Severe Flow Blockage

Brock Sanderson, Manager

Fuel and Fuel Channel Safety (F&FCS) Branch

Presented to US Nuclear Regulatory Commission

Washington DC

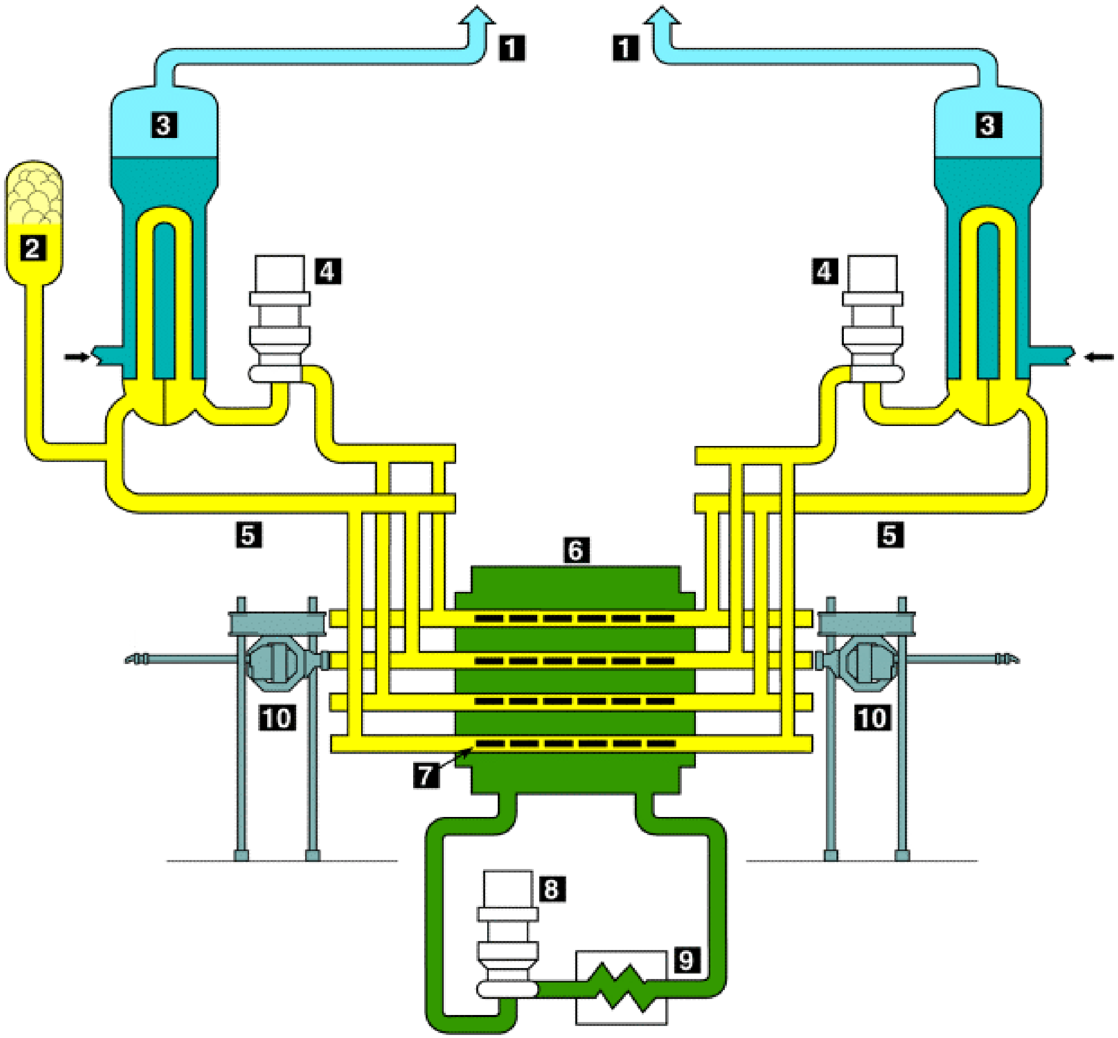
May 6-7, 2003

AECL TECHNOLOGIES INC.

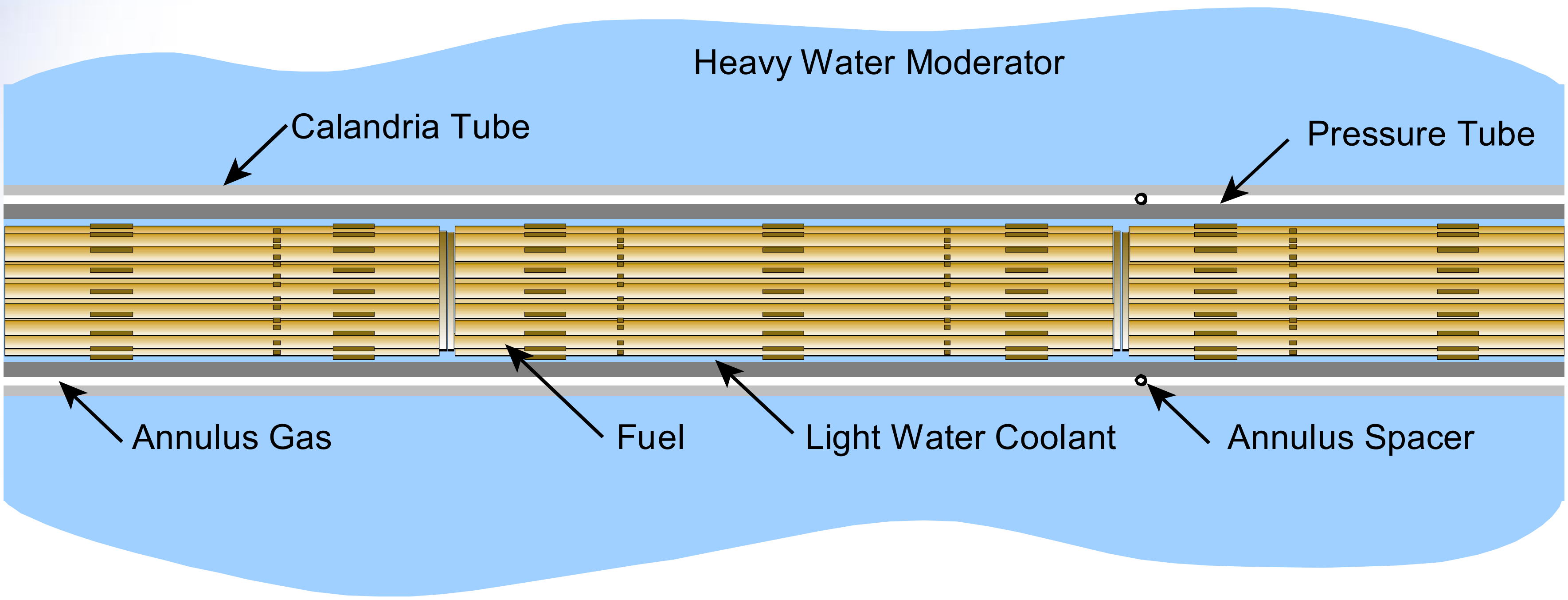
Outline

- Introduction
  - Background
  - Consequences of a Severe Flow Blockage Event
- Generic Technology Base
  - Channel Response to Blockage
  - Fuel Channel Failure Mechanisms
  - Molten Fuel Coolant Interaction
- ACR Design
- Concluding Remarks

Simplified CANDU Reactor Circuit



Fuel Channel Details



Fuel is UO_2 clad with Zircaloy-4, in short bundles

Moderator is unpressurized heavy water below 100°C

Flow Blockage

- The consequences of flow being blocked to a fuel channel depend on the extent of the blockage
- For blockages up to ~98% of the flow area:
  - In extreme cases, there can be dryout of the fuel cladding and failure releasing fission products to the RCS
  - The pressure tube remains intact, and any releases are contained in the RCS
- Severe flow blockages in excess of ~98% of the flow area (very rare) can lead to channel failure

Severe Flow Blockage

- **Sequence of Events:**
  - Conditions in affected channel: reduced coolant flow, full pressure, full power
  - Fuel rapidly heats up, transferring heat to the pressure tube
  - As the pressure tube temperature increases, it will start to balloon outward under the system pressure
  - Pressure tube is likely to fail due to strain localization (circumferential temperature gradient)
  - If there is essentially complete blockage (less than 0.5% of the flow area remaining), there could be limited melting of fuel cladding before pressure tube failure

Severe Flow Blockage (cont.)

- Sequence of Events (cont.)
  - Rupture of the pressure tube pressurizes the annulus with the calandria tube, causing the channel bellows to fail
  - If the pressure tube does not fail prior to ballooning contact with the calandria tube, small amounts of molten material will cause failure of both tubes
    - Discharge of steam, hot fuel, etc., from the channel into the moderator will cause some limited damage to core components
  - In either case (pressure tube failure, or pressure and calandria tube failure) the reactor trips and there are no further consequences

Severe Flow Blockage (CANDU 6)

- In a CANDU 6 single channel event, the pressure tube (PT) is expected to rupture due to non-uniform strain prior to ballooning contact and generation of any significant amount of molten material
- It is postulated that if the PT did not fail during ballooning and contacted its calandria tube (CT), then the generation of molten material is possible
- Bounding calculations have been used to provide an estimate of amount of molten material available to interact with moderator under such a scenario (~15 kg)

Initial Conditions
(for CANDU 6)

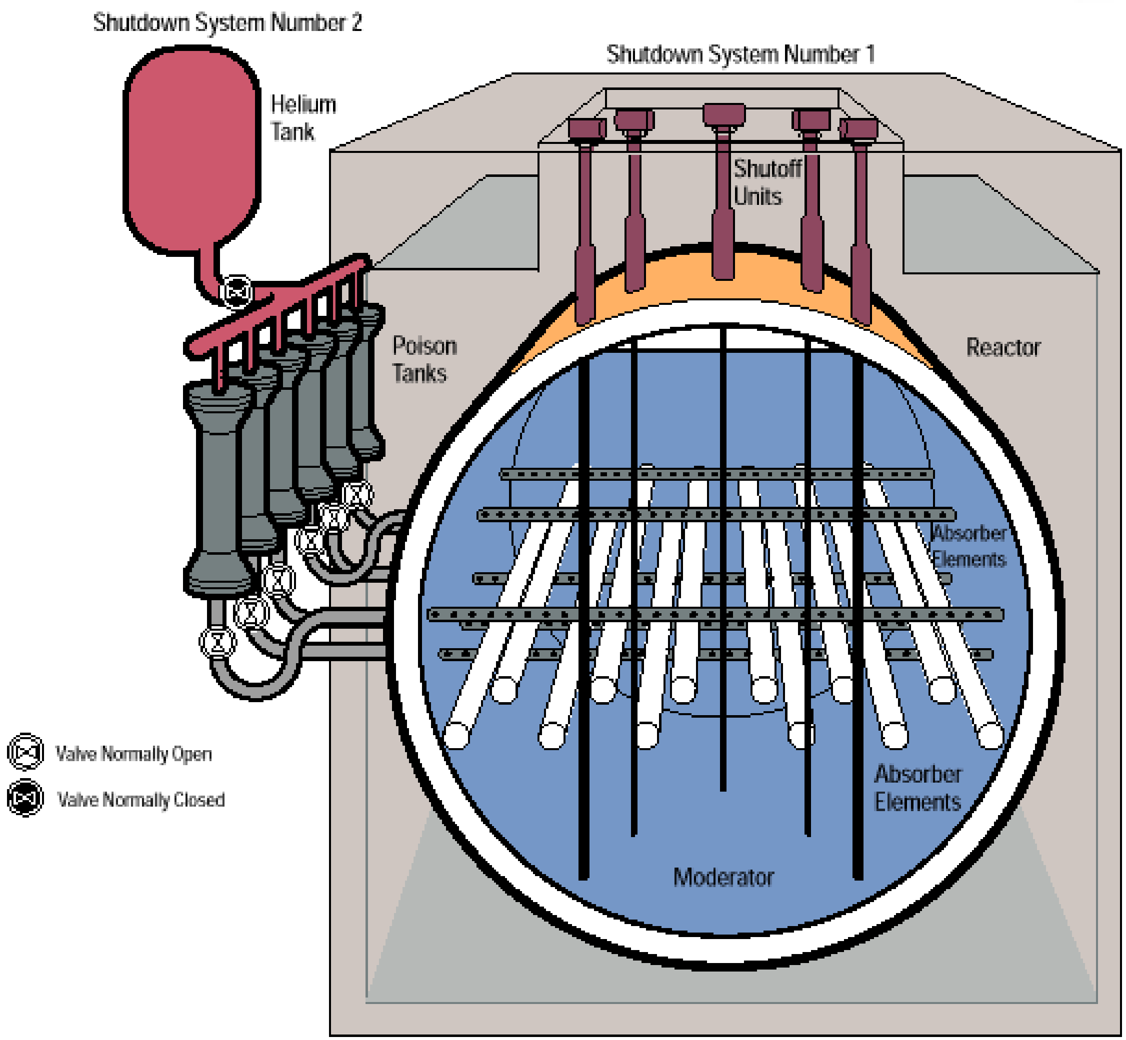
- 15 kg of molten material; Canadian nuclear industry position
  - 10 kg of molten Zircaloy from clads, fuel element end-caps, end-plates
  - 5 kg of UO_2/Zircaloy alloy (dissolution by molten material)
- Molten material temperature is ~2400°C
- Channel pressure is 10 MPa
- Before channel rupture, superheated steam and/or hydrogen in channel
- Cool moderator temperature (65°C); calandria cover gas pressure is 125 kPa(a)

Safety Assessment
(for CANDU 6)

- **Assess integrity of in-core components following channel rupture:**
  - adjacent channels (propagation failure)
  - shut-off rod guide tubes (sufficient negative reactivity to keep the reactor sub-critical)
  - calandria vessel (loss of moderator)
- **Assess fission product release from fuel in the affected channel (fission products transported through broken channel into moderator)**
- **Remainder of heat transport system is affected as for a small pipe break (i.e., no clad failures)**

Potential Damage Mechanisms

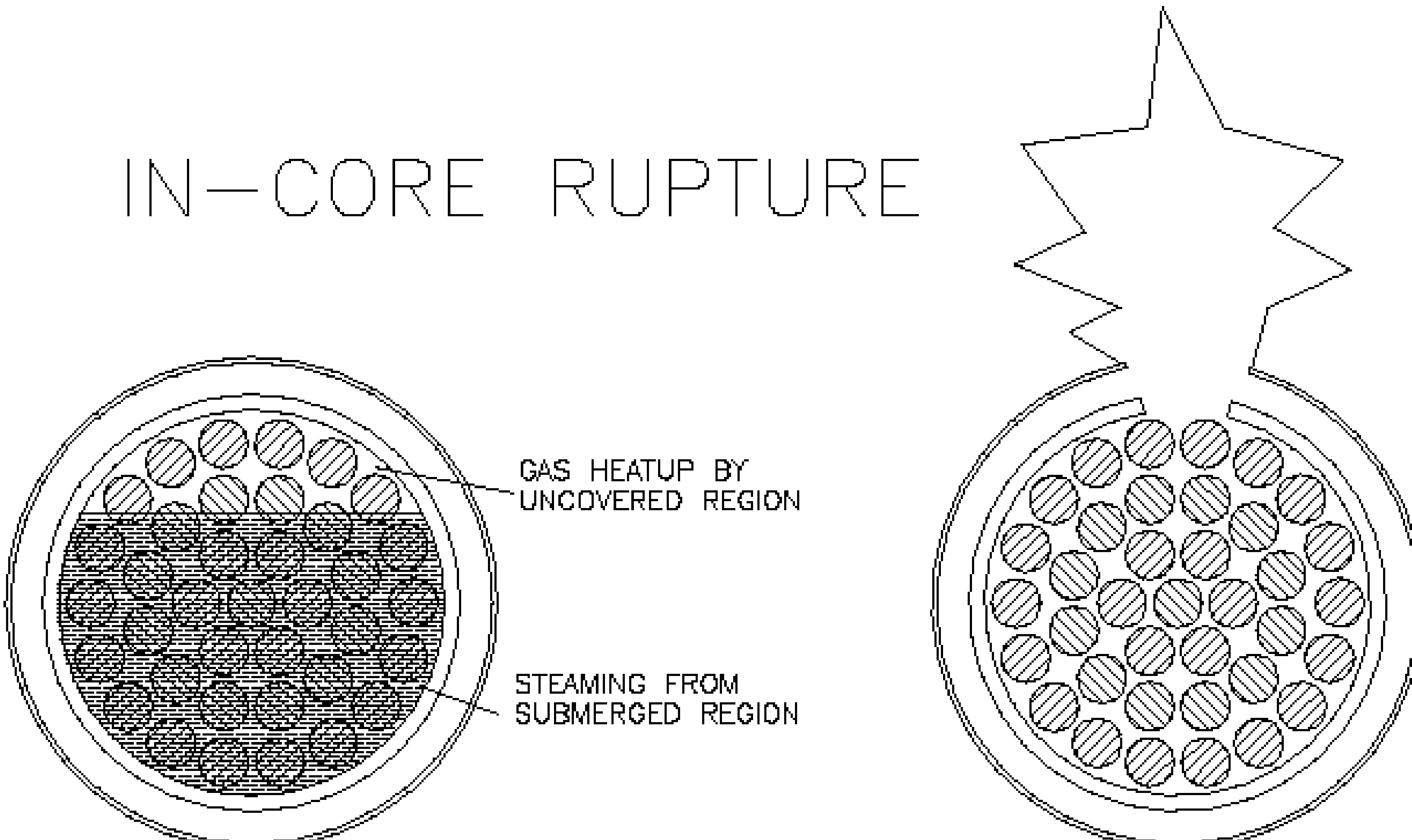
- hydrodynamic transient
- pipe whip
- fuel ejection
- jet force impingement
- ablation due to molten material ejection



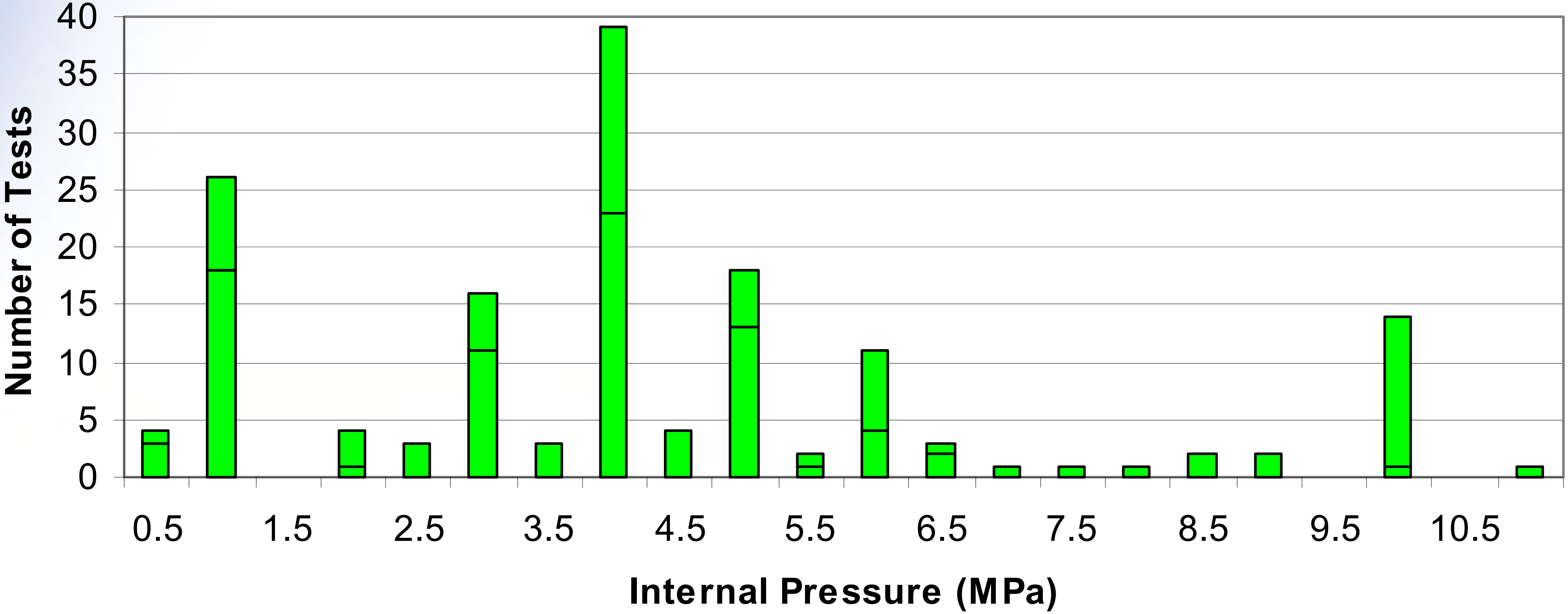
HIGH-PRESSURE PRESSURE TUBE DEFORMATION AND FAILURE

- Numerous pressure tube ballooning tests performed above 9 MPa
  - Tests demonstrated that small temperature gradients (~50°C) were sufficient to fail pressure tube prior to contacting its calandria tube
  - Tests used for validation of deformation model in CATHENA
- The tests show that it is very unlikely that the pressure tube would not fail during ballooning for a single channel flow blockage event

Channel Failure at High Pressures



Pressure-Tube Ballooning Tests



High Pressure Ballooning Test

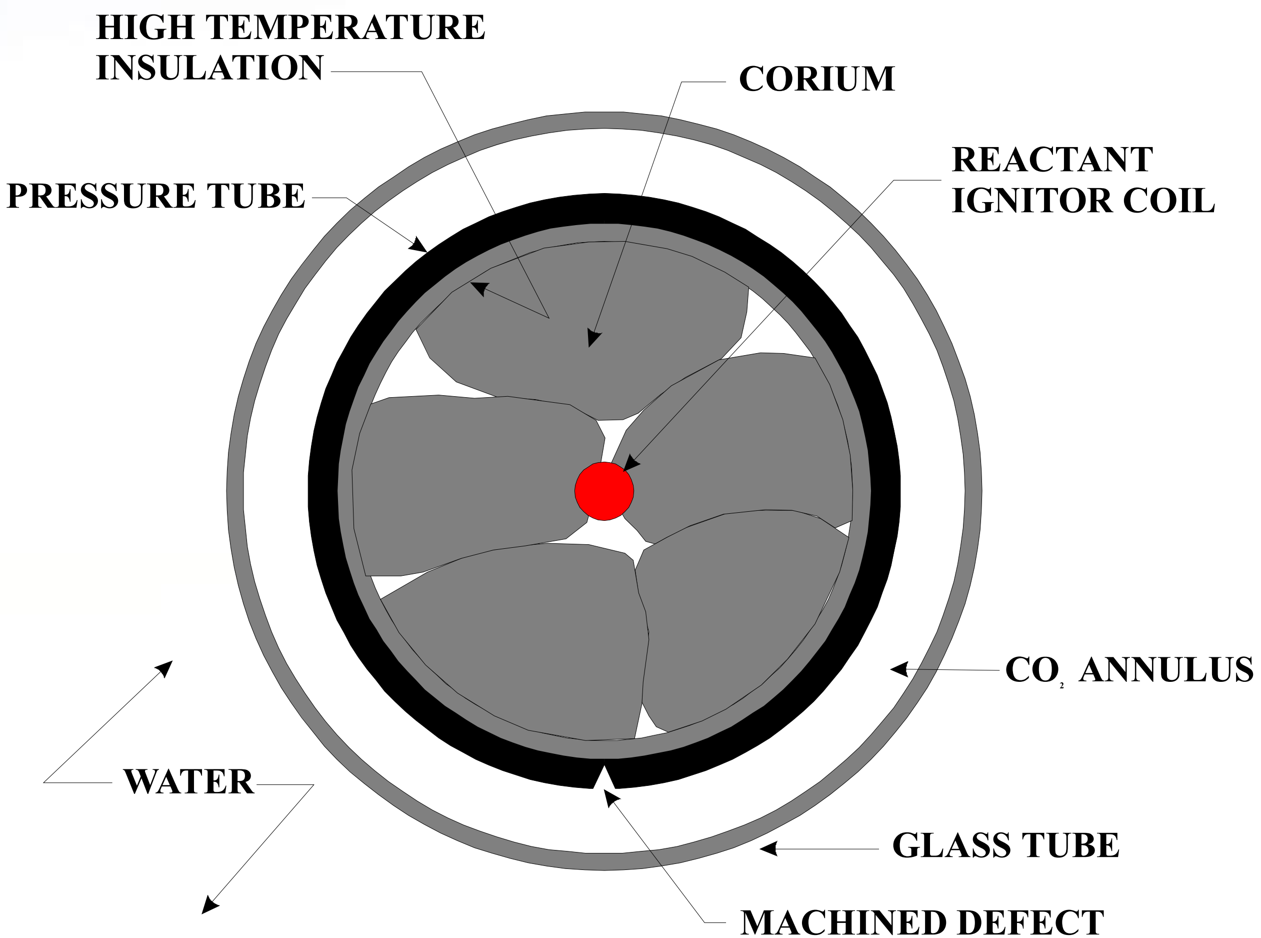
MFMI EXPERIMENTAL PROGRAM

- The overall objective of the program is to confirm (or otherwise) that the forced interaction model represents the dominant mechanism of interaction between molten fuel (ejected at 10 MPa) and the moderator under CANDU accident conditions
- A secondary objective of the experimental program is to provide data for code validation

MFMI Apparatus

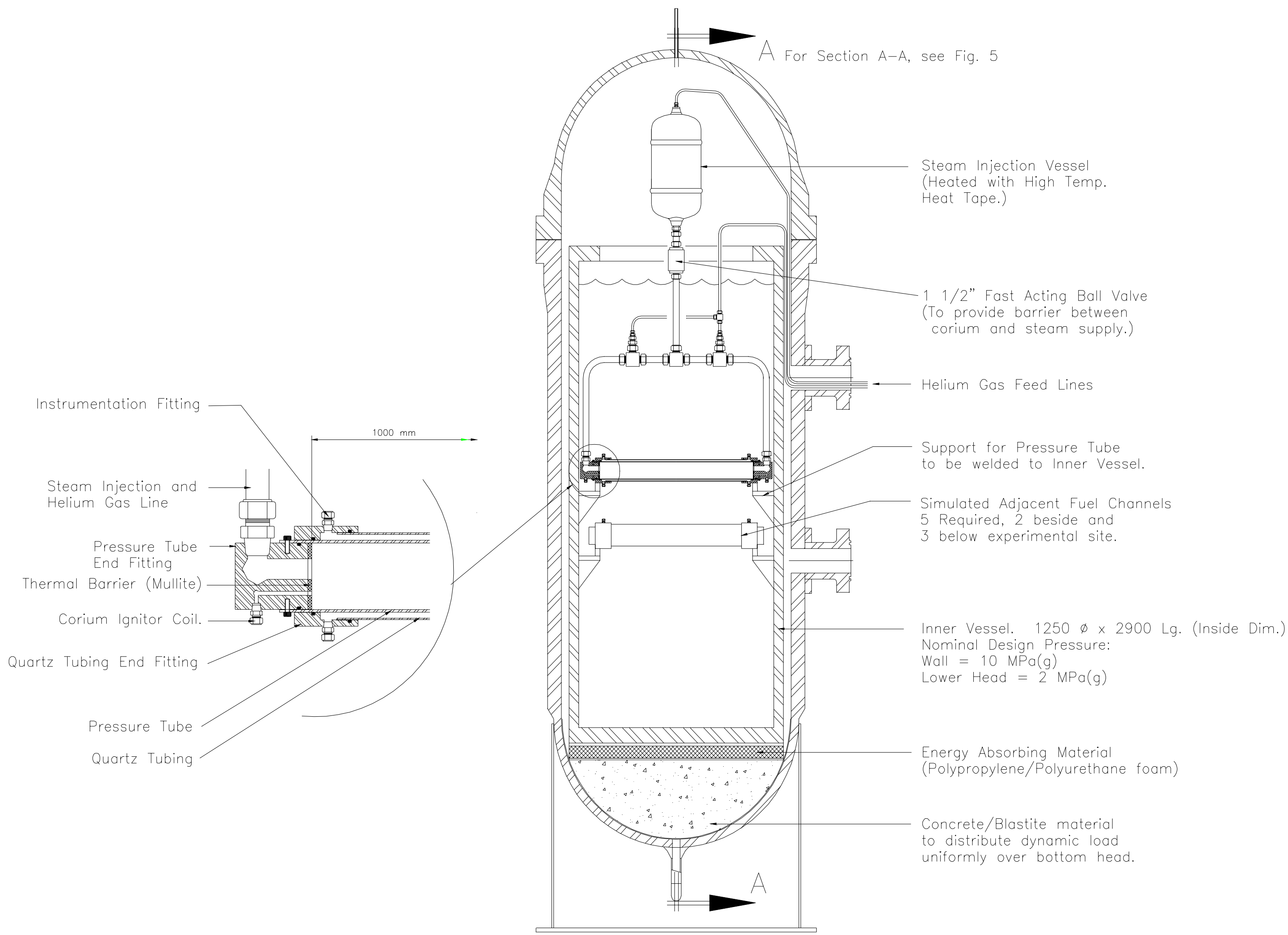
- **Pressure Tube Assembly**
  - **PT loaded with ~ 25 kg of a corium thermite mixture**
  - **corium mixture composition will be used (wt%)**
    - **0.58 U / 0.08 U_3O_8 / 0.15 Zr / 0.19 CrO_3** ***which yields***
    - **0.73 UO_2 / 0.11 Zr / 0.06 ZrO_2 / 0.10 Cr @ ~2400°C**
  - **PT thermally insulated from corium by 5 mm thick Zircar tube and from surrounding water by a glass tube and CO_2 annulus system**
  - **defect machined into PT to provide predictable rupture times, location and geometry upon pressurization**

Schematic showing PT assembly



haacke/moltcorium.cdr

MFMI Confinement Vessel



ARRANGEMENT

Test Matrix - Commissioning

- A series of “dry” tests will be performed to characterize the melt ejection when the PT ruptures and to proof-test the concept. The tests will be pressurized with an inert gas and performed by Argonne National Laboratory (ANL).

- Two base-line reference tests with no melts present will be performed in the MFMI facility to establish the pressure pulse and subsequent response of the inner vessel to a PT rupture when pressurized to 10 MPa with a steam / helium mixture

- Commissioning tests will also be performed with small quantities of melt (<5 kg) to evaluate system response prior to embarking on proposed test matrix

Proposed Test Matrix (CANDU specific)

Test Matrix
(all tests at 10 MPa internal pressure)

Parameter	Base-line	Base-line	Com1	Test #1	Test #2	Test #3	Test #4*
Mass of melt (kg)	None	None	5	25	25	25	25
Obstacles (Y/N)	No	Yes	Yes	Yes	Yes	No	No

* Test 4 is an optional test which may not be performed depending on the outcome of the previous tests

Proposed Test Matrix (ACR specific)

Test Matrix
(all tests at ~14 MPa internal pressure)

Parameter	Test #1	Test #2
Mass of melt (kg)	25	25
Obstacles (Y/N)	Yes	No

Post-Test Analysis

- Results will be evaluated to determine if they are consistent with the forced or free interaction models

- Post-test analysis will also quantify the energy released from the molten material/coolant interaction by assessing:
  - pressure history and vessel strain measurements
  - debris characteristics
  - changes in dimensions of inner vessel due to plastic strain

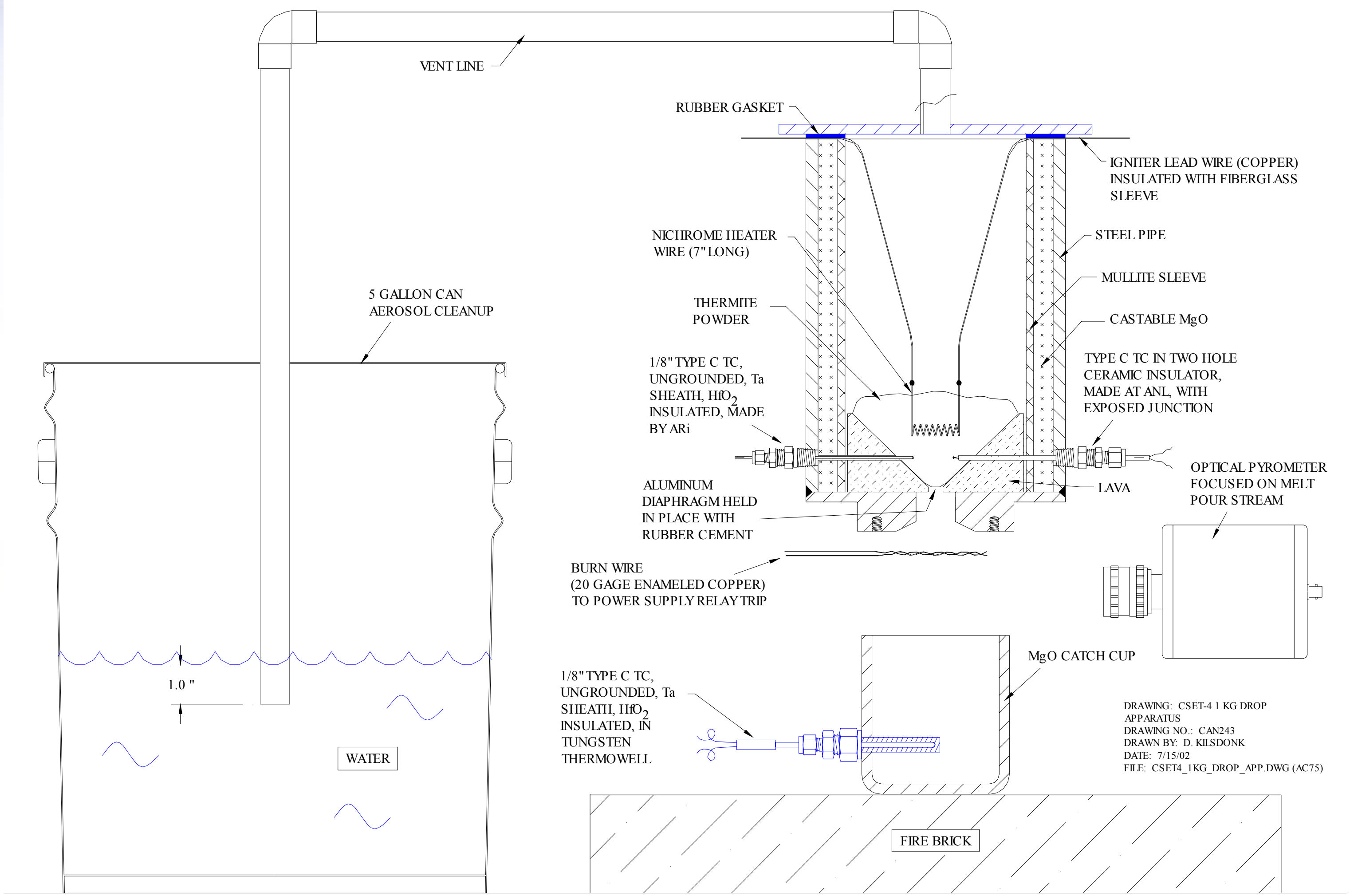
MFMI Development Work - ANL

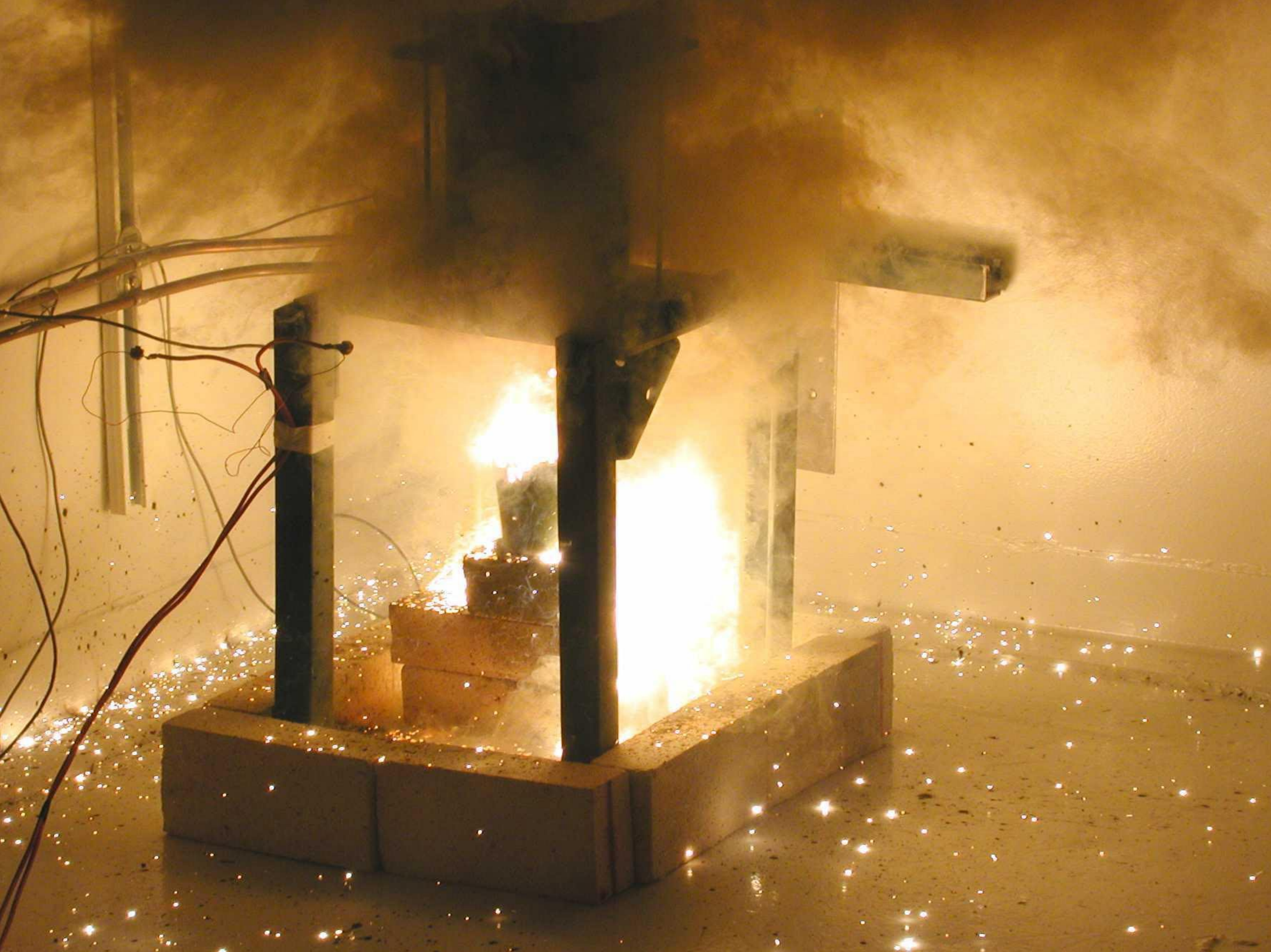
- **Scope:**
  - ANL has been contracted to develop a CANDU-specific corium thermite and transfer this technology to AECL
  - Perform 2 mass scale-up tests in a representative fuel channel geometry to proof-test concept of melting ~25 kg of corium in a pressure tube and retaining melt for some time
  - Perform melt ejection test in a representative fuel channel geometry to proof-test concept of ejecting ~25 kg of corium with a driving pressure of 10 MPa

Highlights

- **6 small-scale corium melt tests performed to evaluate corium burn characteristics**
  - Peak corium temperatures of 2200 - 2400°C
  - Some difficulties encountered with reliable measurement of temperatures
  - Plan to use small-scale tests to "back-up" temperature measurements in integrated tests

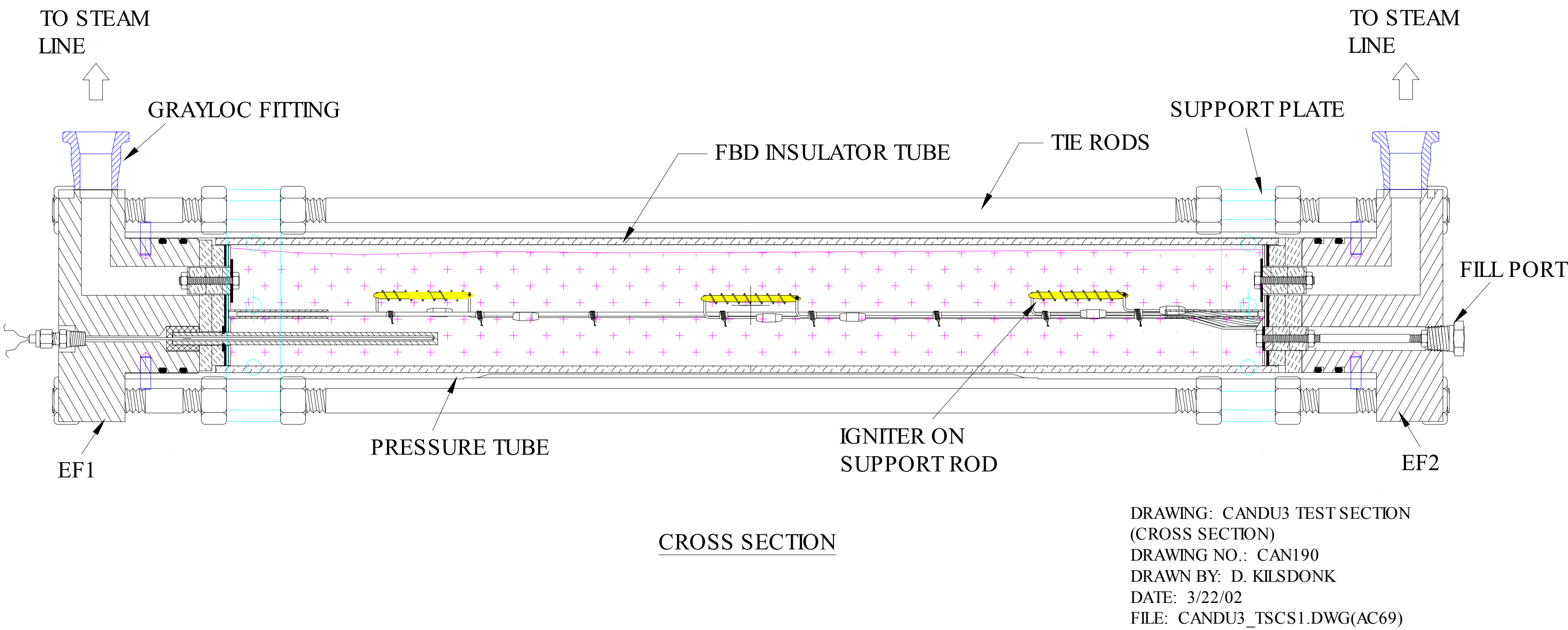
Schematic of Small-Scale Test Apparatus





Highlights

- 2 integrated tests performed where ~25 kg of corium was ignited in a 1-m long PT section
  - First test showed inadequacy of felt insulation for insulating PT from corium and difficulty of using bags to load corium
  - Second test successfully commissioned new loading technique and the new insulation contained the corium in PT. There were difficulties, however, with the end fittings and steam injection lines (melt through)
  - ANL staff are addressing these deficiencies and the integrated test with 10 MPa ejection planned for May

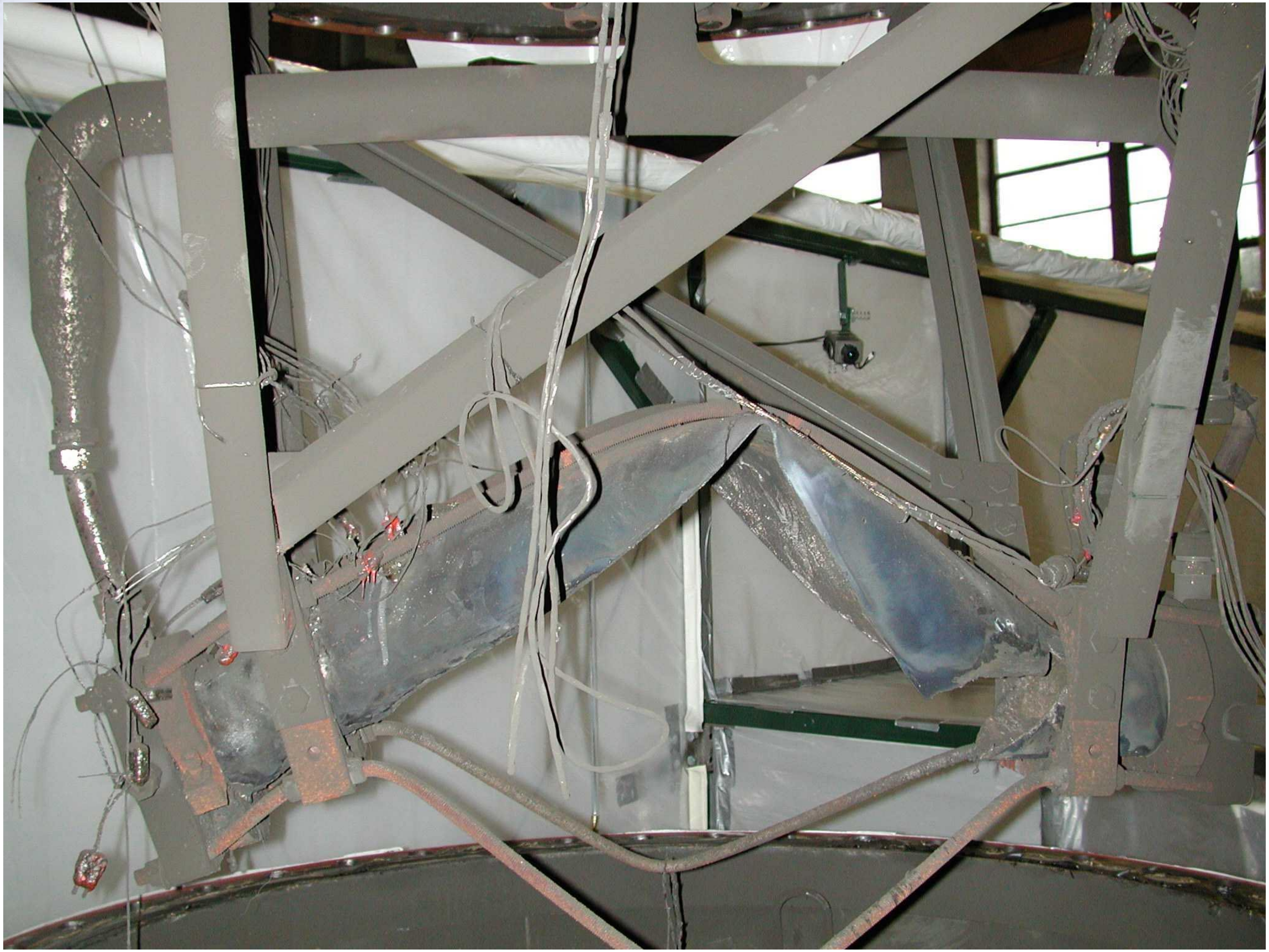


Schematic of Pressure-Tube Assembly

Confinement Vessel Lid Being Lowered (1st Test)

Test Section

Post-test View of Test Section From 1st Integrated ANL Test

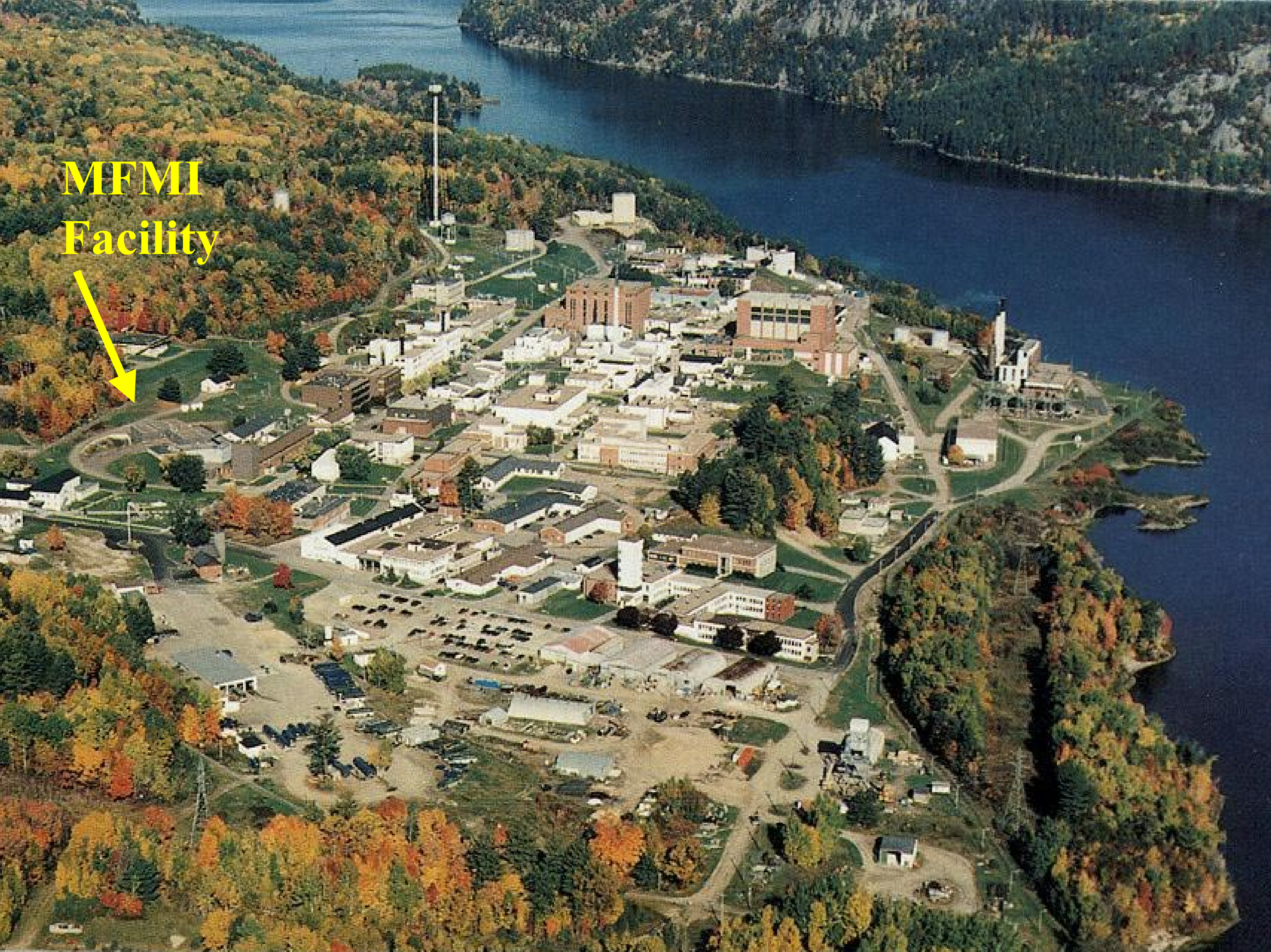


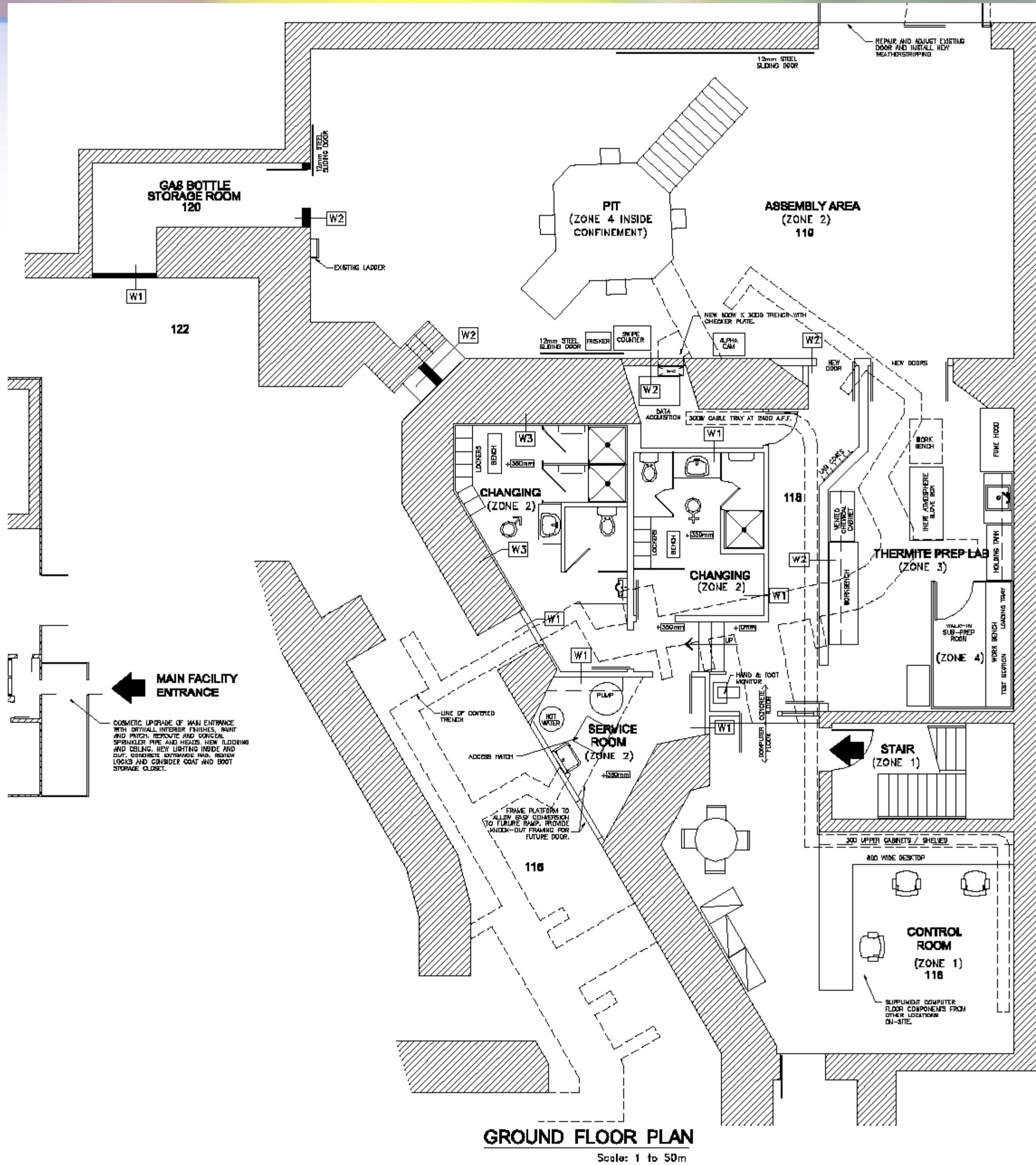
Post-test View of Test Section From 2nd Integrated ANL Test

Post-Test View of Solidified Molten Corium Inside the Pressure Tube (2nd Integrated Test)

MFMI Experiments - AECL

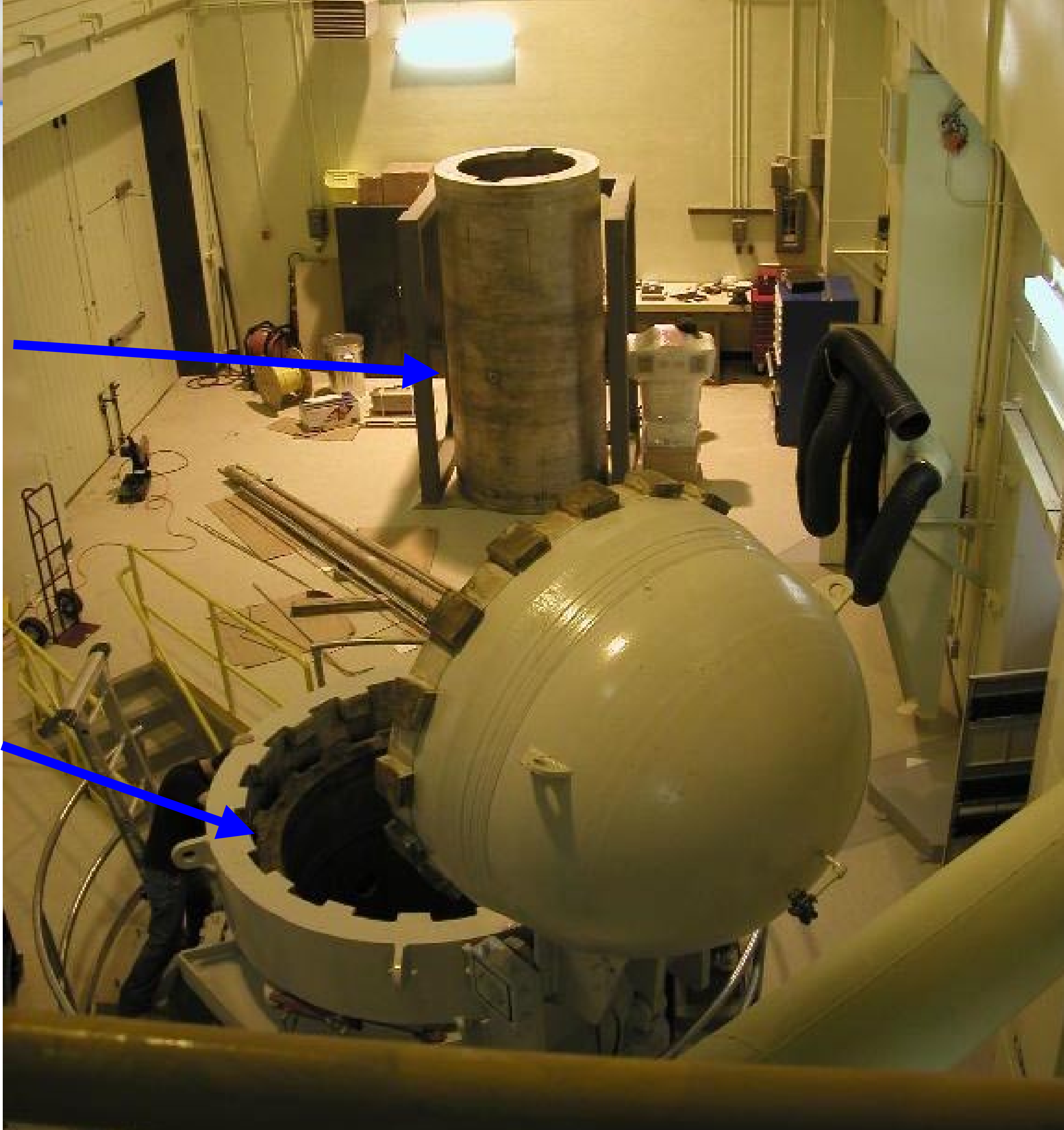
- **Scope:**
  - Confirm (or otherwise) that the forced interaction mode represents the dominant mechanism of interaction between molten material and the moderator under simulated single-channel severe under-cooling events


MFMI
Facility


GAS BOTTLE STORAGE ROOM 120
PIT (ZONE 4 INSIDE CONFINEMENT)
ASSEMBLY AREA (ZONE 2) 119
122
CHANGING (ZONE 2)
CHANGING (ZONE 2)
118
THERMITE PREP LAB (ZONE 3)
MAIN FACILITY ENTRANCE
SERVICE ROOM (ZONE 2)
STAIR (ZONE 1)
CONTROL ROOM (ZONE 1) 116
115
W1
W2
W3
GROUND FLOOR PLAN
Scale: 1 to 50m

Inner Vessel

Confinement Vessel




Dummy Channels
TUBE I.D.
CUT THIS SECTION FOR GLEN KYLE

Schedule

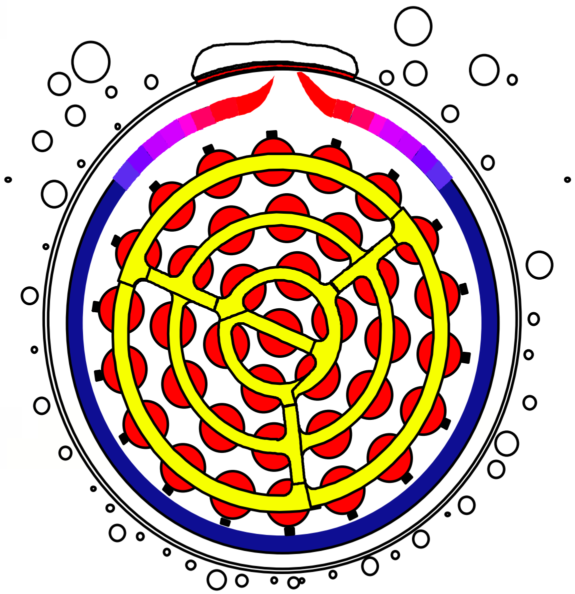
- MFMI facility ready for commissioning (April 2003)
- Complete non-corium commissioning (June 2003)
- Complete commissioning with 5 kg of corium (2003/04)
- Complete 1st MFMI test with 25 kg of corium (2004)
- Complete 3 scheduled CANDU specific MFMI tests (2006)
- Complete 2 scheduled ACR specific MFMI tests (2007)

FC Failure Mechanisms under Severe Flow Blockage

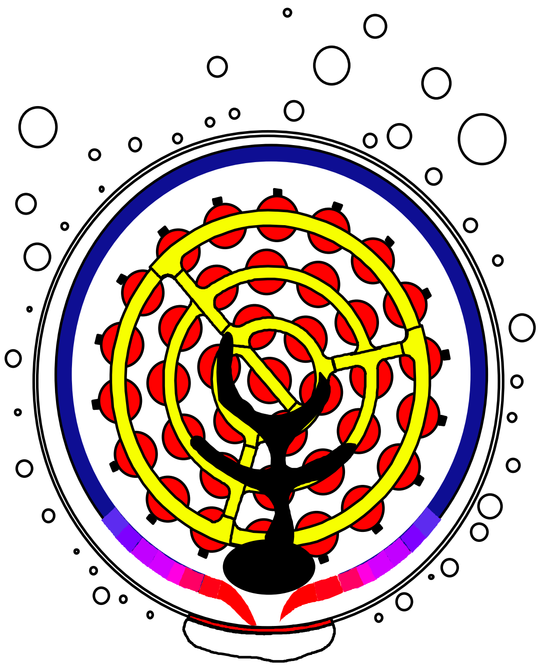
OBJECTIVE

- **To demonstrate (through experiments and analysis) that the maximum amount of molten material available at the time of channel failure will be limited to significantly less than 20 kg during a postulated single channel flow blockage event**

Fuel Channel Behavior During Severe Flow Blockage

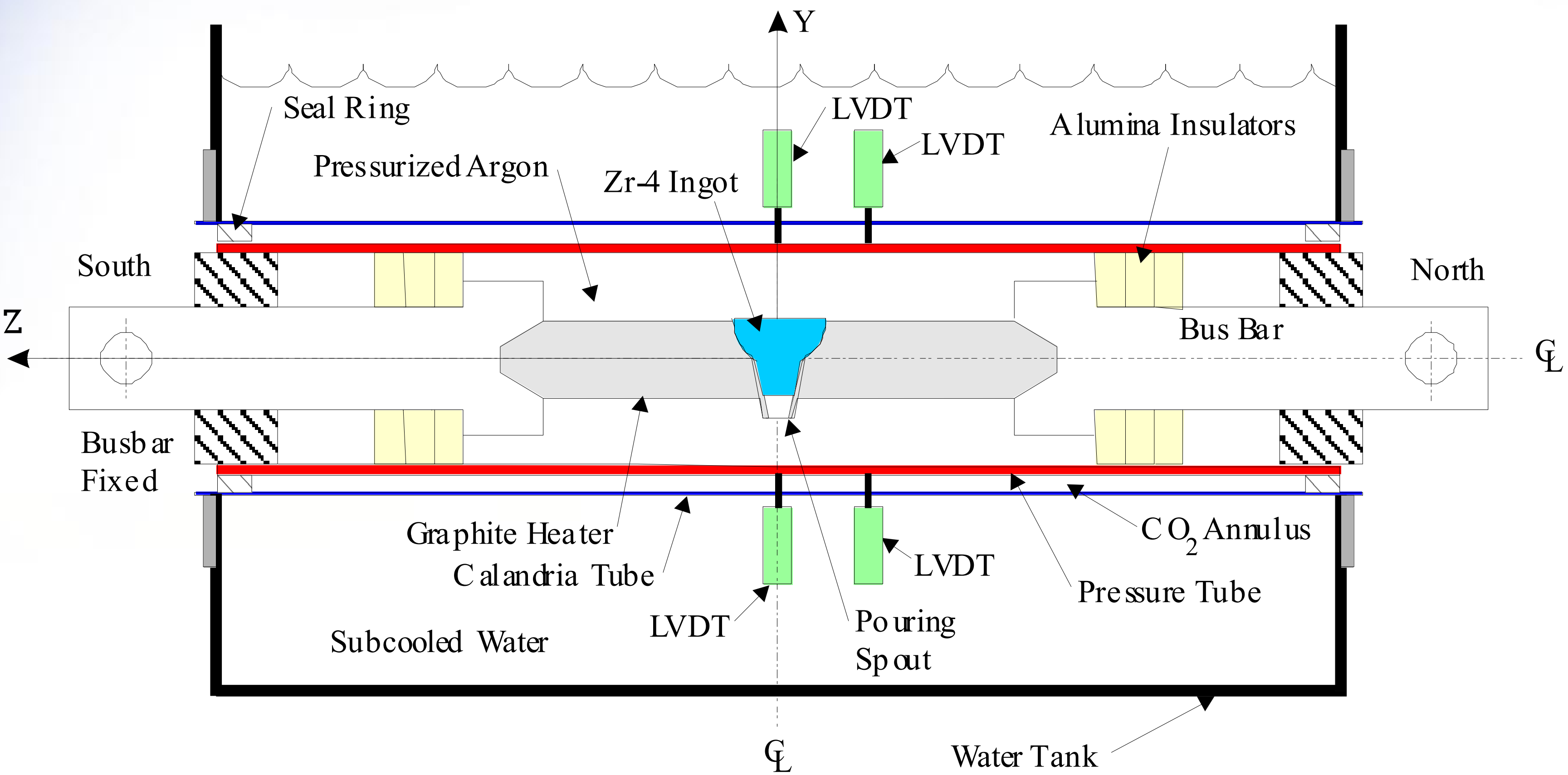


Stratified flow
(likely scenario)

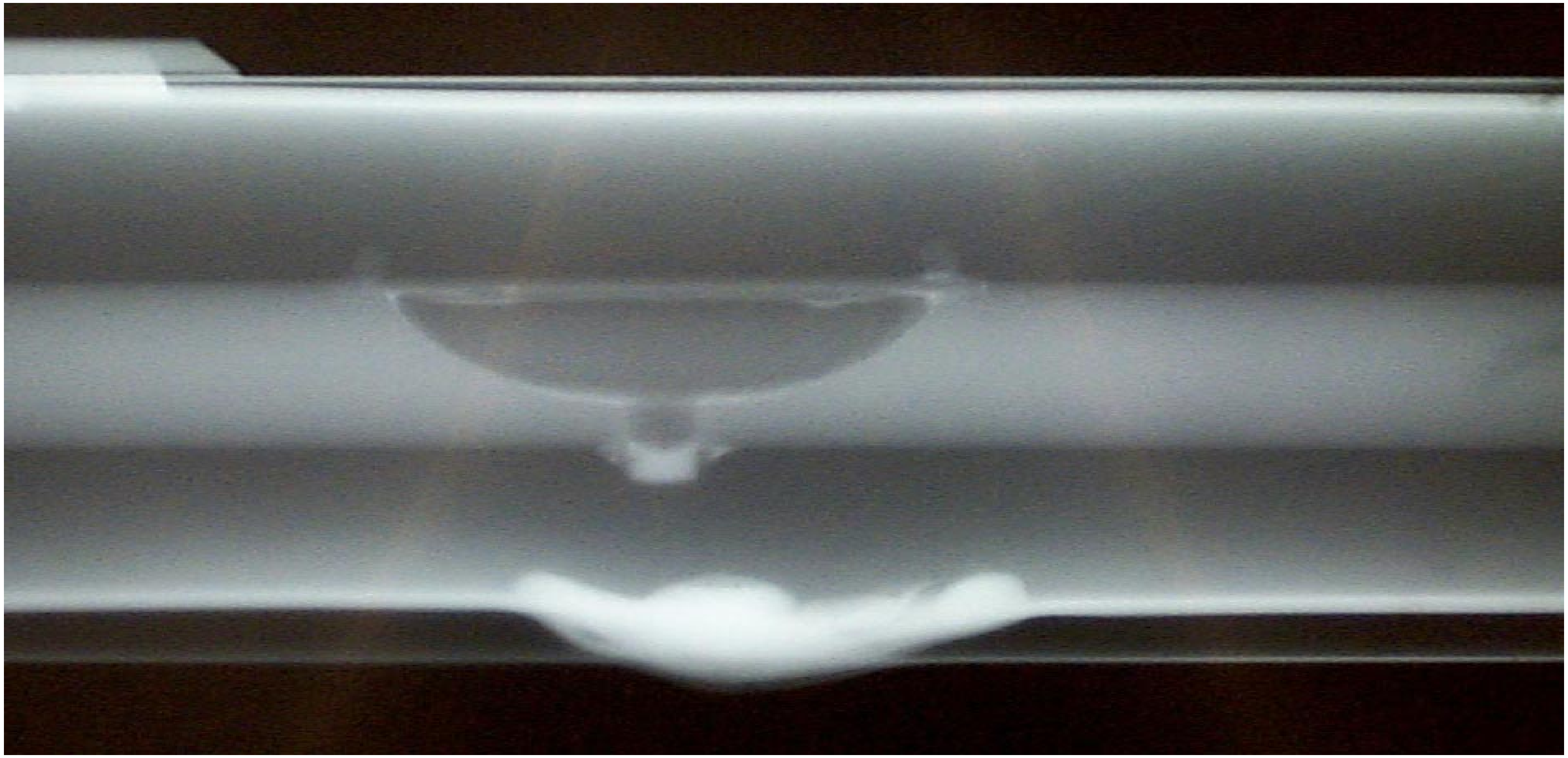


Molten Material Contact
(before and after ballooning)

Test Apparatus (FBCR6)



- **X-ray showing post-test view of heater and relocated melt onto non-ballooned PT. Pressure tube ruptured prior to CT contact**

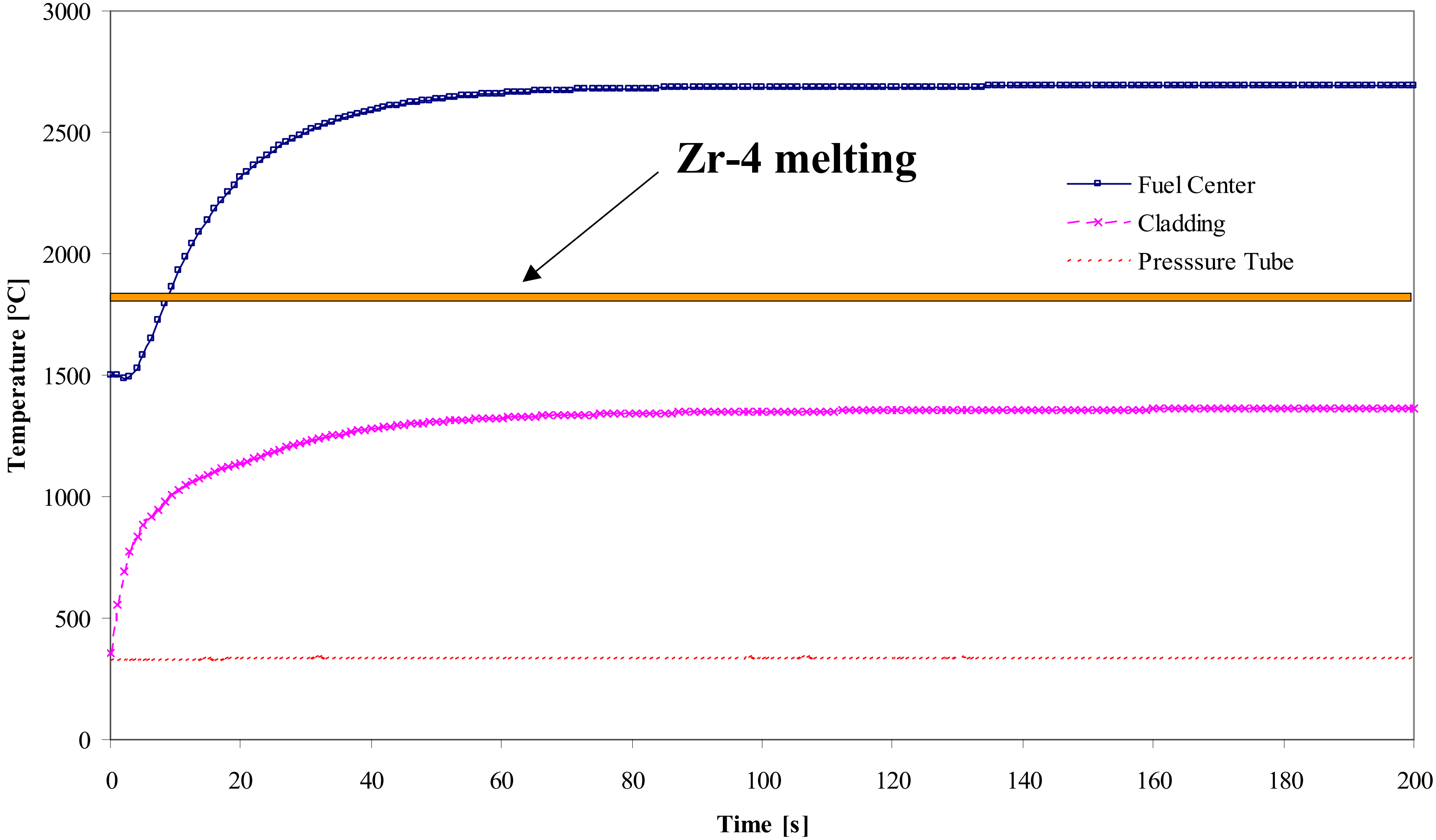


Summary

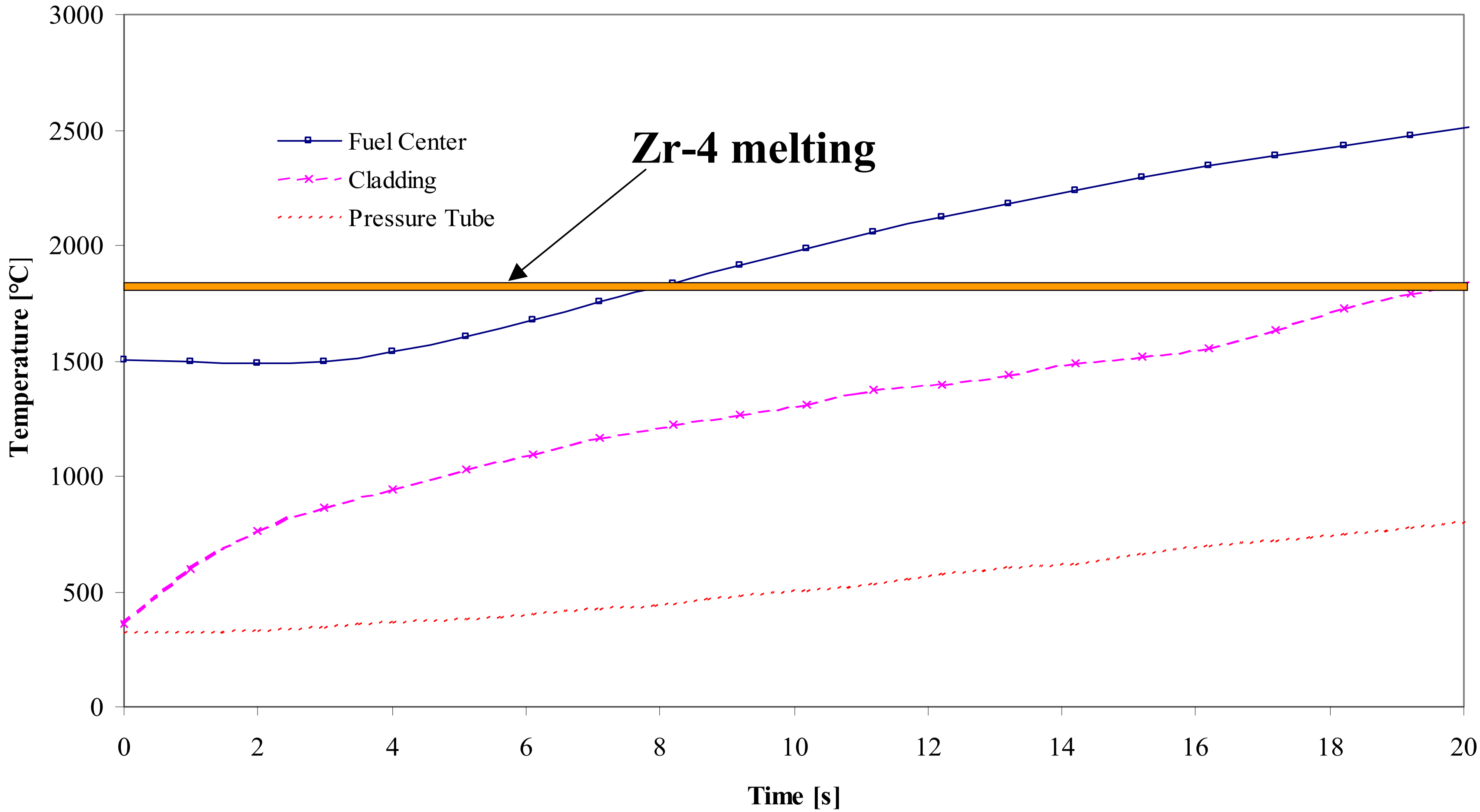
- **There are three programs addressing the issue of Single Channel Events for CANDU 6**
  - **Development Work at Argonne National Laboratory**
  - **MFMI Experiments**
  - **Fuel Channel Failure Mechanisms Under Severe Flow Blockage**

ACR Design

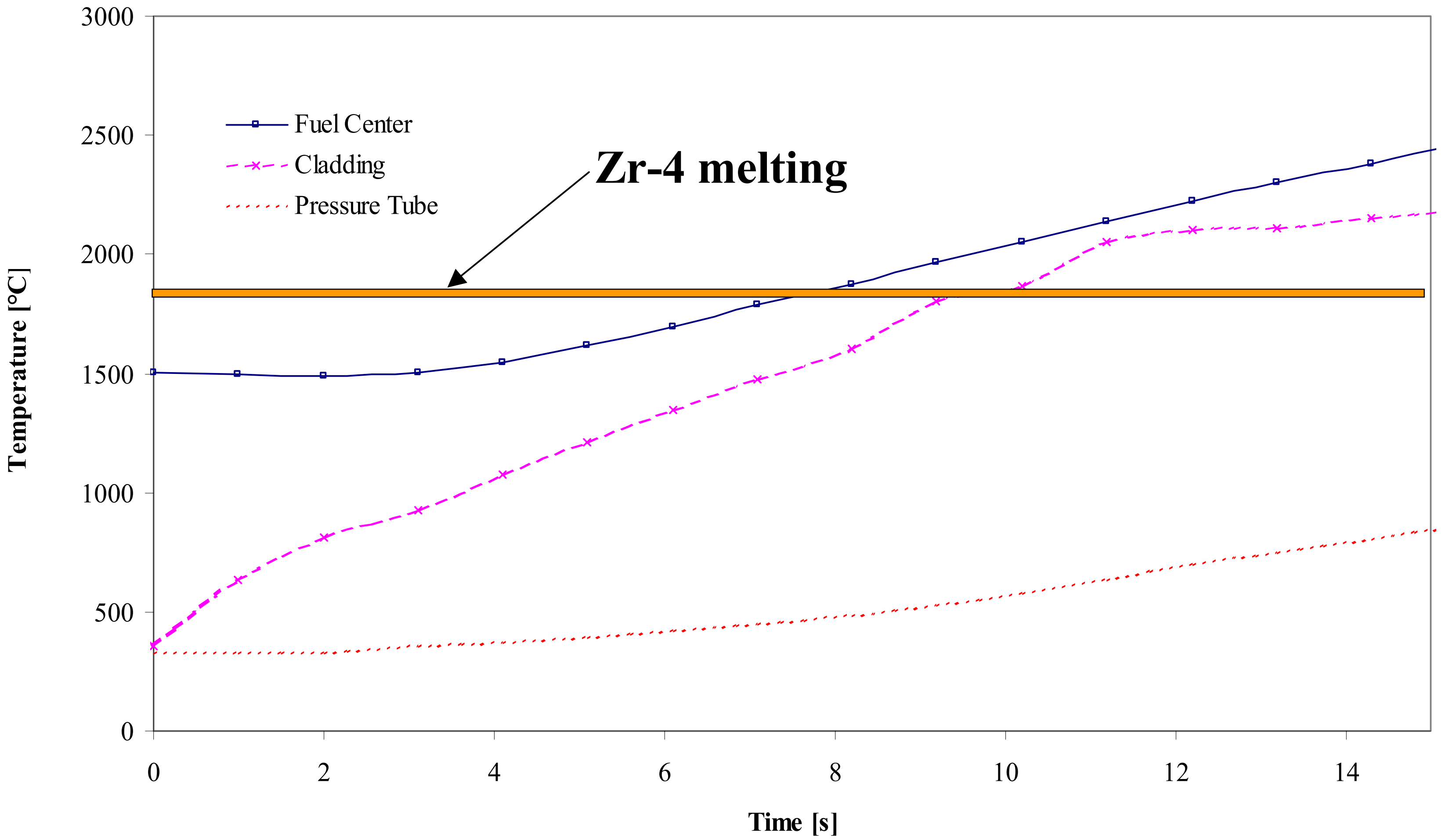
- ACR design aspects that potentially affect progression of a single channel severe flow blockage accident:
  - Higher system pressure
  - Flatter power profile
  - Fuel channel geometry changes
    - Thicker-walled PT
    - Larger diameter, thicker-walled calandria tube
- Higher system pressures and larger annulus gap increase the likelihood that pressure tube would rupture prior to contact with its calandria tube



Temperature Profile for a 7.5 MW Channel (98% Flow Blockage)



Temperature Profile for a ACR 7.5 MW Channel (99.8% Area Reduction)



Temperature Profile for a 7.5 MW Channel (100% Area Reduction)

Conclusions

- Solid technology base for understanding and assessing the response of the core to a single channel event
- R&D programs are underway to confirm impact of ACR design changes on accident progression
  - High Temperature Fuel Channel Laboratory
  - Molten Fuel Moderator Interaction Facility

AECL

TECHNOLOGIES INC.