CANDU Severe Core Damage Experiments and Analysis

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Outline

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  ▪ MAAP-CANDU Code
  ▪ Current Status

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  ▪ Scaling
  ▪ Test Facility, Test Procedure
  ▪ Test Results
  ▪ Modelling Results

• Future Plans & Summary
Introduction

• Severe Core Damage Accident
  - Accident in which substantial damage is done to the reactor core structure whether or not there are serious off-site consequences
  - Reactor Cooling System and Moderator back-up heat sinks are unavailable. In ACR, the Reserve Water System must also fail (very unlikely scenario)

Significant quantity of heat sinks surrounding core; therefore CANDU Severe Core Damage Progression is slow. Operator will have sufficient time to arrest accident progression so that corium can be contained in calandria vessel. Corium-concrete interaction is unlikely. In addition, ACR Reserve Water Tank has 2500 Mg of water for cooling.
CANDU 6 Reactor Core

- H2O in RV: 465 Mg
- D2O in CV: 227 Mg
- D2O in HTS: 95 Mg
- 380 channels

Fuel Bundle, PT, CT
LOCA-LOECC+loss of Moderator cooling (+ACR RWS cooling/make-up lost)

- Typical sequence of events:
  - Reactor shut down, decay heat to be removed
  - Primary system depressurizes, cooling to fuel reduced
  - Fuel heats up, deforms and transfers heat to the pressure tube
  - Pressure tubes heat up and sag into contact with calandria tubes
  - Heat load from fuel channels slowly boils off the moderator
  - Uncovered fuel channels gradually collapse, break up and are quenched in remaining moderator
  - After all moderator is expelled, debris bed heats up
  - Shield water inventory keeps calandria vessel intact
Complex Phenomena During Core Break-Up Transient

- Suspended debris bed motion & properties
- Gas flow patterns
- Debris-water interactions
- Channel disassembly
- Intact channel failure
- Terminal debris bed formation & properties
Severe Core Damage Consequence Analysis

• The progression of a Severe Core Damage Accident in a CANDU reactor is analysed by the MAAP-CANDU code.
• MAAP (Modular Accident Analysis Program) is an integrated code designed for Severe Accident Consequence Analysis in nuclear plants
• MAAP is owned by EPRI
• MAAP developed by Fauske & Associates Inc. (FAI), used by 40+ international PWR/BWR utilities
• MAAP-CANDU, based on MAAP-PWR / BWR, developed by FAI/OPG/AECL
• OPG is the code licensee (code holder)
• AECL holds a sub-license from OPG
MAAP-CANDU

- The main distinguishing feature of MAAP-CANDU are models of the **horizontal CANDU-type fuel channels** and CANDU-specific systems such as:
  - Calandria Vessel
  - Heat Transport System
  - Containment Systems: Dousing Spray, Local Air Coolers, etc.
- MAAP-CANDU contains CANDU core module developed by Ontario Power Generation (OPG)
- Lumped parameter code
- Current Industry Standard Toolset (IST) version of the code: V4.0.4A+
Core Disassembly Tests

- Tests conducted for **CANDU 6** channel and core geometry
Considerations for CANDU 6 Core Disassembly Tests

• Full-scale tests very costly, scaled down to one-fifth size
• Maintain same material (Zr-2.5Nb) and same stress levels as in full size channel
• Up to four channels stacked one on top of other
• Sag at mid-point, channel temperature, channel axial movement, channel end-load and channel disassembly monitored
• A number of Tests in inert atmosphere completed and two tests with a single channel completed in oxidizing atmosphere
Scaling Methodology

• Factors affecting channel deformation and failure:
  – Creep Deformation Behavior
    creep rate = A \cdot \sigma^n \cdot \exp(-B/T)
    ▪ Maintain same \sigma, T and heat-up rate and same material (Zr-2.5Nb) in scaled-down channel
    ▪ Same creep rate is achieved in scaled-down channel
  – Stiffness, Support provided by lower channels and end-restraint: achieved by geometric Similarity: one-fifth scale
    ▪ Geometry considered: PT ballooned into contact with CT, powered heaters to represent fuel bundles
    ▪ Four channels, one on top of other
  – Physical and chemical Processes
    ▪ Localized wall-thinning as a result of creep
    ▪ Oxidation (Tests in inert and in oxidizing atmosphere)
Small scale tests underway, ~ 1/5 scale

12 heaters to simulate fuel bundles of a CANDU 6 channel
Photograph of Heater
Core Disassembly Test Facility: Test Chamber
Typical Test Procedure Single Channel Tests

- Initial channel temperature maintained in the range 300 - 400 ºC in an inert atmosphere
- Channel power increased up to $T_{\text{max}} \sim 1400$ ºC in an inert or in an oxidizing atmosphere
- Heat-up rate varied from 0.1-1.2 ºC/s, typical heat-up rates when channels are uncovered
- Channel held at maximum temperature: range 600-5500s in selected tests
- Powered heaters varied from 4 and 10 central heaters to study effect of heated length (axial temperature gradient) on sag
Post-test Examination

- Channel radio-graphed to determine final location of bundles
- Axial sag profile of channel measured
- Channel sectioned along vertical axis
- Wall thickness along the top and bottom side of channel measured
- Metallographic examination of wall in tests oxidizing environment
## Summary of single channel Tests

<table>
<thead>
<tr>
<th>Test No</th>
<th>No. of Heaters</th>
<th>Atmosphere</th>
<th>Max. Temp. at Mod-point (°C)</th>
<th>Heatup Rate from 800°C (°C/s)</th>
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<tr>
<td>CD-3</td>
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<td>Inert</td>
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<td>Oxidizing</td>
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</table>
Measured Sag for Two Tests with Different Heat-up Rates

- Slower heat-up gives higher sag (Creep effect)
- Model development must include creep
- Significant sag: $T > 800 \, ^\circ C$
- End-load during sagging and cooling small, insufficient for channel pull-out from end-fitting
Post-Test Results

- Bundles did not move significantly from original position
- Significant wall-thinning in the bundle-to-bundle gap regions in inert tests

**Oxidizing atmosphere**
- In oxidizing atmosphere less wall thinning in the middle; but significant wall thinning at the ends, where less oxidation was observed.
- Cracking of base metal, vulnerable to failure induced by stresses developed during deformation, observed under oxide layer

Wall Thickness of Top and Bottom channel side from Fixed End (CD-7) inert gas test
Typical Test Procedure for Multiple Channel Tests

• Initial channel temperatures maintained at temperature range 300-400 °C
• Top channel power increased to $T_{\text{max}} \sim 1400$ °C
• Channels below heated up, when it was uncovered by the moderator, as predicted by the MAAP4-CANDU calculations
• Channels held at maximum temperature upto $\sim 6000$ s
• Tests in inert completed; in oxidizing atmosphere under preparation
Two-Channel Test
Failure observed at a bundle junction at temperature $\sim 1200 \, ^\circ\text{C}$
Post-test Close-up View of Channel Break-up (CD-10)
Findings from Multiple Channel Tests in inert atmosphere

• Bundles did not move significantly from original position
• Significant sag only if temperature >800 °C
• Significant wall-thinning and break-up of the bundle-to-bundle gap regions near the channel ends for the top row, since support provided by lower channels
• Debris are coarse, can be as long as ~10 bundles long
• Observed end-load applied by the top row on the next row is small, not sufficient for pull out that channel from the end-fitting
Model Development to Support Experimental Findings

• First step to model single channel tests
• Used ABAQUS FE code, simple beam model
• Measured channel temperatures used as input
• Localized accelerated creep deformation observed at bundle junctions is represented by a stress concentration factor in the creep equation
• Future modeling of multiple channel tests
Comparison of Measured Sag at Channel Midpoint with and without Localized Strain Model (CD-9)
Comparison of Measured Sag at Channel Midpoint with Localized Strain Model (CD-7)

CD-7 (12 Heaters, 10 heated)

Model

Experiment
Comparison of Post-test Permanent Sag with Model (CD-7)

CD-7 (12 Bundles, 10 heated)
Conclusions from Tests

• Sag at channel mid-point increases with heated length, significant sag for $T > 800 \, ^\circ C$
• Sag is time-dependent, so channel deformation by creep mechanism
• Multiple channel tests in an inert atmosphere and single channel tests in an oxidizing atmosphere suggest coarse debris formation, debris as long as 10 bundles long. Channel perforation $T \sim 1200 \, ^\circ C$
• Mechanism for Debris Formation:
  – As channel temperature increases, channel’s lower half grips the bundle tightly at both ends of the bundle. Sagging continues and bundle moves with channel. Channel material between bundles deforms locally, leading to significant wall-thinning at bundle junctions leading to break-up and debris formation. Oxidizing atmosphere promote cracking of base metal, induced by stresses during the deformation process, under the oxide layer.
Future Work

• Effect of oxidation
  – Multi-channel test in an oxidizing atmosphere
• Develop models to explain the findings
• Implement findings in MAAP4 CANDU
  – Temperature for Debris Formation
  – Size of Debris
• Perform Tests for ACR geometry
Summary

• Understand phenomena leading to CANDU severe core damage
• MAAP-CANDU is a versatile code for assessing integral response of CANDU plant under severe core damage conditions; can be used for Level 2 PSA Applications
• Most important phenomena are in the code
• Code benchmarking activities are in place
• CANDU 6 debris formed during core damage are expected to be coarse; candling-type of behavior is not expected
• The CANDU core disassembly process is driven by creep mechanism, which is slow and predictable