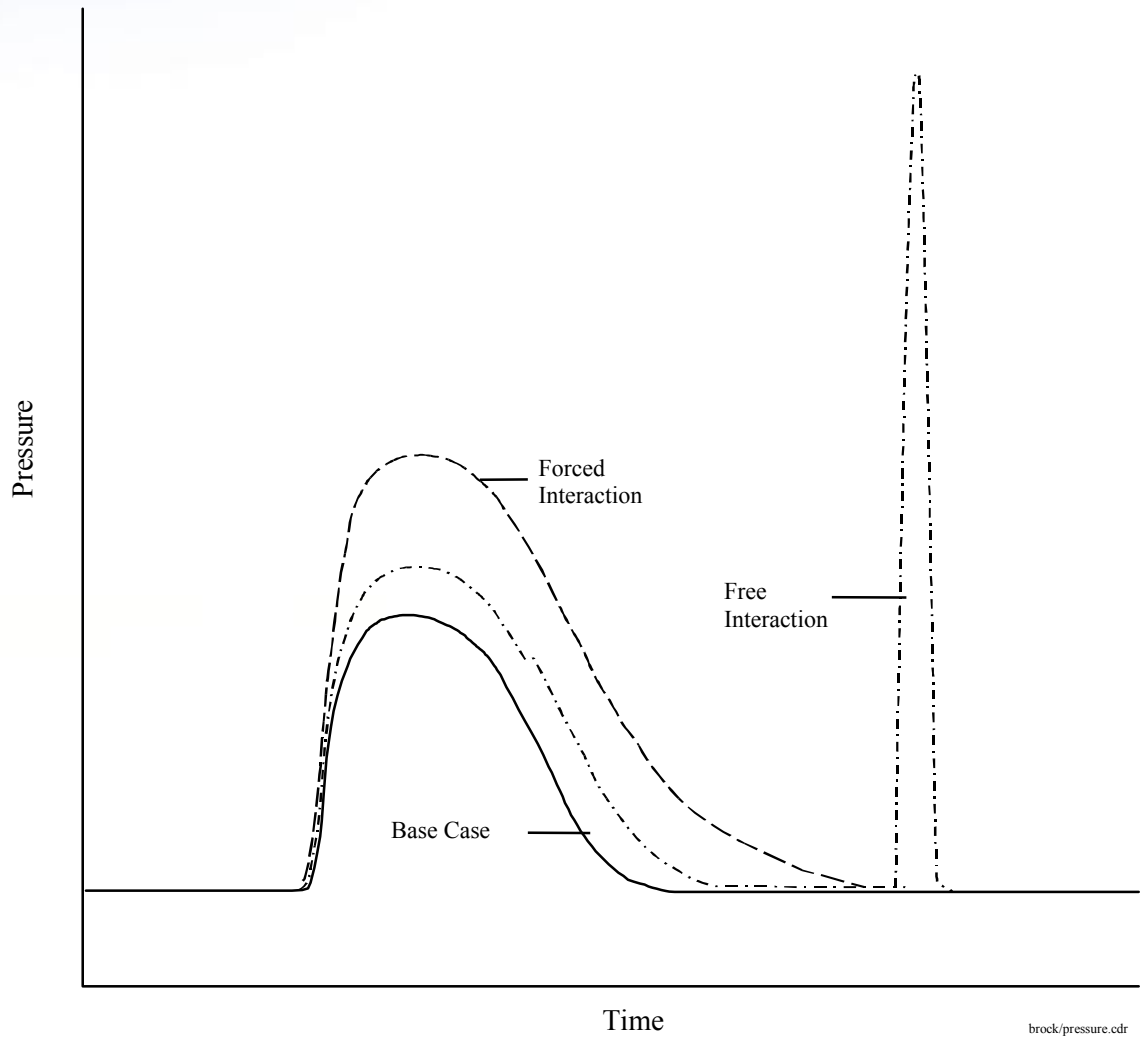
Overview of the Molten Fuel Moderator Interaction Program

- The overall objective of the program is to provide data on the consequences of ejecting molten material into water with a driving pressure of 10 MPa
- The tests must be as reactor typical as possible
  - Representative channel configuration
  - Representative melt composition
  - Representative melt temperature and pressure

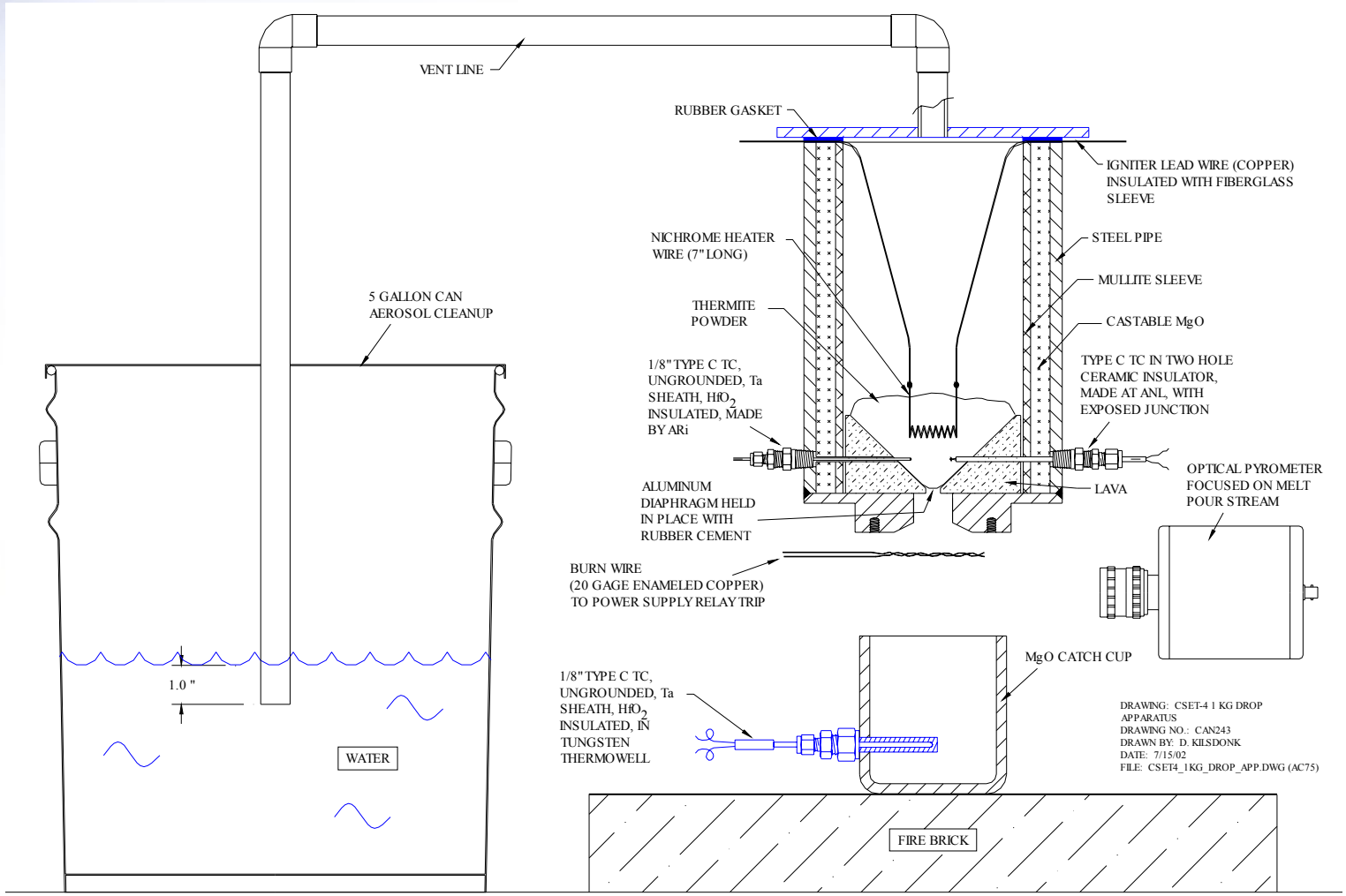
Test Matrix - Commissioning

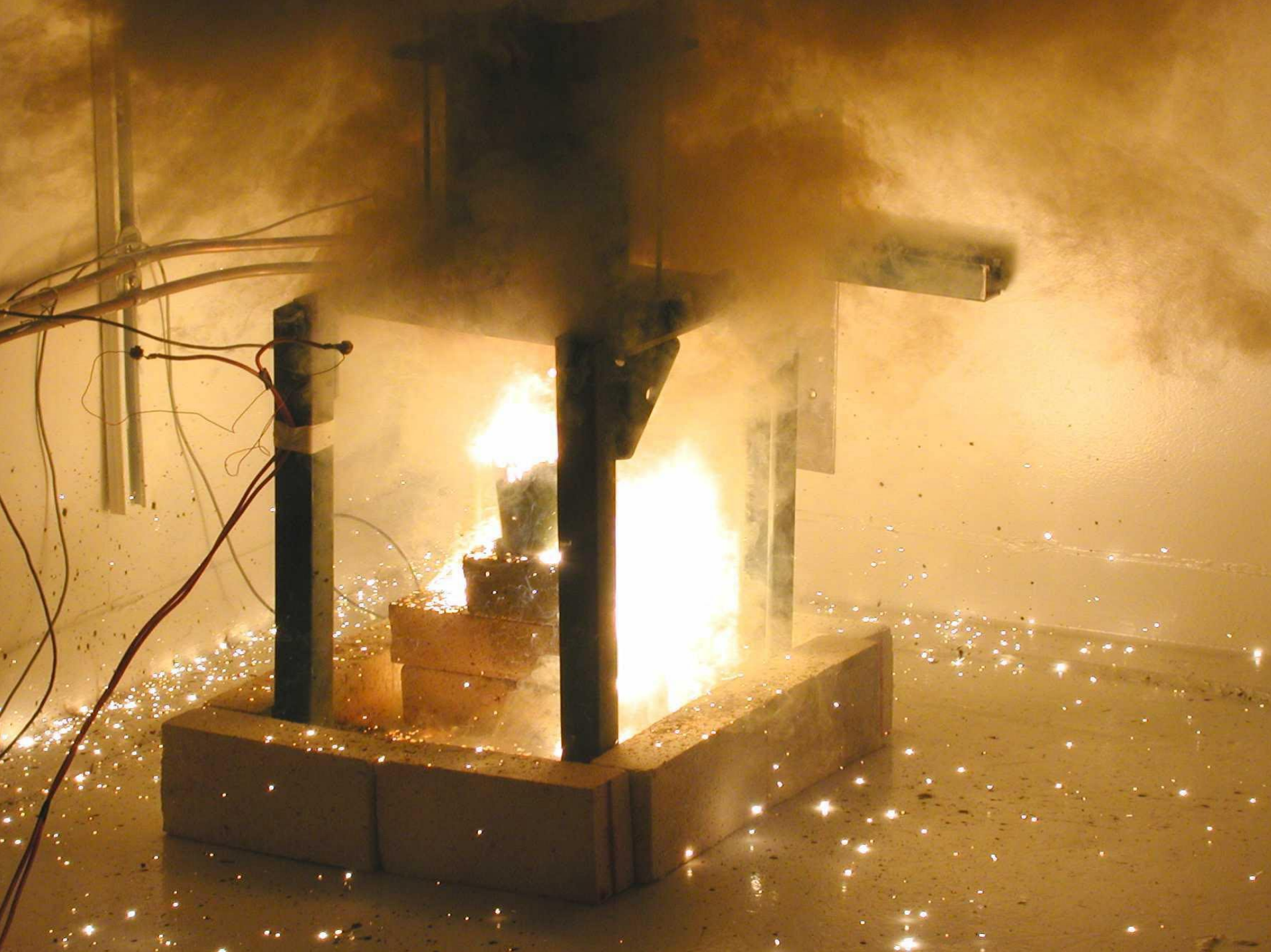
- A series of “dry” tests were performed at Argonne National Laboratory (ANL)
  - to characterize the melt ejection when the PT ruptures and
  - to proof-test the concept.
- Two base-line reference tests with no melts present were performed in the MFMI facility
  - To establish the pressure pulse and
  - the response of the inner vessel to the rupture when pressurized to 10 MPa with a steam / helium mixture
- Commissioning tests planned with small quantities of melt (<5 kg) to evaluate system response prior to embarking on proposed test matrix

Molten Fuel / Moderator Interaction Experiments



Schematic of Mass Scale-Up Test Apparatus





Corium Development at ANL

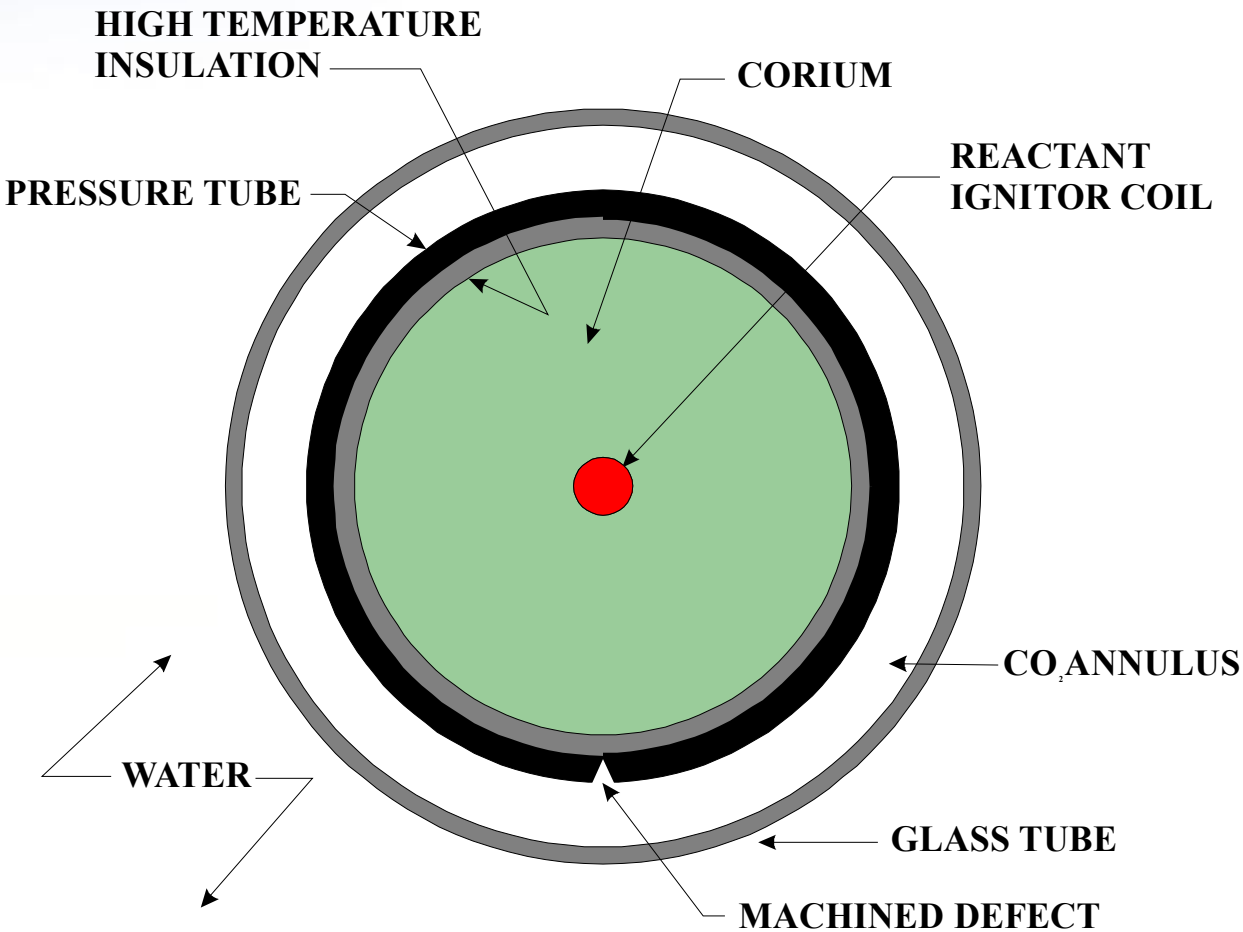
- The key features for CANDU typical corium are:
  - 0.9 UO_2 / 0.1 Zr (wt fraction)
  - 2400°C
- Thermite composition (wt fraction)

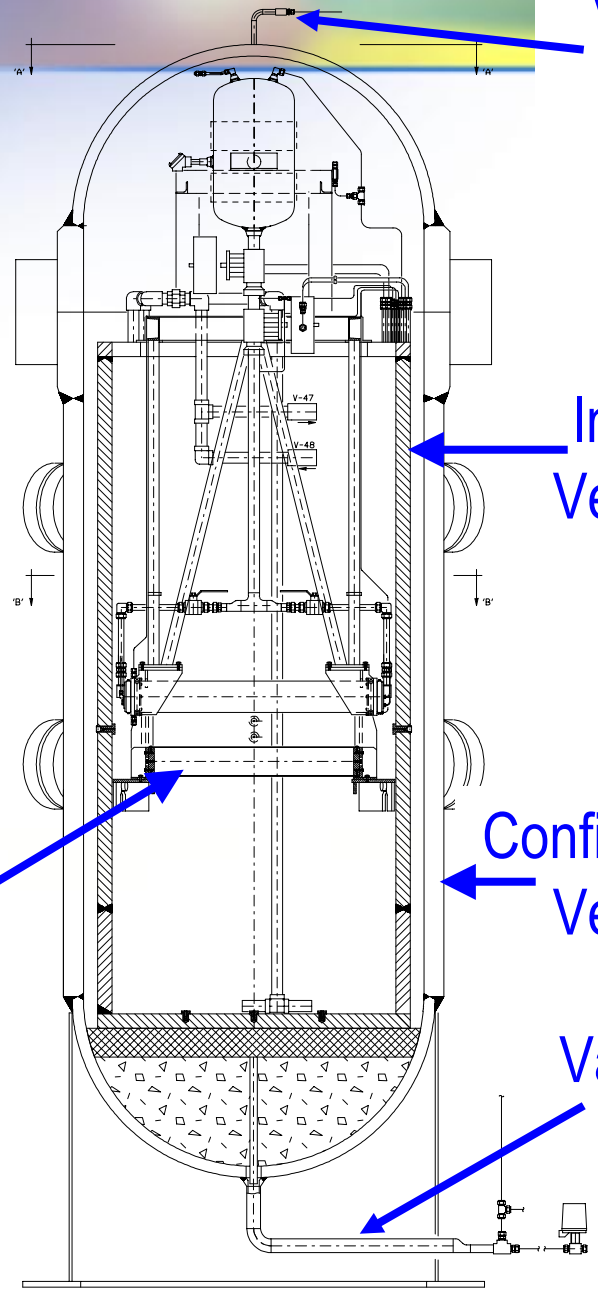
  0.582 U / 0.077 U_3O_8 / 0.151 Zr / 0.19 CrO_3

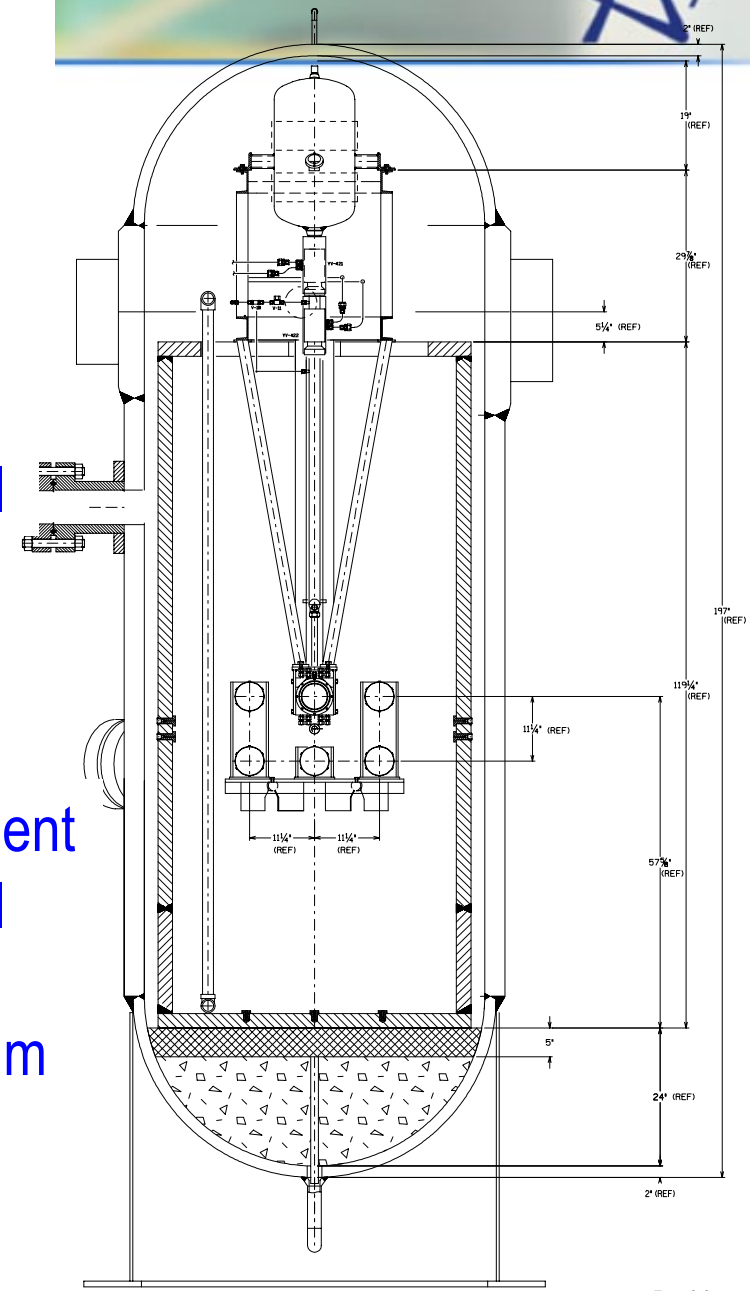
  which yields

  0.73 UO_2 / 0.11 Zr / 0.06 ZrO_2 / 0.10 Cr @ ~2400°C
- The peak melt temperature of a candidate thermite is confirmed from thermite reaction tests

Schematic showing PT assembly

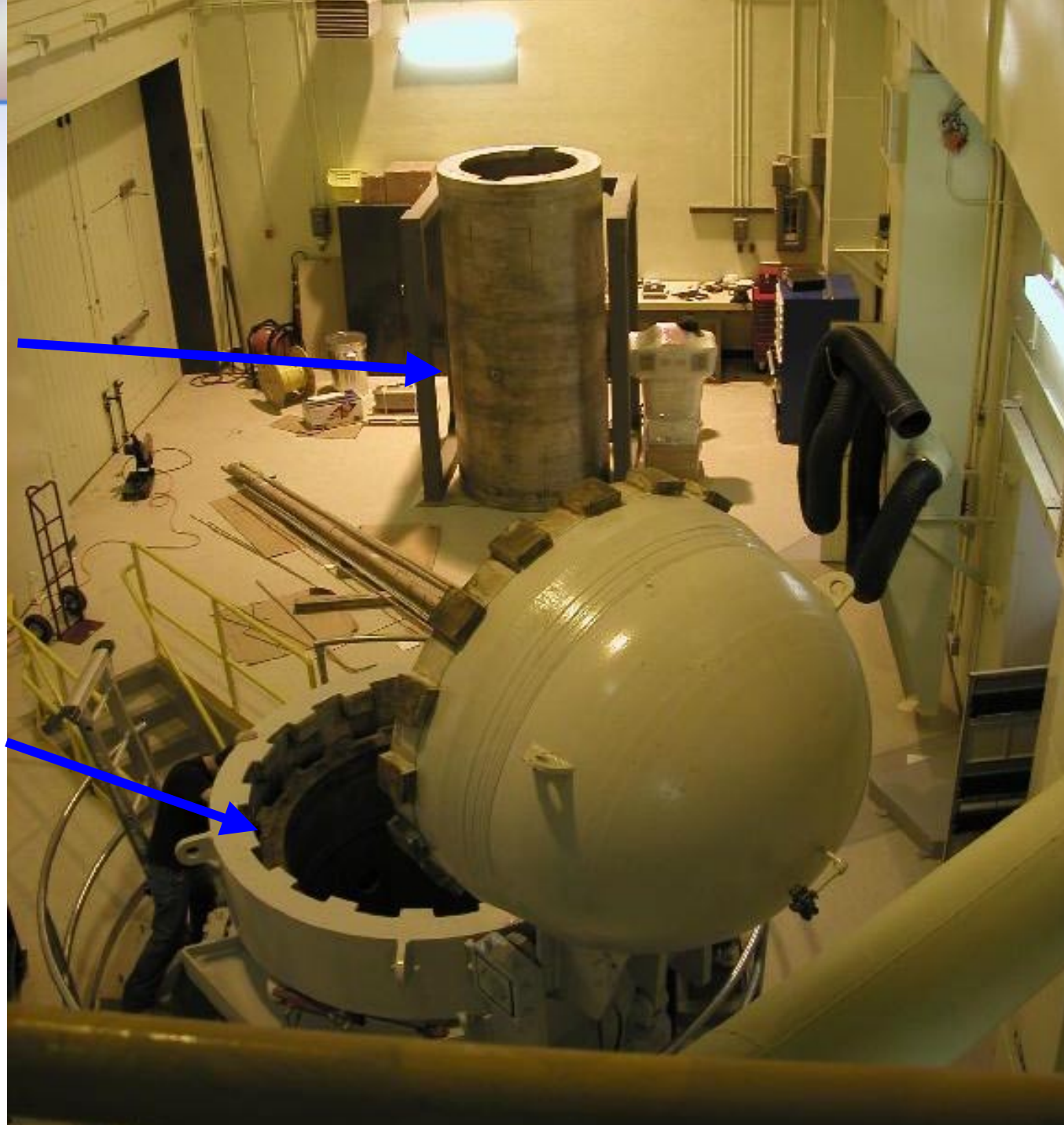



Vent Line
Inner Vessel
Confinement Vessel
Dummy Channels
Vacuum Line
V-47
V-48
'A'
'B'

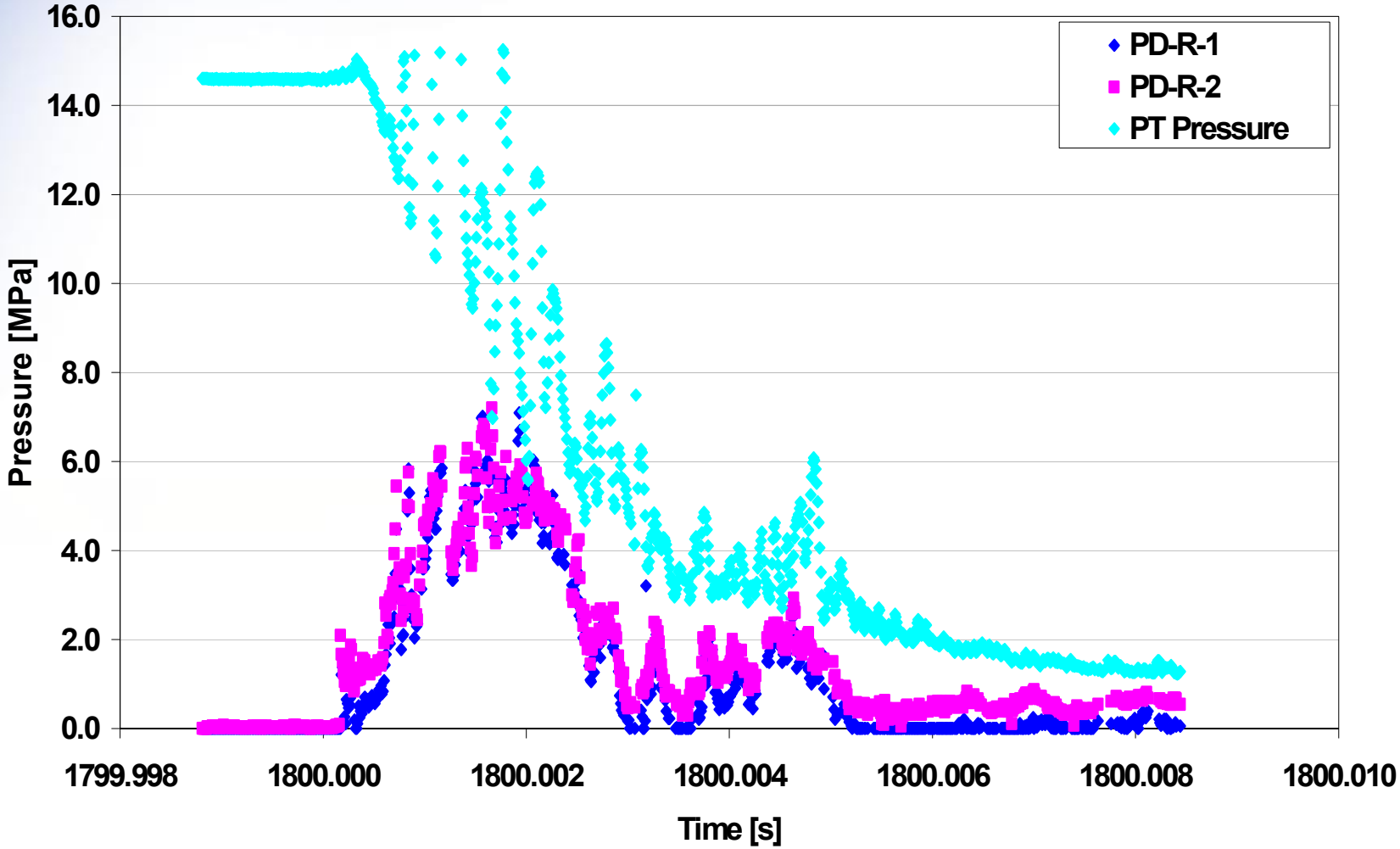

2" (REF)
19" (REF)
29⅞" (REF)
5¼" (REF)
197" (REF)
119¼" (REF)
11¼" (REF)
11¼" (REF)
11¼" (REF)
57⅞" (REF)
5"
24" (REF)
2" (REF)

Inner Vessel

Confinement Vessel



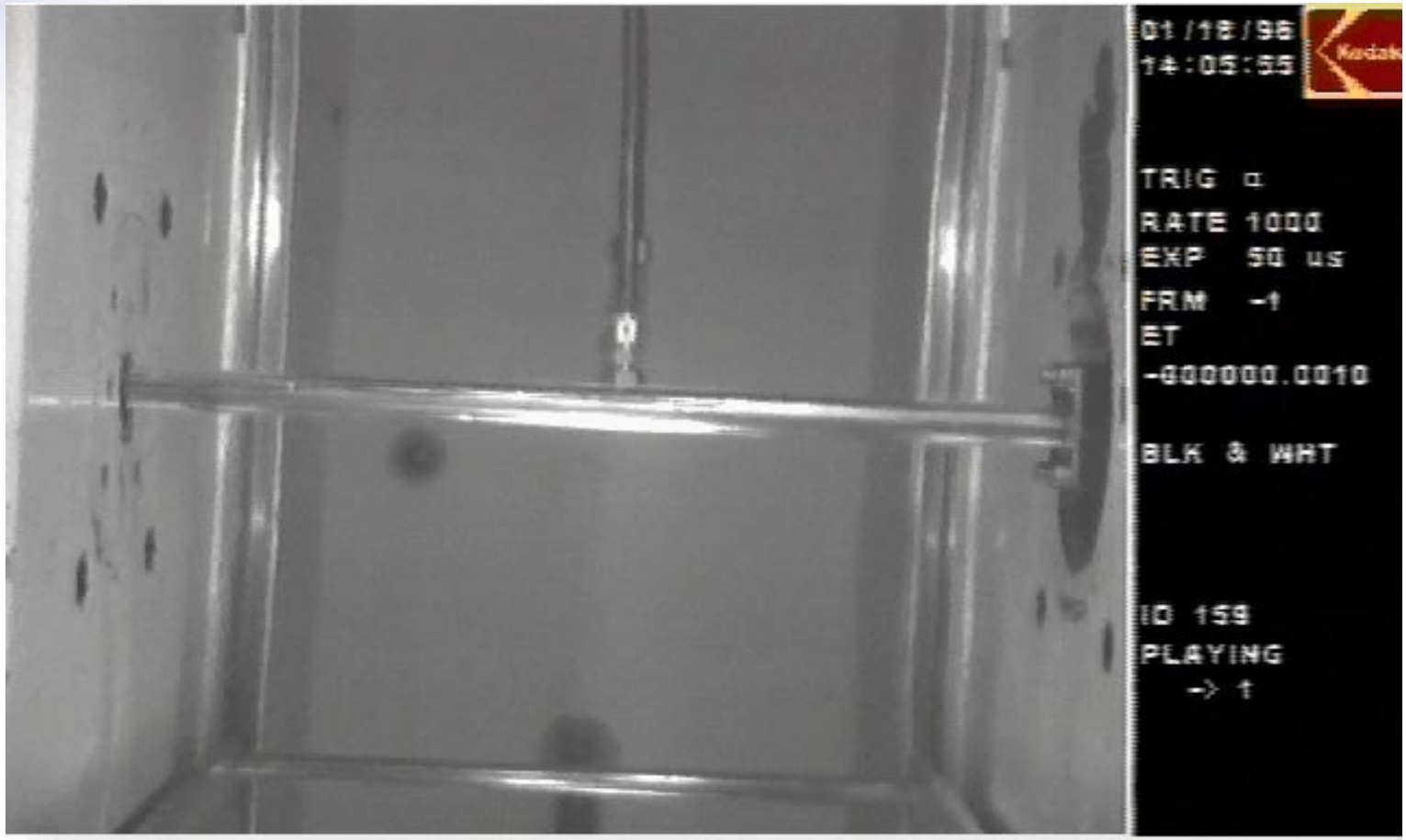
The Peizoresistive Pressure Transducers on the Bar – NC#2



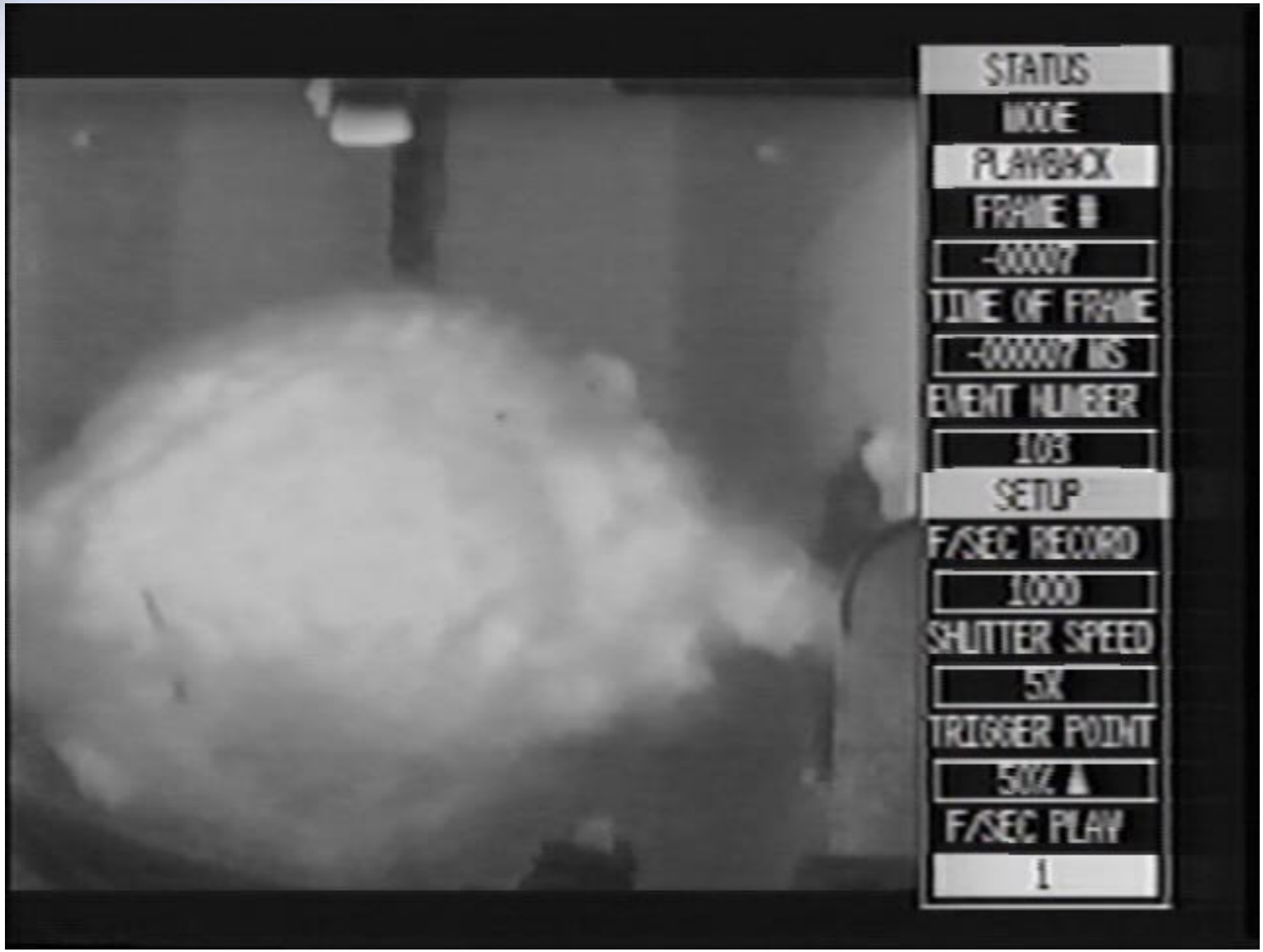
Damage Propagation Experiments

- Small-Scale Burst Test
- Full-Scale Multi-Channel Burst Tests
- TUBRUPT Validation

SMALL SCALE BURST TESTS



SMALL SCALE BURST TESTS



Small-Scale Burst Tests

- Provides qualified data to validate TUBRUPT code
- Apparatus has been scaled to account for higher operating temperature and pressure, smaller calandria vessel, smaller lattice pitch, and larger CT diameter

Post-test View Showing Collapsed Calandria Tubes (MCBT Facility)

The Collapse of calandria tubes provides extra volume to mitigate consequences of rapid pressurization

Planned MFMI Experiments with ACR Conditions

- Difficult to preclude presence of molten material at time of channel failure with current analysis tools
- Assessing consequences of ejecting ~25 kg of molten material from an overheated fuel channel into water with a driving pressure of ~13 MPa
- The 25 kg melt provides a bounding melt mass for the experimental program
- Two tests will be completed in the MFMI facility that forced interaction is the dominant mode of interaction between the molten material and moderator

Summary

- Atomic Energy of Canada Limited partnered with Argonne National Laboratory to develop a CANDU reactor typical corium
- Tests conducted indicated that a mixture of

  0.582 U/0.077 U_3O_8/0.151 Zr/0.19 CrO_3 (wt%)
  produces a corium consisting
  0.73 UO_2/0.11 Zr/0.06 ZrO_2/0.10 Cr (wt%)
- The peak melt temperature of ~2400°C was confirmed from thermitic reaction and mass scale-up tests

SUMMARY

- Extensive R&D on pressure tube rupture mechanisms and consequences of pressure tube and calandria tube ruptures
- No propagation of fuel channel rupture observed in any test
  - MCBT
  - Small-scale burst tests
- Jet impingement not a significant load
- Hydrodynamic loads on fuel channels collapse calandria tubes onto pressure tubes, mitigating pressure pulse
- Hydrodynamic loads on guide tubes acceptable
- Undertaking an R&D program on consequences of melt ejection to demonstrate defense in depth. No melt ejection is anticipated, but the design is robust enough to tolerate it.

SUMMARY

- It is anticipated that the ACR calandria tube will not fail due to hydrodynamic loads following a pressure tube rupture (calandria tube is ~3X stronger)
- ACR has stronger calandria tubes and smaller calandria vessel $\Rightarrow$ hydrodynamic transient in calandria vessel following a calandria tube rupture will be more severe, but still acceptable
- Confirmatory R&D and analysis to demonstrate above is underway

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