Core Disassembly

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Outline

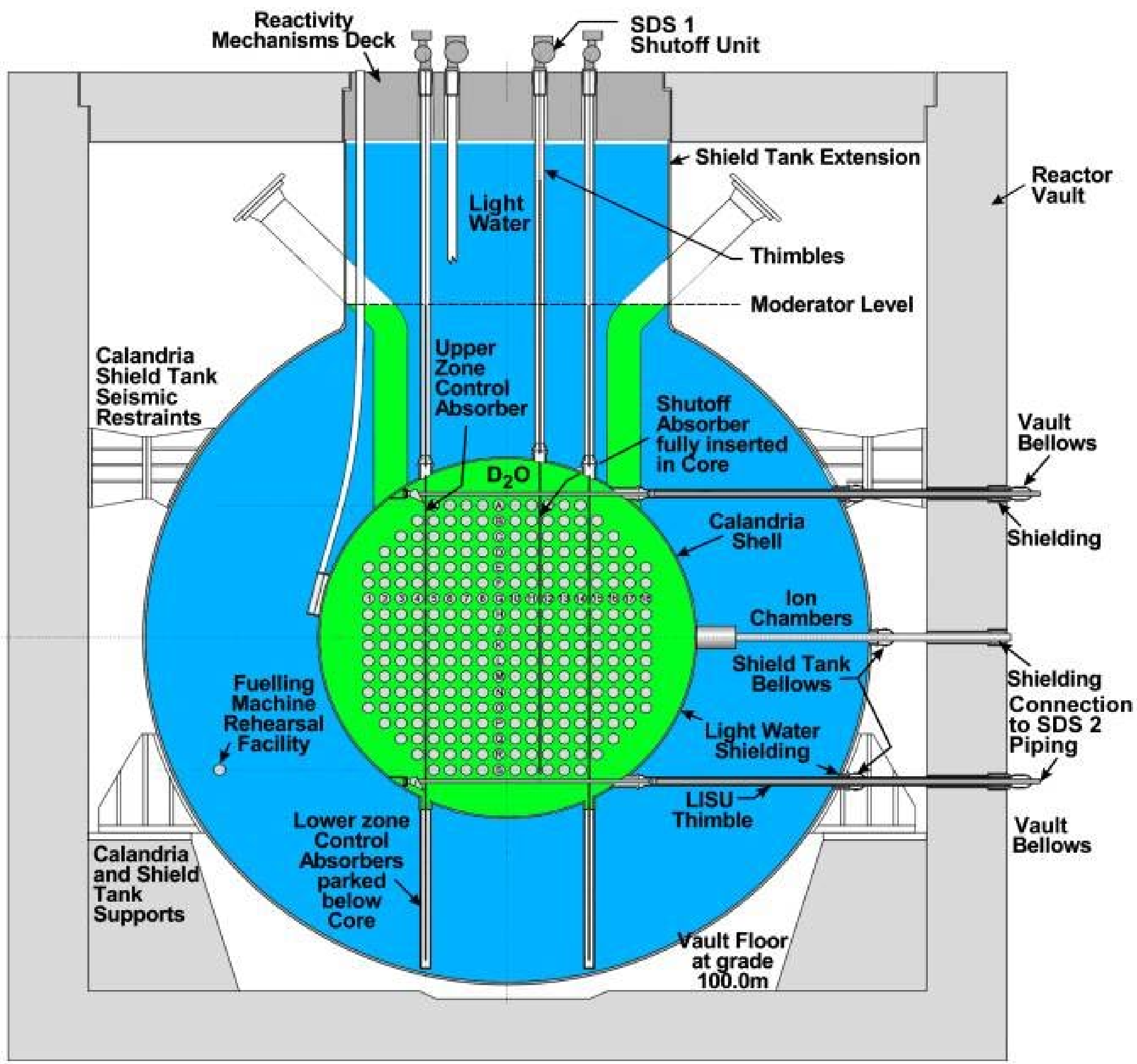
- Introduction
- Scaling Methodology
- Pre-Test Calculations
- Experimental Facility
- Test Procedure and Post-Test examination
- Model Development
- Results and Discussion
- Conclusions and Future Work

Introduction

- **Presentation addresses CANDU channel behavior under a Severe Core Damage Accident Scenario**
- **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-700, RWS 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."

ACR-700 Reactor Core



284 channels

H2O in PHTS: 118 Mg

H2O in ST: 456 Mg

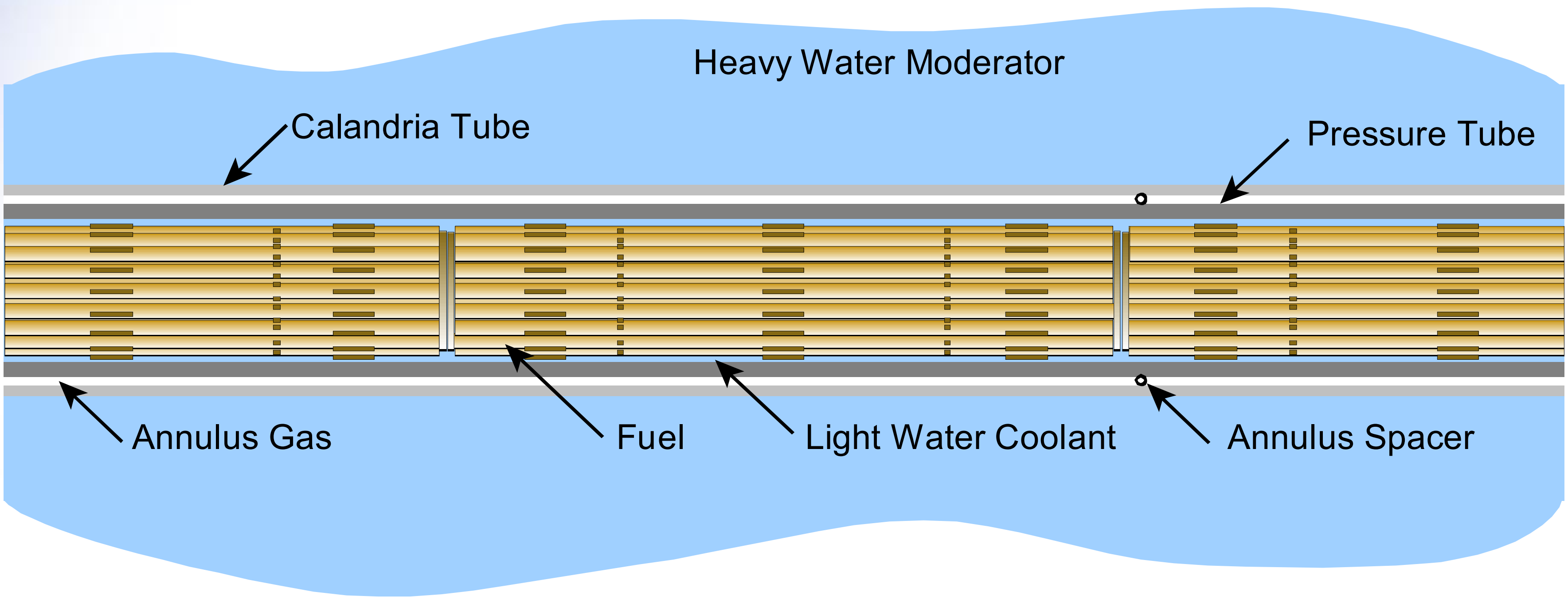
D2O in CV: 102 Mg

RWT: 2500 Mg

Severe Core Damage Progression in CANDU is slow

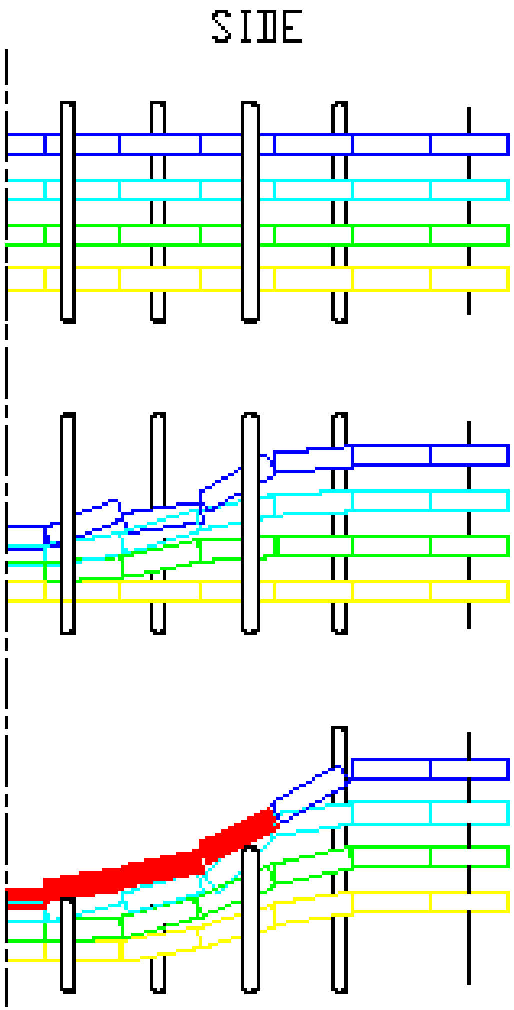
- **Progression of Severe Core Damage Accidents in CANDUs**
  - Reactor shutdown (Decay Heat Removal)
  - Reactor Cooling System, Moderator heat sink and makeup from Reserve Water System are lost (system depressurized: low pressure scenario)
  - Moderator surrounding channel heats up, boils off and expelled
  - Uncovered fuel channels collapse, break up, form debris (UO2 is expected to be solid), which fall into the bottom of calandria vessel, where they are quenched in remaining moderator
  - After all moderator expelled, debris bed heats up, eventually debris melting
  - Makeup from the Reserve Water System ensures shield tank water surrounding the calandria vessel keeps calandria vessel intact
  - Accident Progression is slow

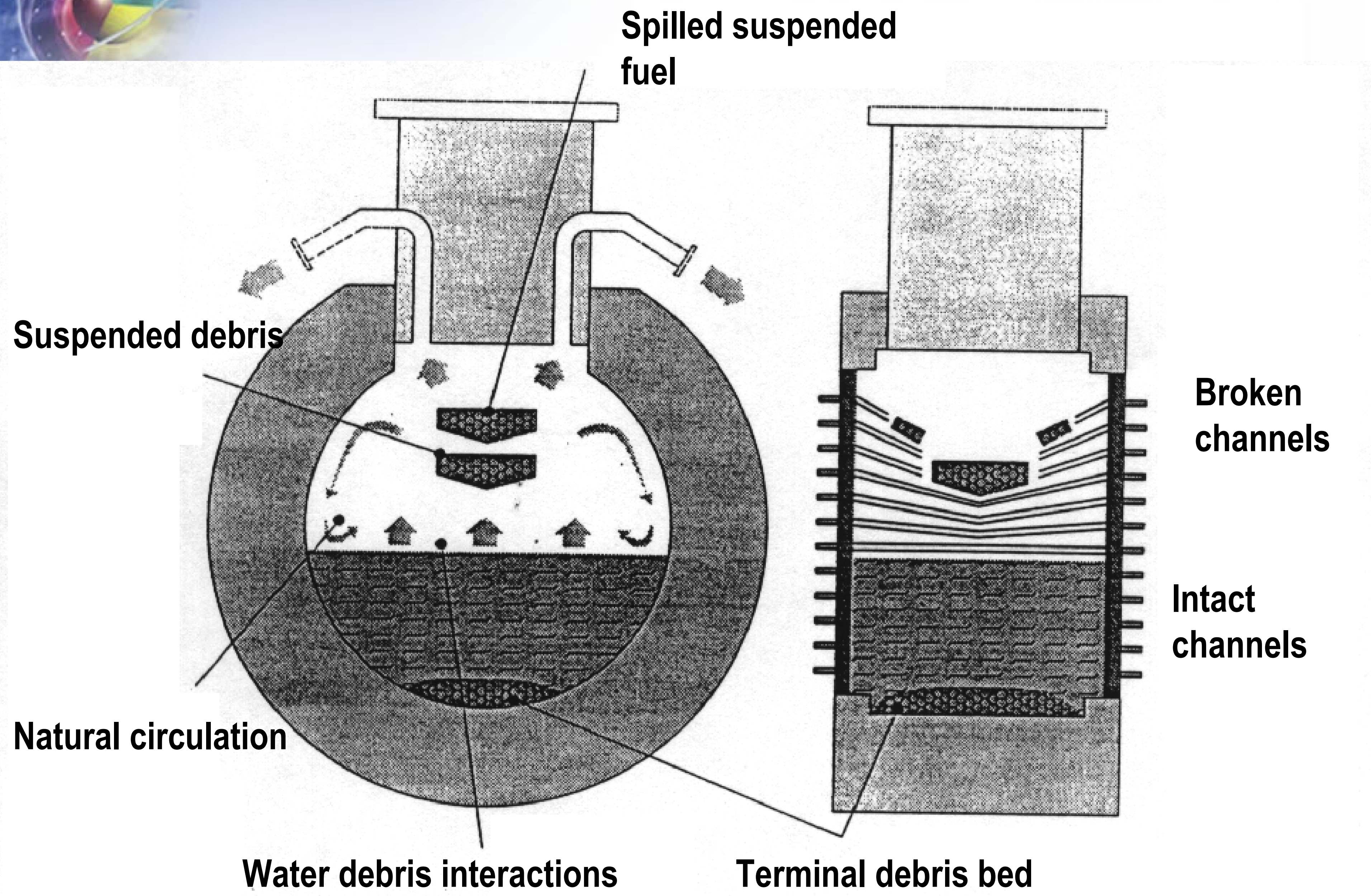
ACR Fuel Channel



Severe Core Damage when Reactor Cooling System, Moderator heat sink and RWS make-up are lost in ACR-700

CANDU Core Disassembly



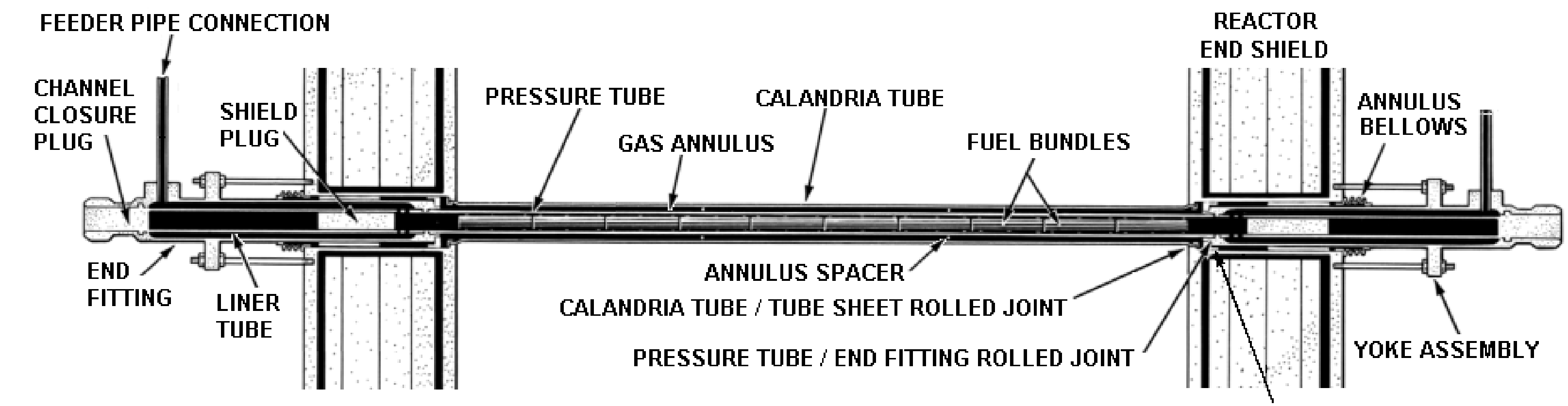

Spilled suspended fuel
Suspended debris
Broken channels
Intact channels
Natural circulation
Water debris interactions
Terminal debris bed

- **Uncertainties in Accident Progression are addressed through**
  - **Participation in RASPLAV/MASCA Projects**
    - **Corium Behavior in Calandria Vessel (geometry: a slice through lower half of calandria vessel)**
    - **Thermophysical properties of corium**
  - **Core Disassembly Tests, specific to CANDU core geometry (addressed in this presentation)**

Core Disassembly Test Channel and Core Geometry

- Tests conducted for CANDU 6 channel and core geometry
- Details provided here to demonstrate the distinct and different nature of core damage progression in CANDUs

CANDU 6 Fuel Channel Assembly



Fuel Channel Assembly

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
- First Tests in an inert atmosphere, then tests in oxidizing atmosphere

Scaling Methodology

- **Factors affecting channel deformation and failure:**
  - Creep Deformation Behavior

    creep rate = $A \bullet \sigma^{n} \bullet \exp(-B/T)$

    - Maintain same σ, 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 (Current tests in inert atmosphere to address deformation behaviour, future tests in oxidizing atmosphere)

Test Channel Dimensions/Scaling Ratio

Parameter	CANDU 6 Channel	Small-scale Test Channel	Scaling Ratio
Channel Length (m)	5.994	1.2	5.0
Channel Vert. Separation (mm)	160	32	5.0
Channel ID (mm)	122.1	24.1	5.1
Bundle O.D. (mm)	102.8	20.8	4.9
Bundle Length (mm)	495.3	99	5.0
Bundle-Channel Gap (mm)	19.3	3.3	5.8
Wall Thickness (mm)	5.0	0.4	12.5 (*)
Max. Stress at Mid-span (MPa)	14.5	14.5	1.0
Channel Aspect ratio (L/D)	49	50	1.0
Bundle Aspect Ratio (L/D)	4.9	4.8	1.0

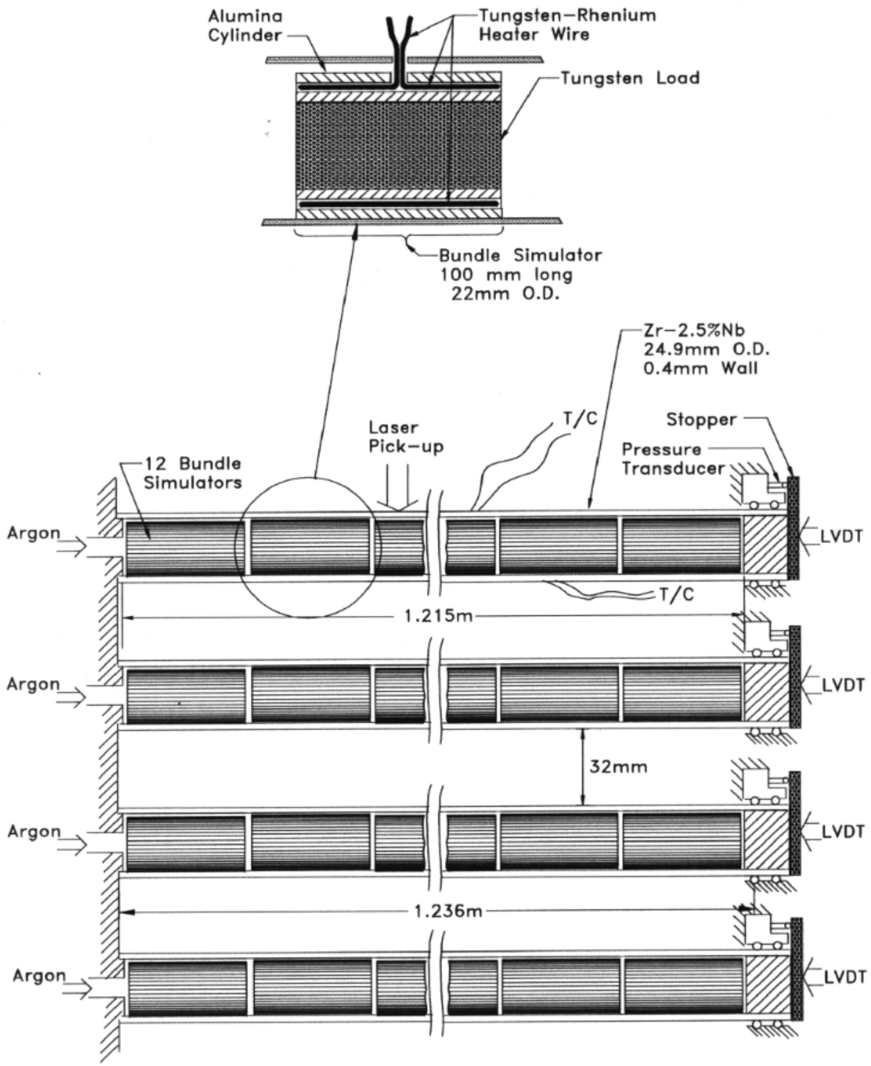
*) Wall thickness scaling will be addressed in tests under oxidizing atmosphere by scaling the heat-up rate

Pre-Test Calculations/Results

- **ABAQUS Beam Model** (Parametric Study: sag calculated)
  - Heated length (axial temperature gradient) is a critical parameter
  - Circumferential temperature gradient less significant
  - Axial restraint at the floating end of channel important to preserve channel integrity during sag

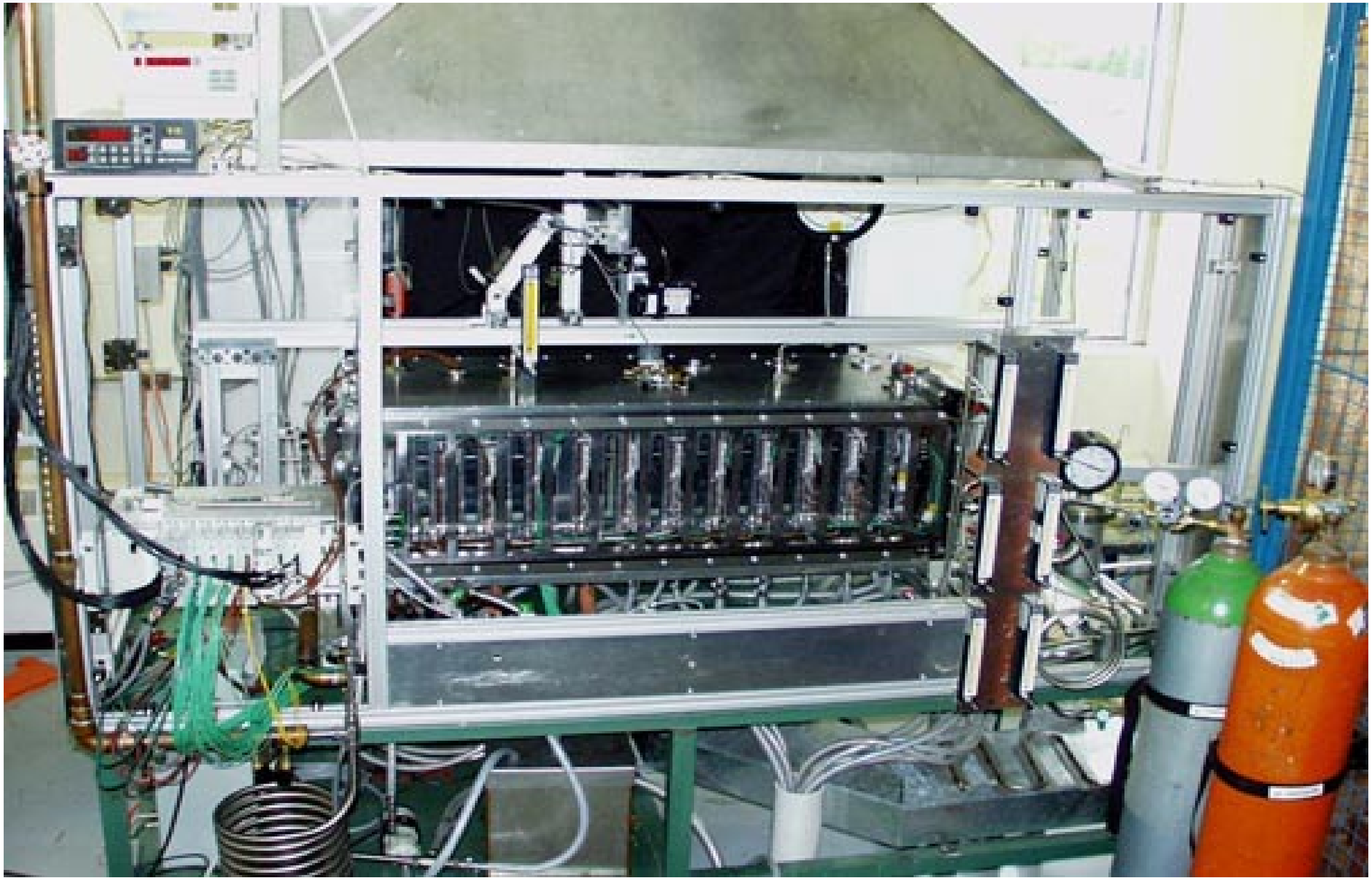
General Setup of Peripheral Equipments

Schematic of Channel Layout

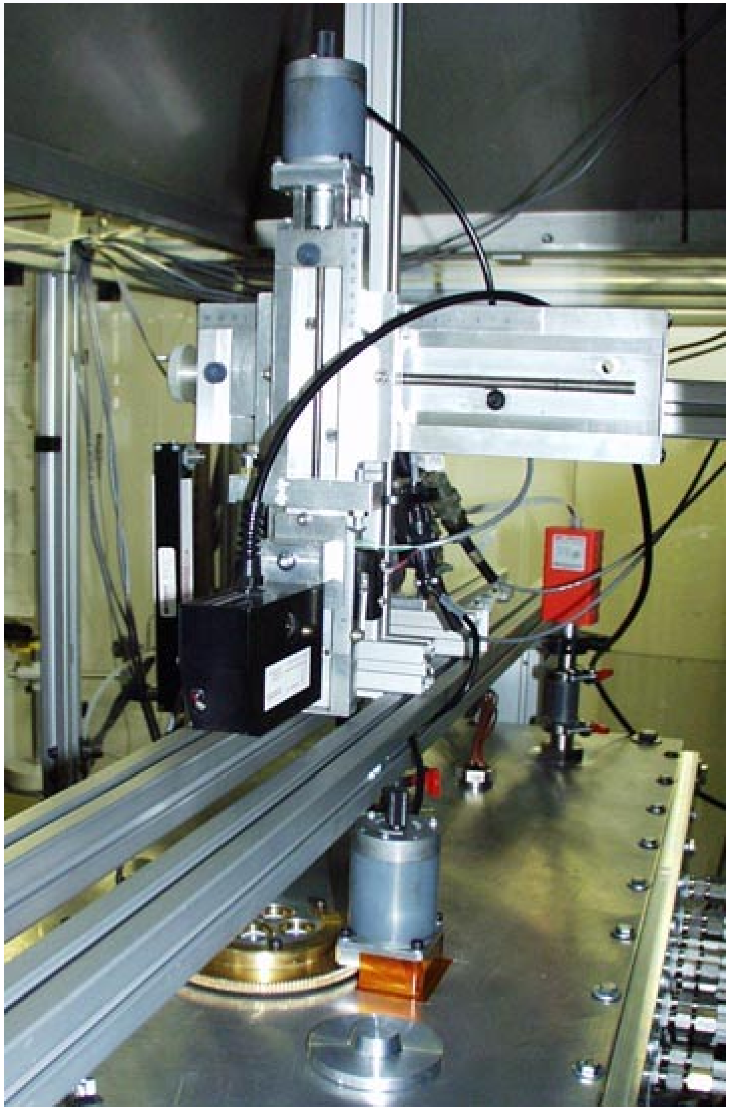


- Small scale tests underway, ~ 1/5 scale
- 12 heaters to simulate fuel bundles of a CANDU 6 channel

Core Disassembly Test Facility: Test Chamber



Laser Device for Sag Measurements



Typical Test Procedure Single Channel Tests in an Inert Atmosphere

- Initial channel temperature maintained at ~ 300 C, operating temperature in an inert atmosphere
- Channel power increased so that T_{max} ~1300-1400 C
- Heat-up rate varied from 0.1-1.2 C/s, typical heat-up rates when channels are uncovered
- Channel held at maximum temperature: range 600-5500s
- Powered heaters varied from 4 and 10 central heaters to study effect of heated length (axial temperature gradient) on sag

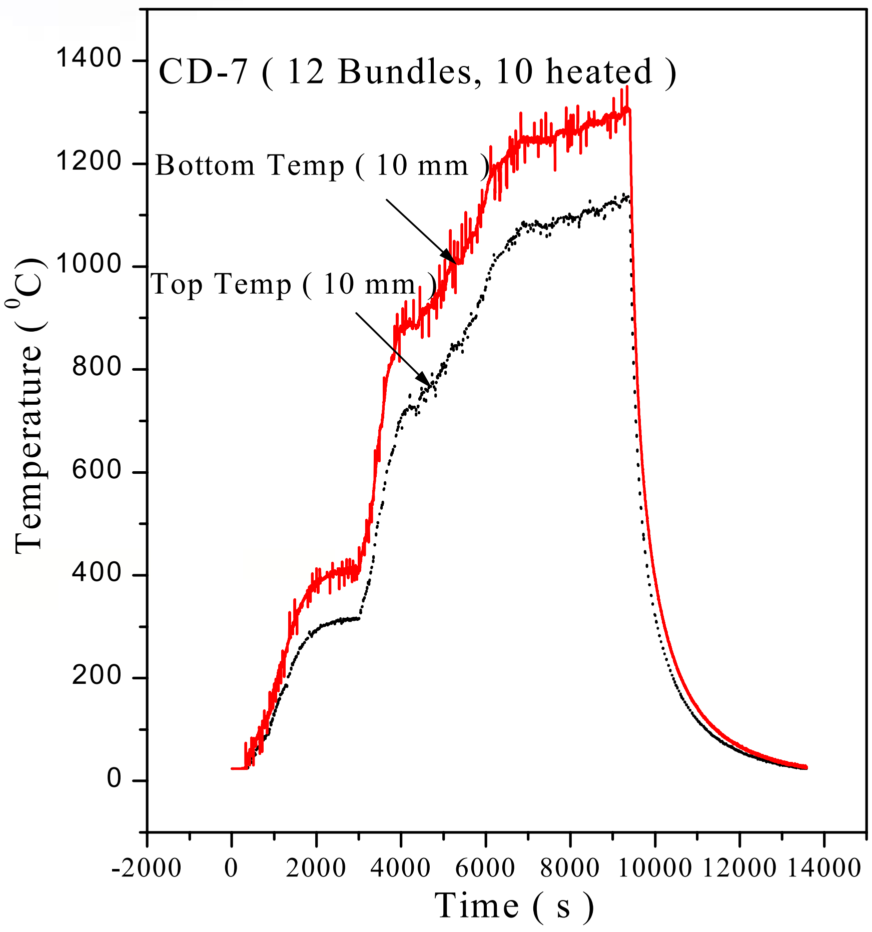
Post-test Examination

- 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
- Axial strain at bundle-to-bundle gaps measured

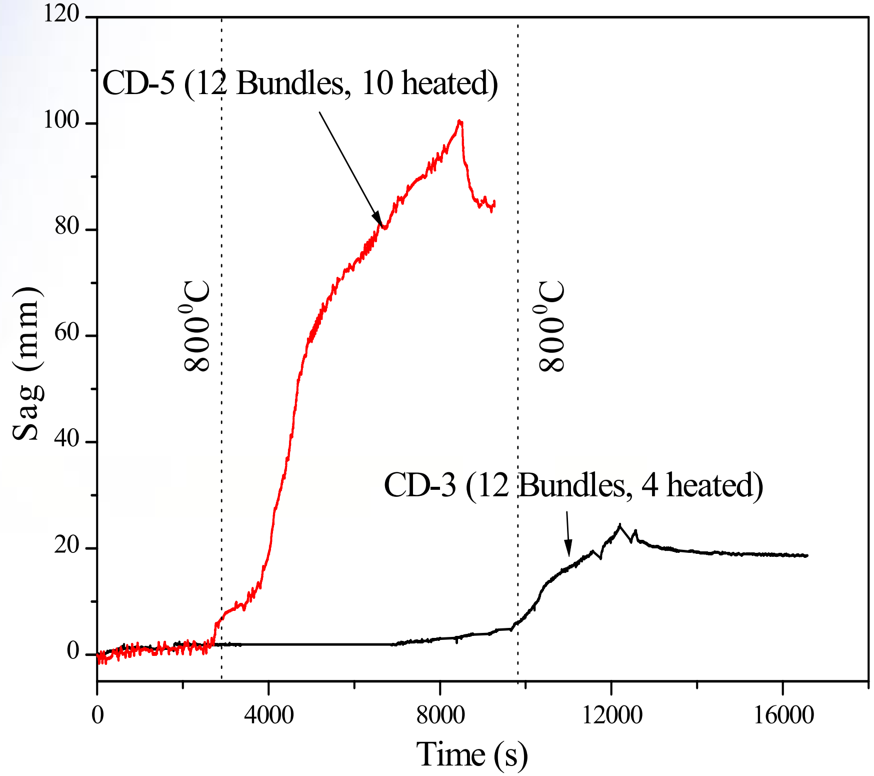
Summary of Single Channel Test Results

Test No.	No. of Heaters	Max. Temp. at mid-point (°C)	Heat up rate (°C/s)	Max. Sag (mm)
CD-3	4	1415	0.26	24
CD-4	10	1320	0.10	117
CD-5	10	1415	0.11	100
CD-6	10	1310	1.20	88
CD-7	10	1307	0.09	120
CD-9	10	1390	0.048	132

Top and Bottom Test Channel Temperature 10 mm from Channel Mid-point for Test CD-7

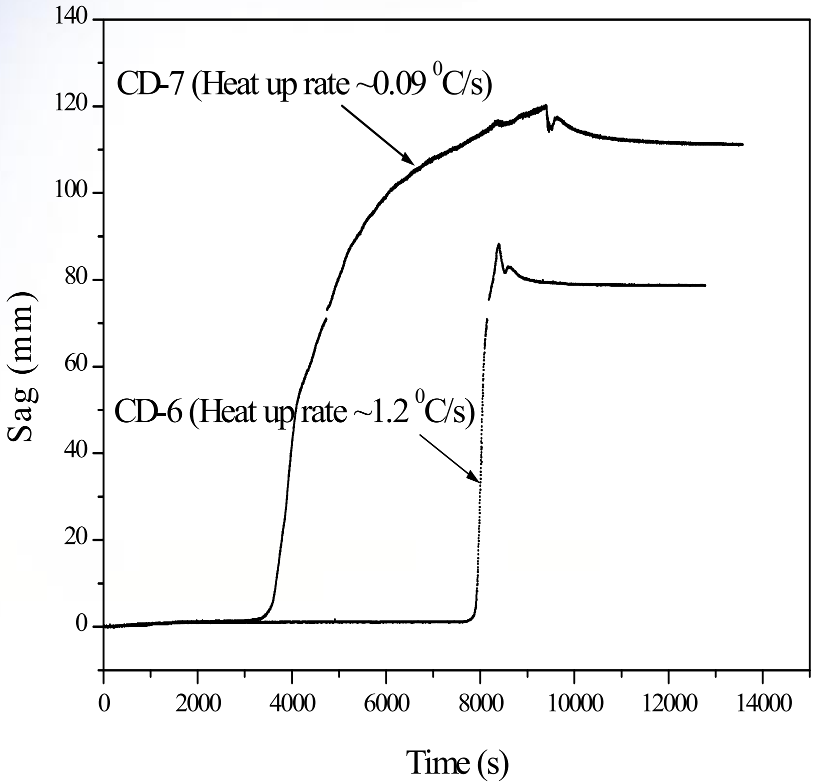


Relationship Between Measured Sag at Channel Mid-point and Heated Length



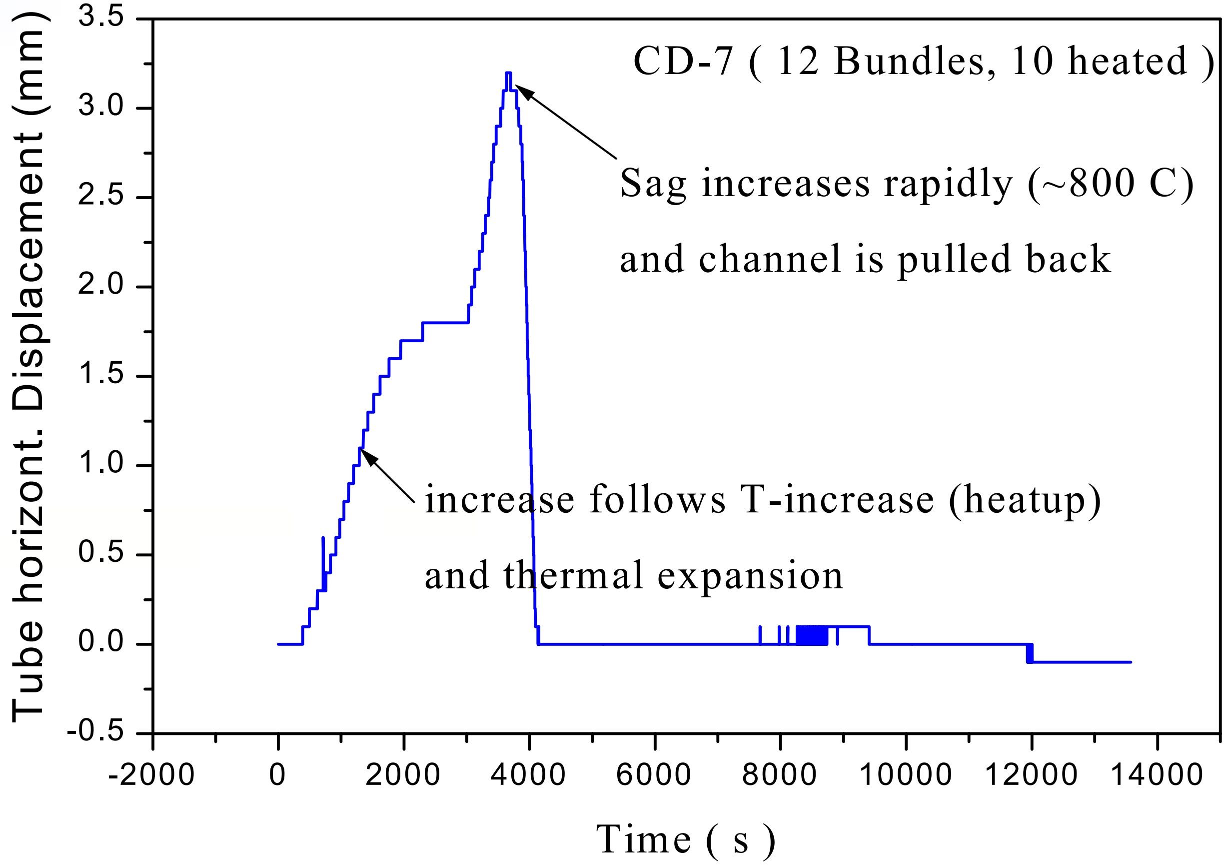
- **Significant sag: T> 800 C**
- **Significant effect of heated length**

Measured Sag for Two Tests with Different Heat-up Rates

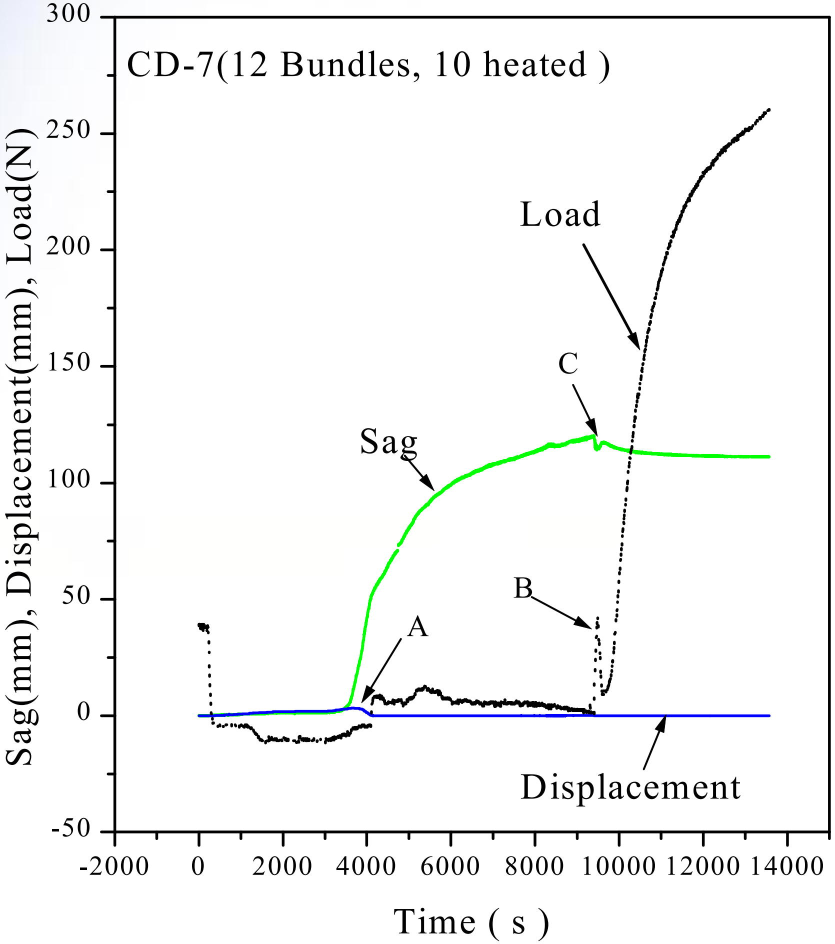


- **Slower heat-up gives higher sag (Creep effect)**
- **Model development must include creep**

Channel Horizontal Displacement

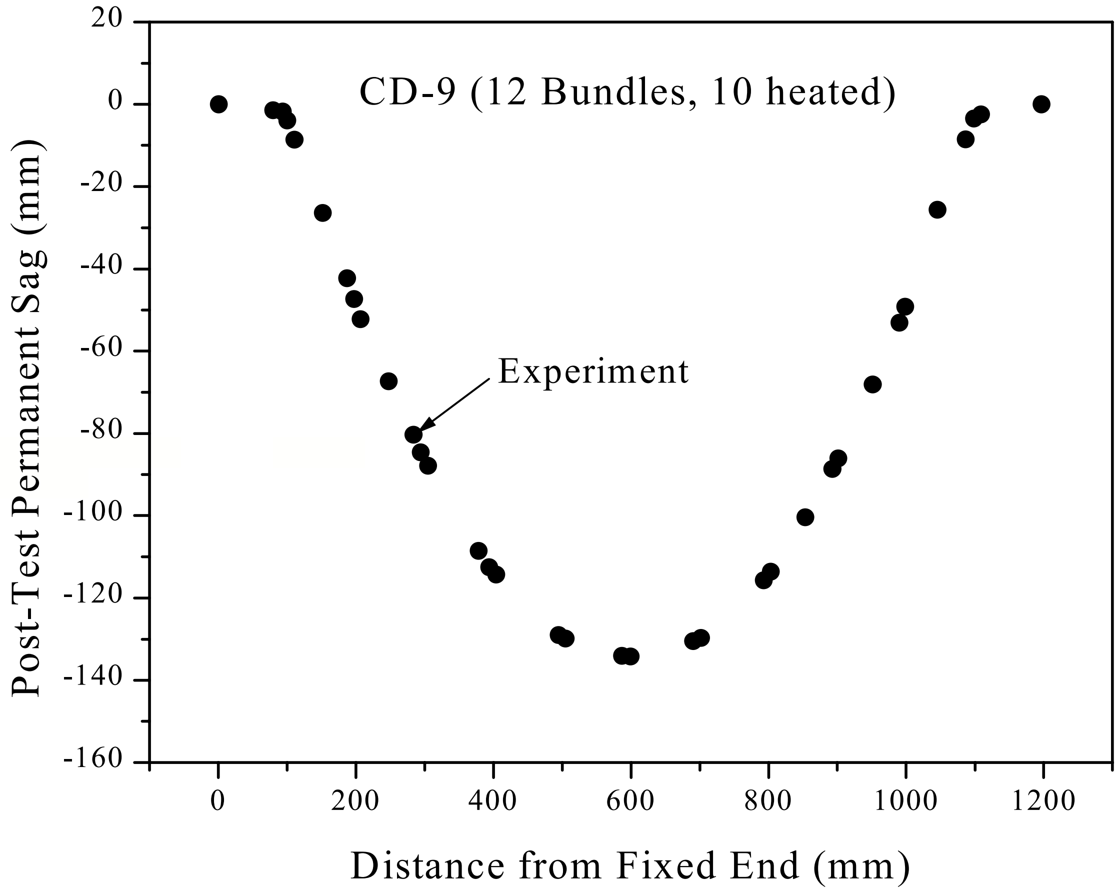


Sag at Mid-point, Horizontal Displacement and End-load for Test CD-7

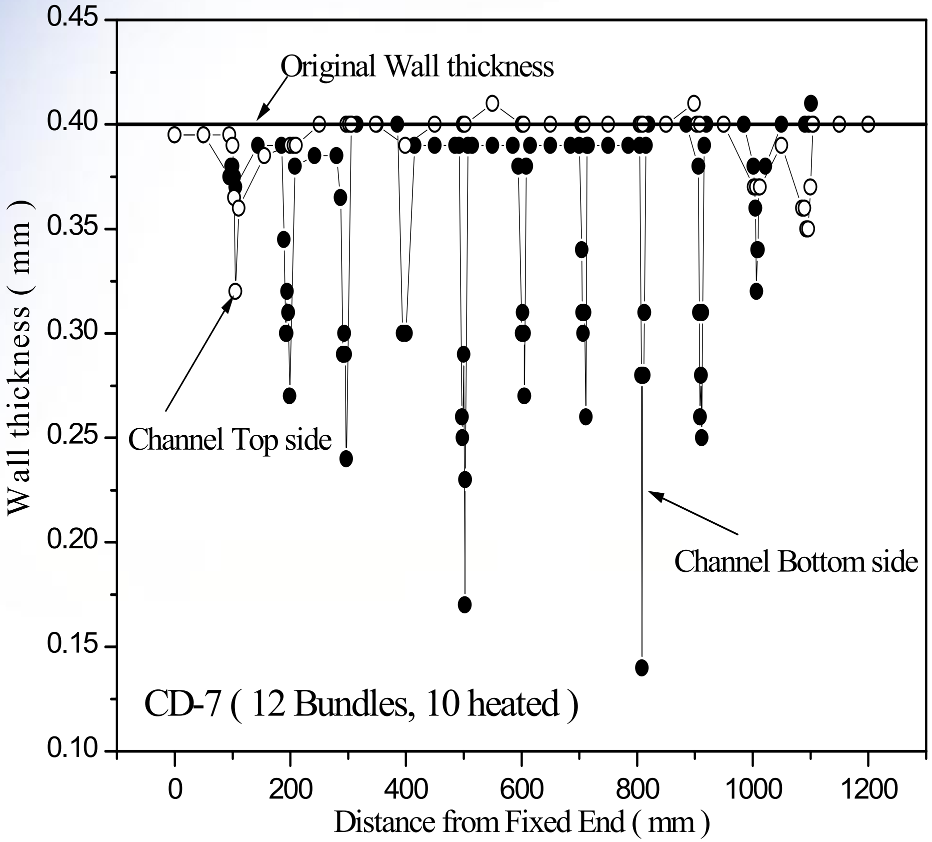


- Significant sag: T> 800 C; creep is the main deformation mechanism
- "B" and "C", alpha-beta transition
- End-load during sagging and cooling small, insufficient for channel pull-out from end-fitting

Post-Test Axial Profile of a Single Channel



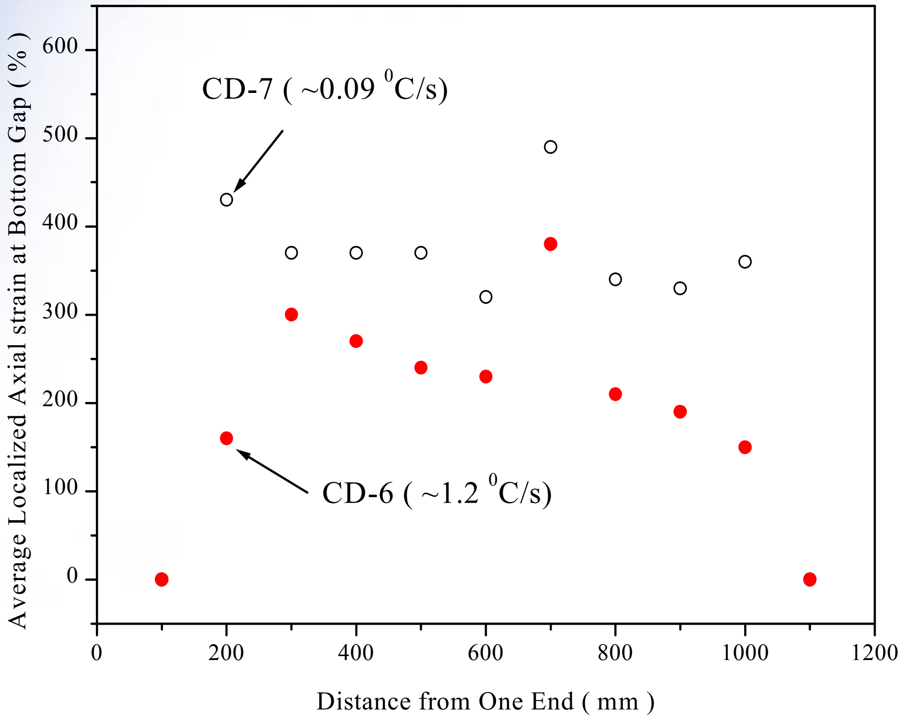
Post-Test Results



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

Wall Thickness of Top and Bottom channel side from Fixed End (CD-7)

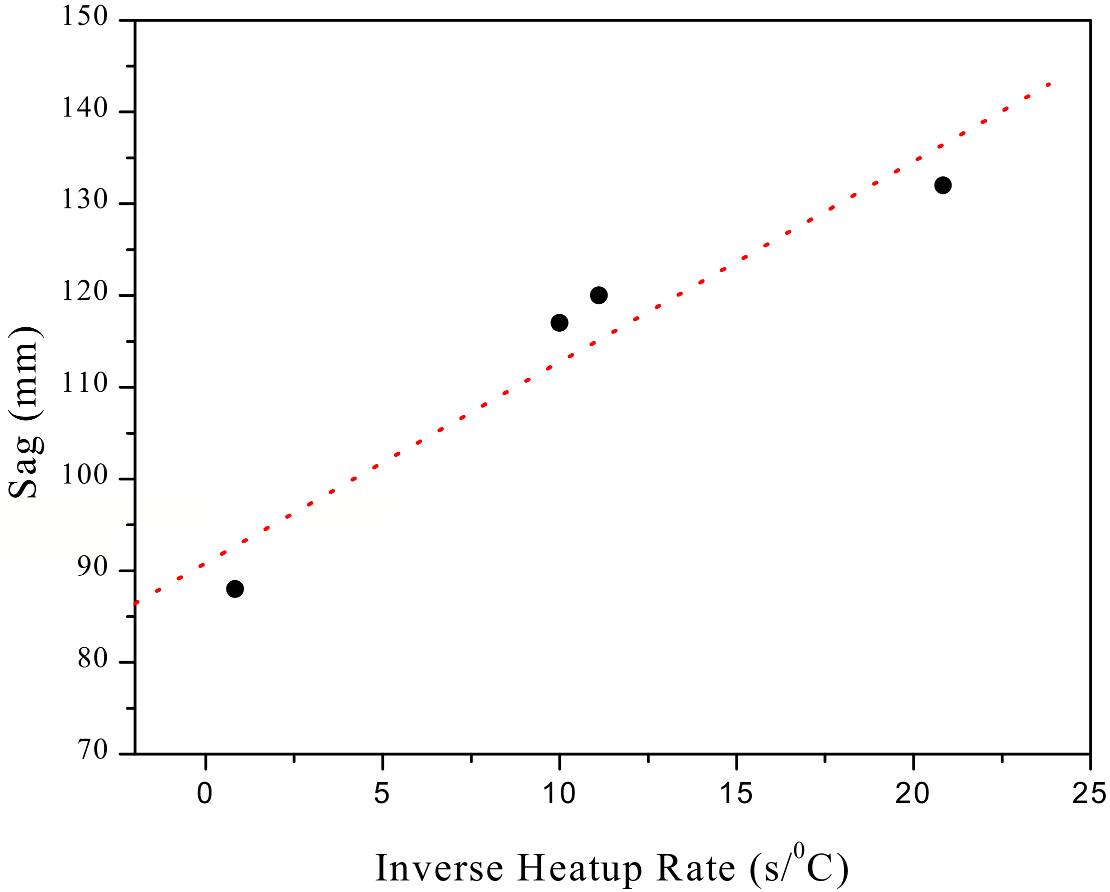
Post Test Results



- **High axial localized strain observed in the gap region between the bundles, consistent with the observed high wall-thinning in gap region**
- **Channel O.D. measurements from front-to-back showed oval shape at bundle junctions, suggesting gripping of bundles by channel during sag**

Average Axial Localized Strain at Channel Bottom, Bundle-to-Bundle Gap Region (CD-6 and CD-7)

Linear Relationship Between Sag and Inverse Heat-up Rate



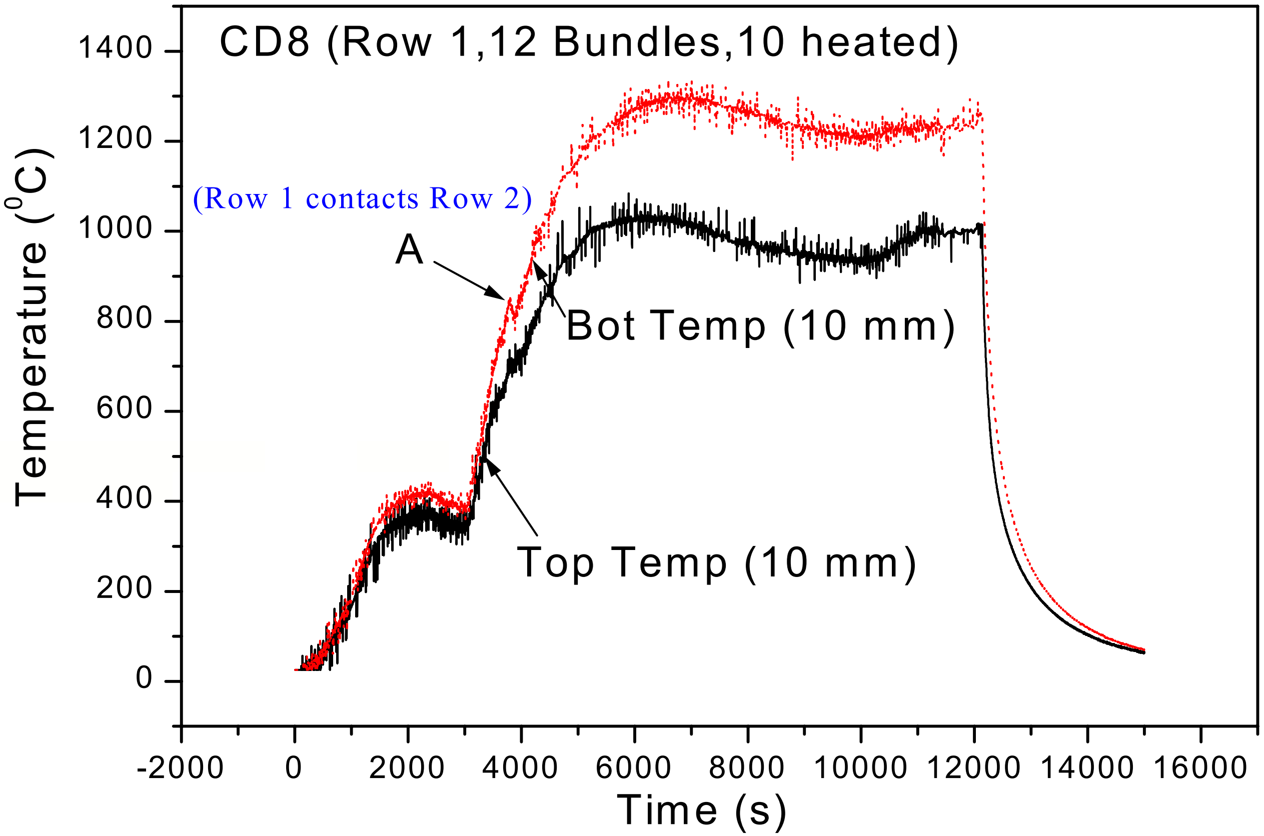
Typical Test Procedure for Multiple Channel Tests in an Inert Atmosphere

- Initial channel temperatures maintained at ~ 300 C, operating temperature
- Top channel power increased so that T_{max} ~1300-1400 C
- Channels below heated up, when it was uncovered by the moderator, as predicted by the MAAP4 CANDU calculations
- Channels held at maximum temperature: ~6000 s

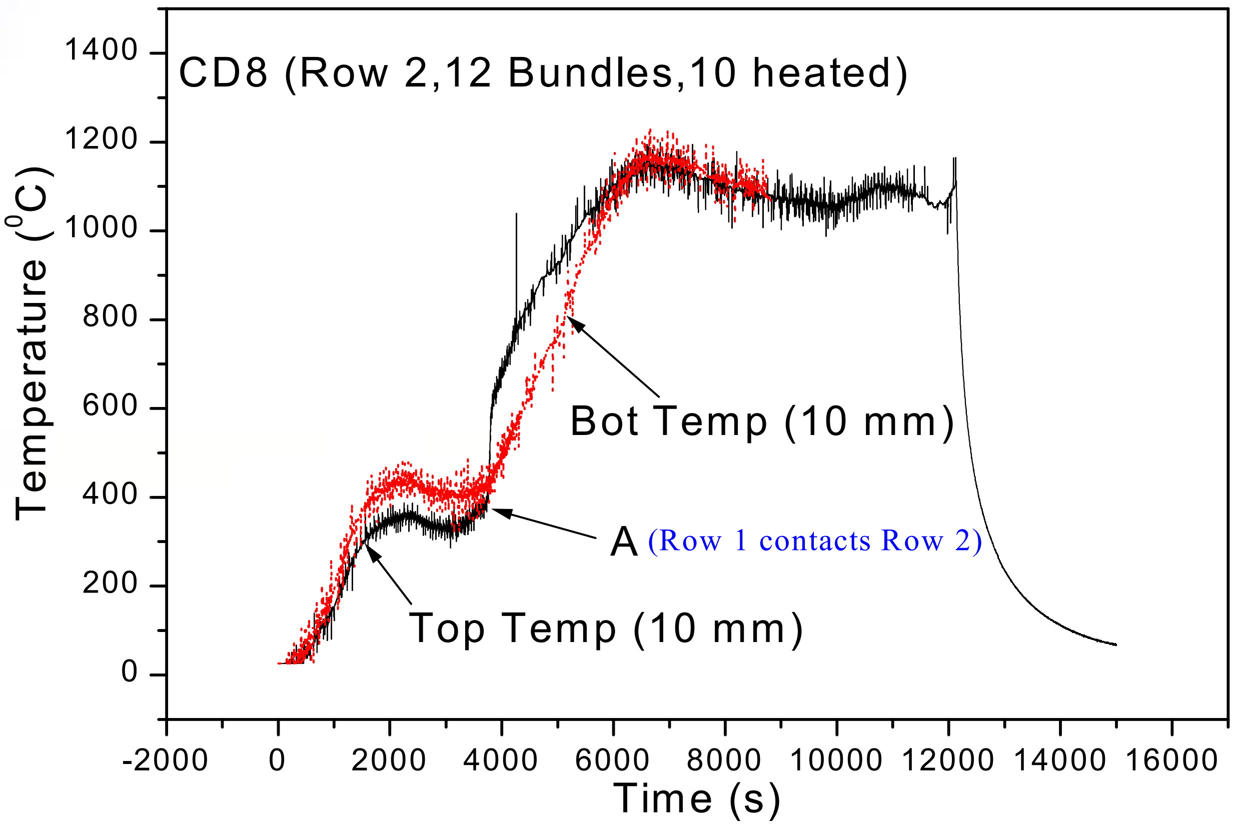
Two-Channel Test

Failure observed at bundle junction at temperature

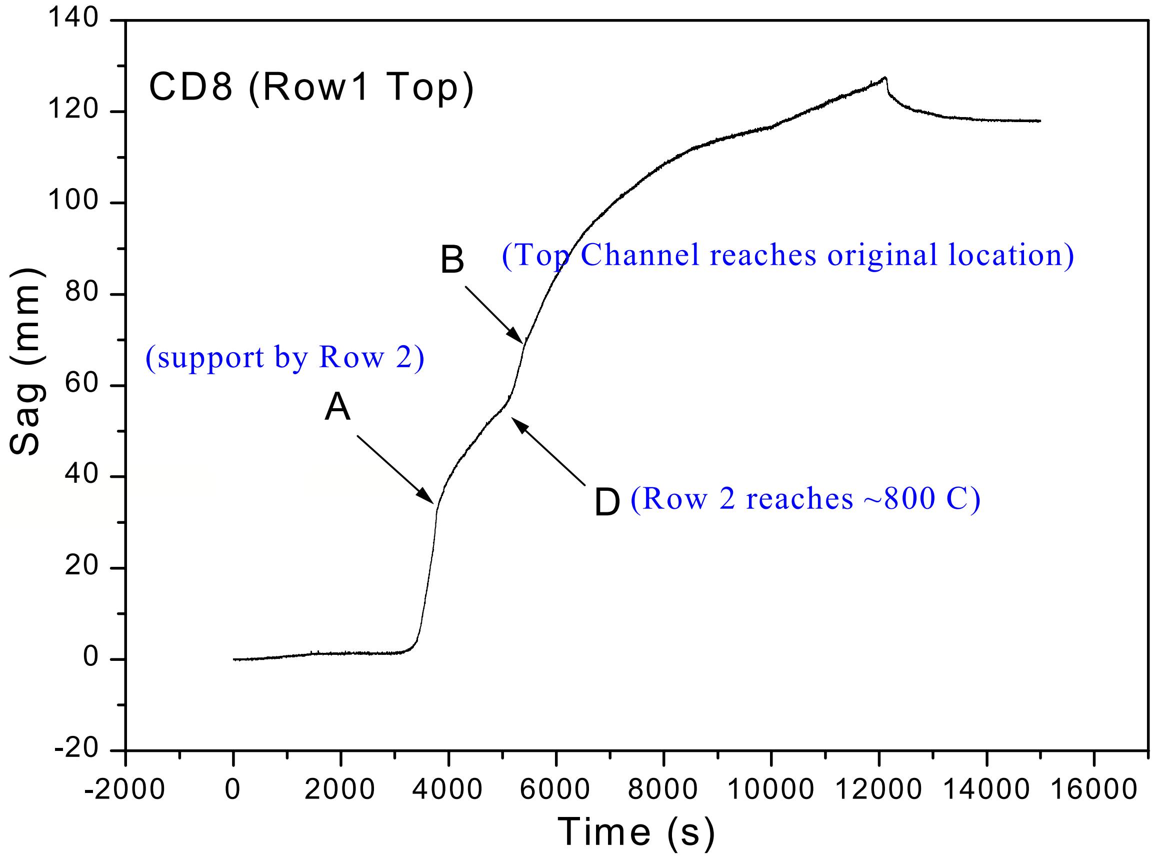
Two-Channel Test (CD-8): Row 1 Temperatures



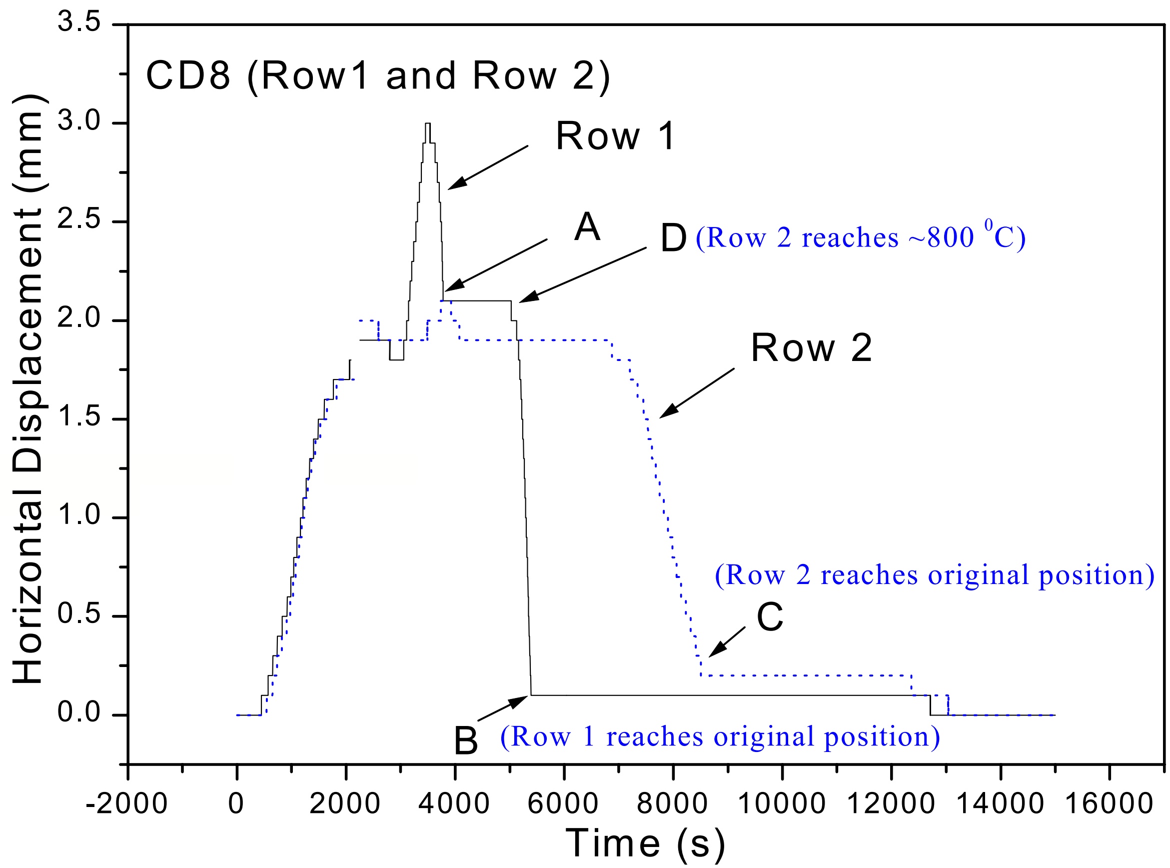
Two-Channel Test (CD-8): Row 2 Temperatures



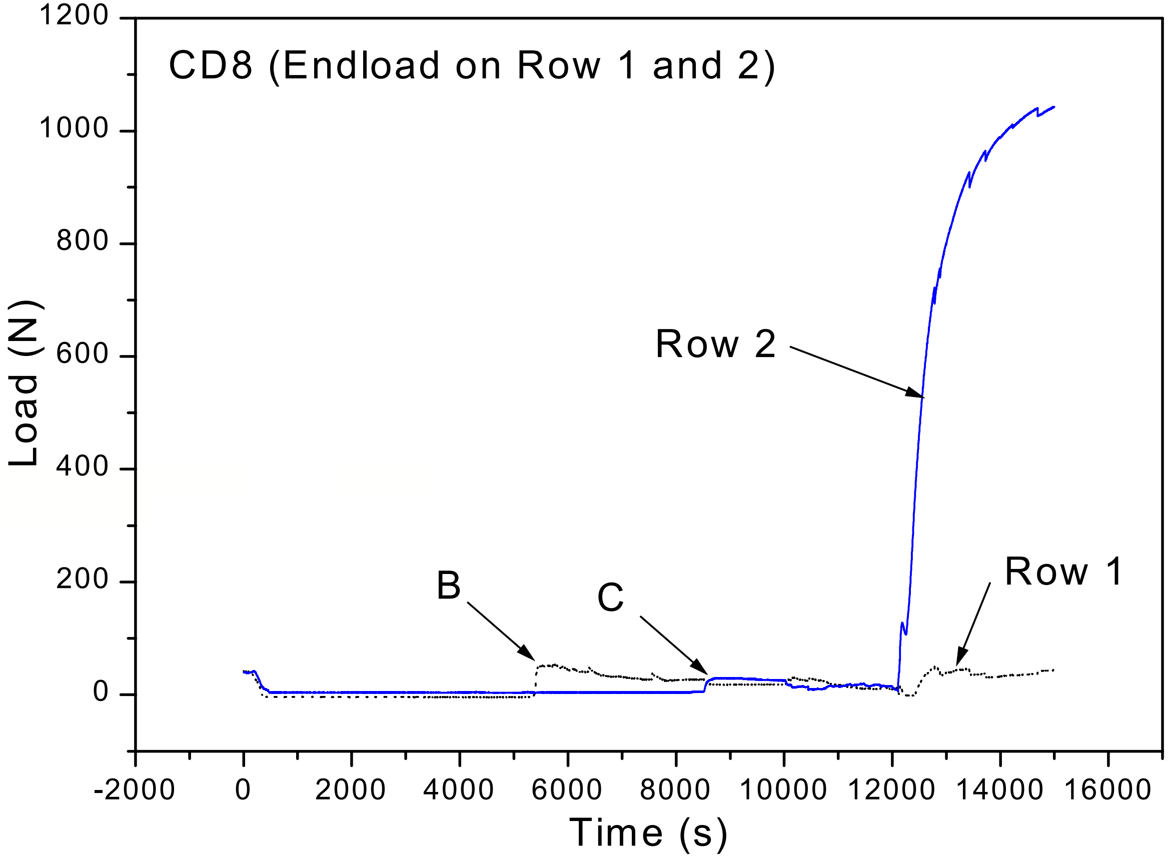
Measured Sag of Top Channel (CD-8)



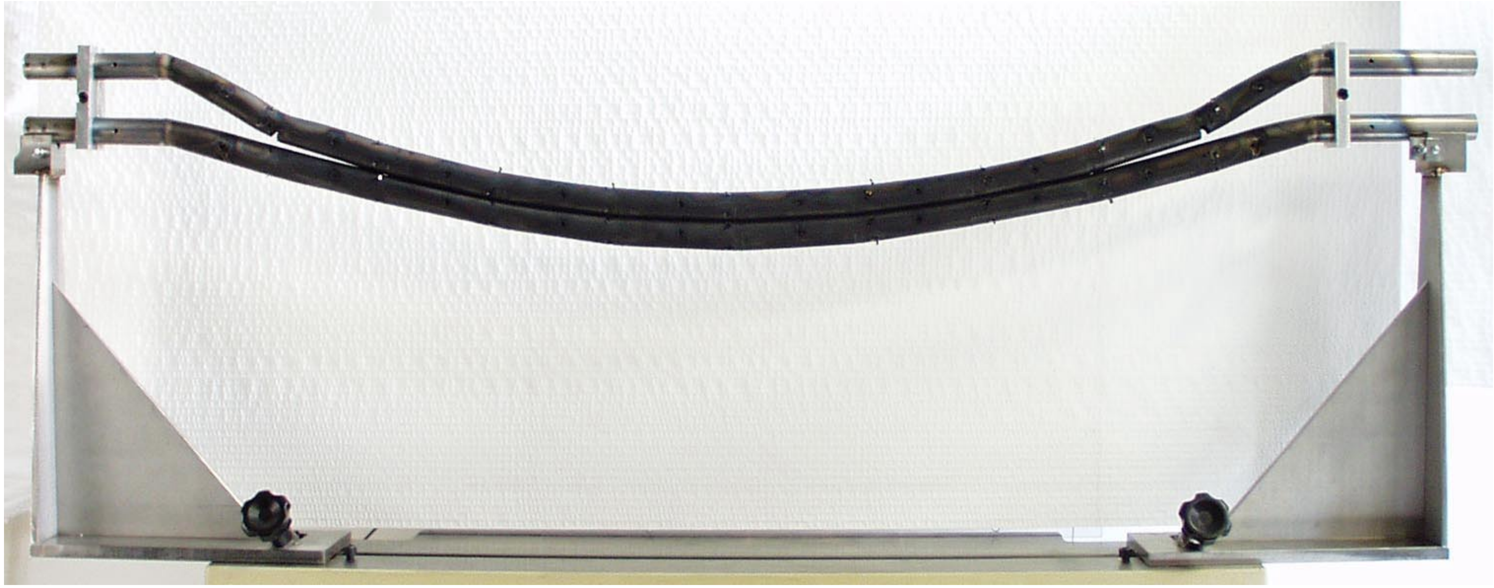
Horizontal Displacement of Top and Bottom Channels (CD-8)



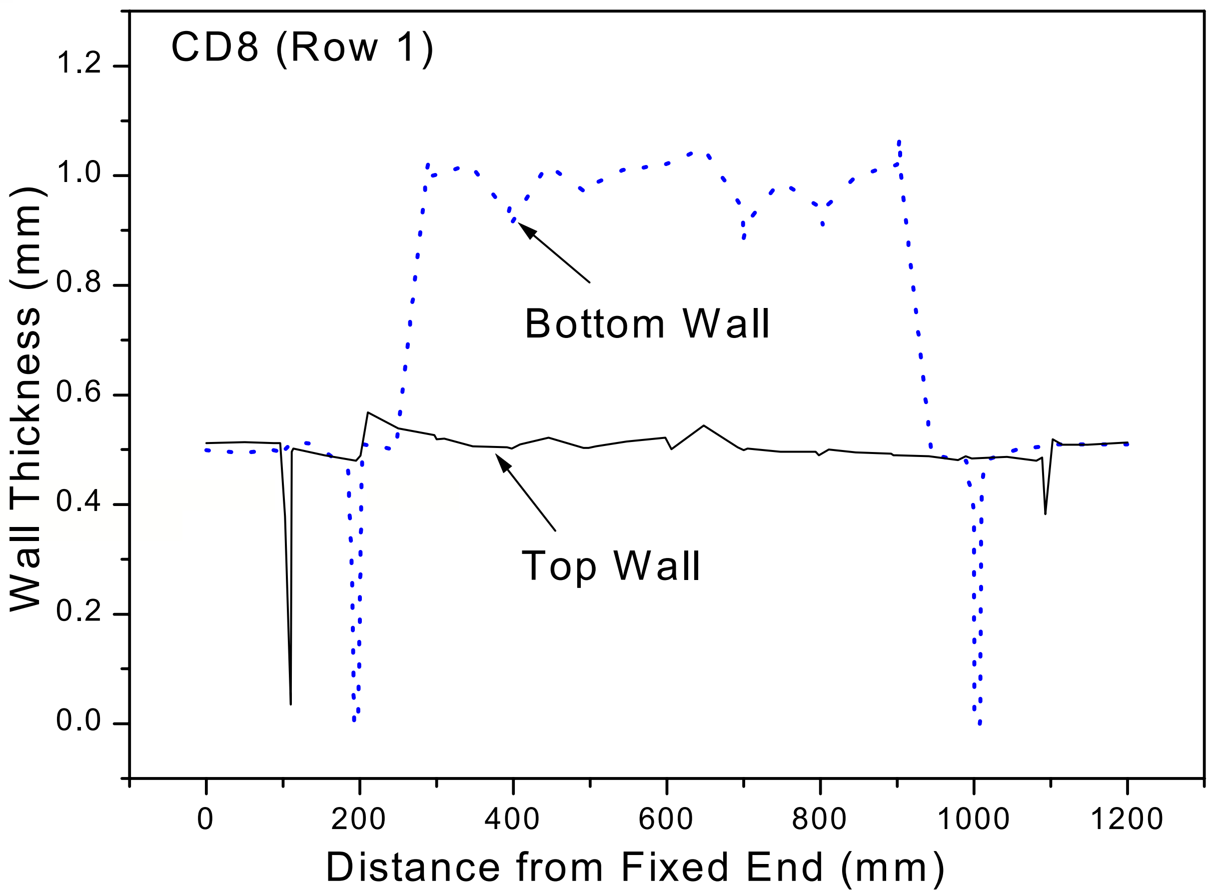
End Load Applied by the Channels at the Ends (CD-8)



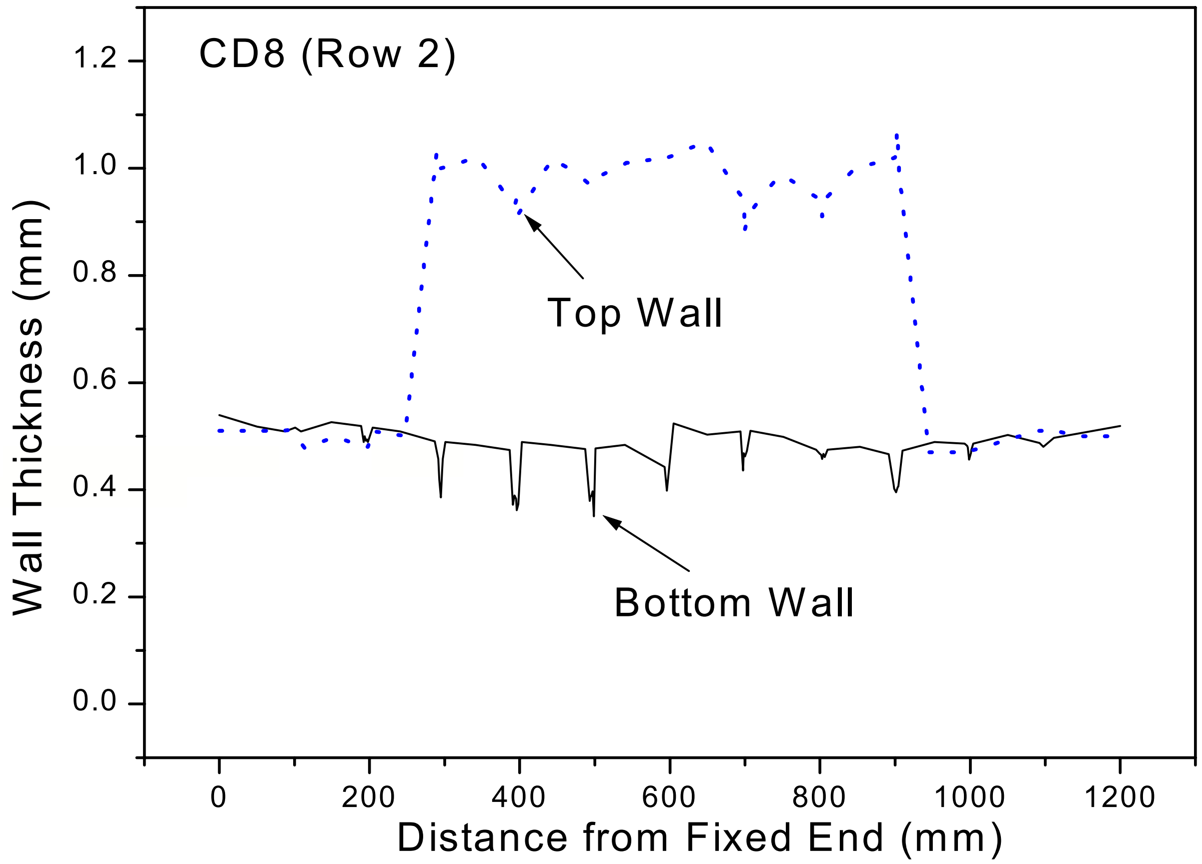
Post-test View of Channels (CD-8)



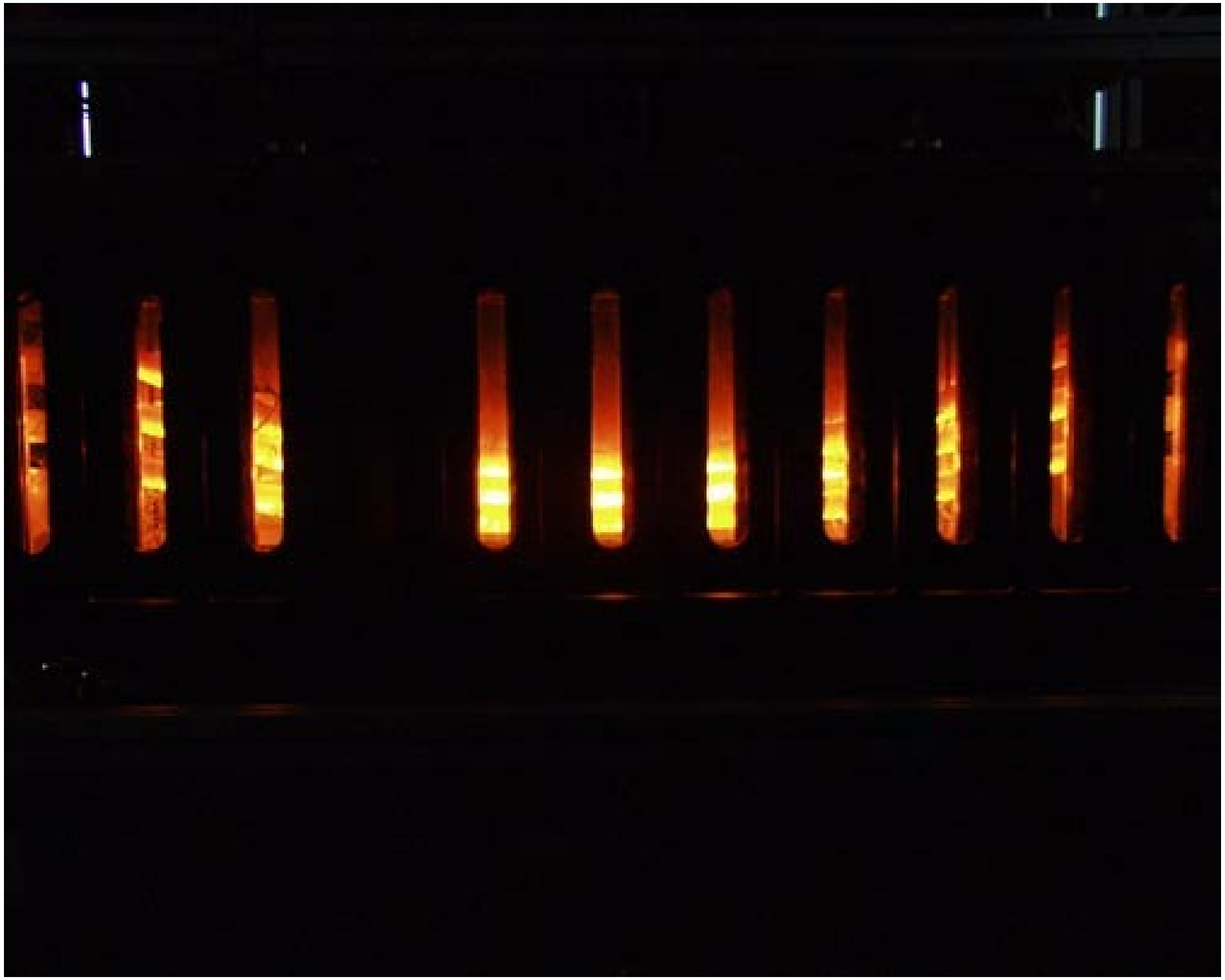
Wall Thickness of the Top and Bottom Wall of Top Channel (CD-8)



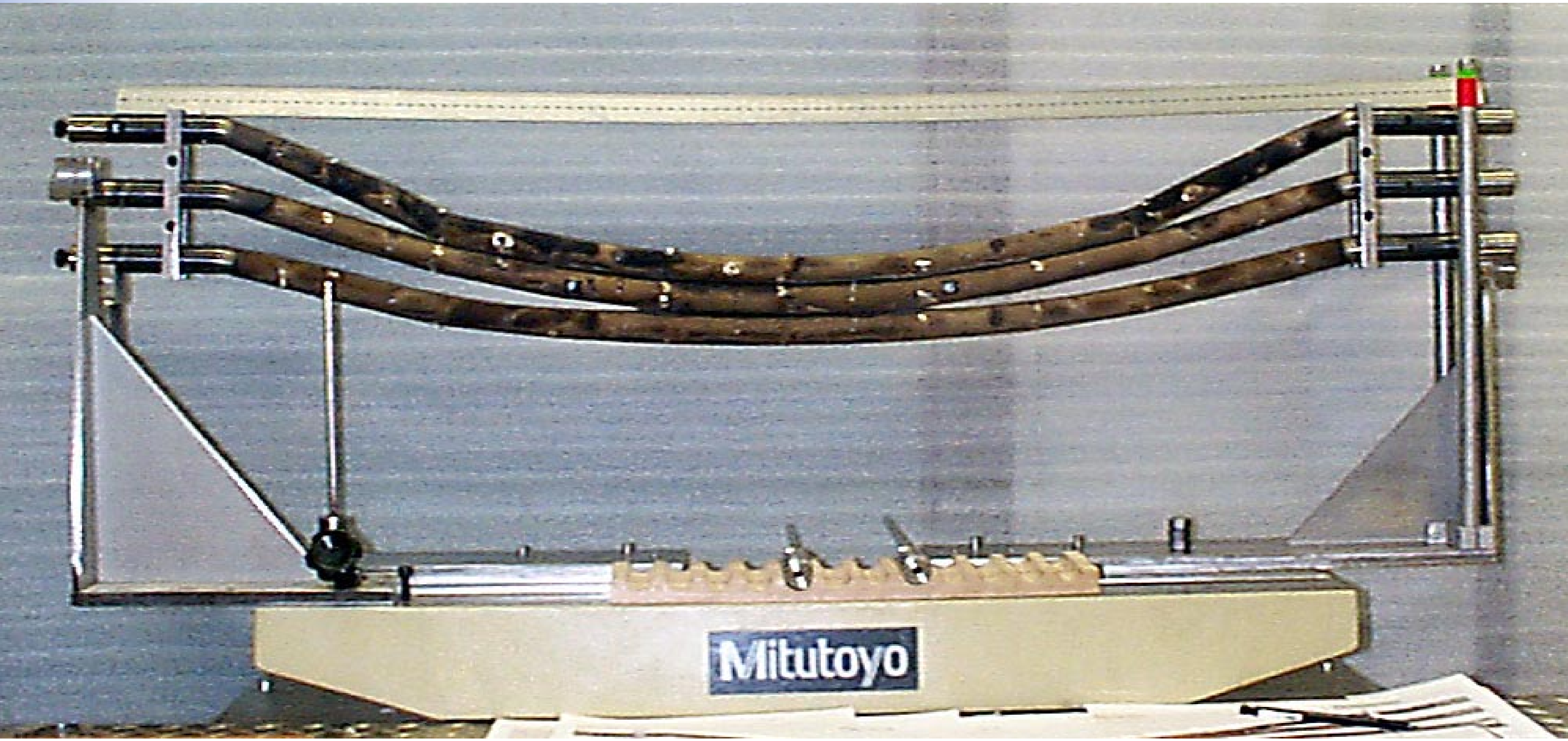
Wall Thickness of the Top and Bottom Wall of Channel in Row 2 (CD-8)



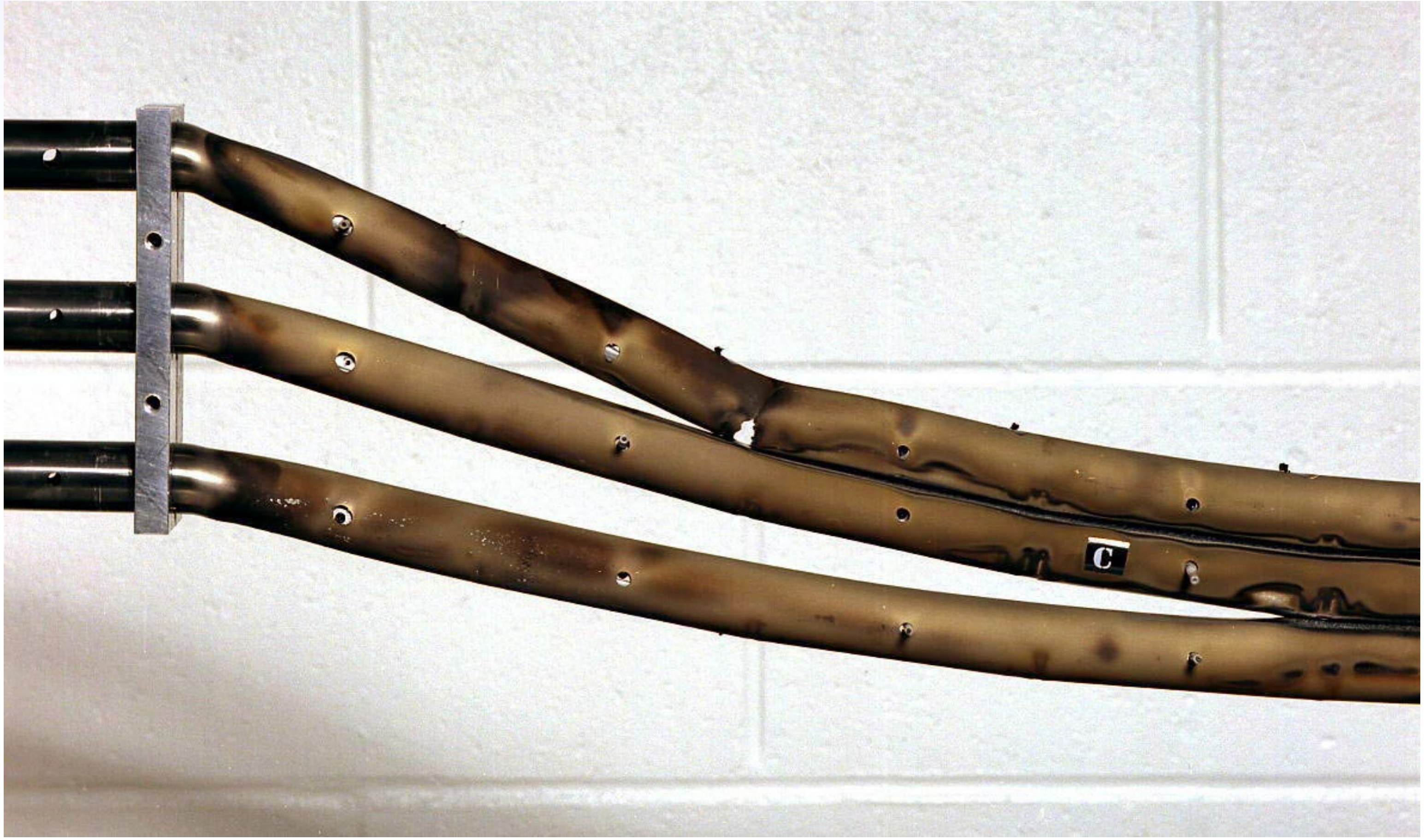
Three Channel Test (CD-10)



Post-test View of 3 Channel (CD-10)



Post-test Close-up View of Channel Break-up (CD-10)



Findings from Multiple Channel Tests

- 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
- Heat transferred from higher row to lower row
- 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 Experiments

- First step to model single channel tests
- Use ABAQUS code, simple beam model
- Measured channel temperatures used as input
- Two single channel tests were simulated
- 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

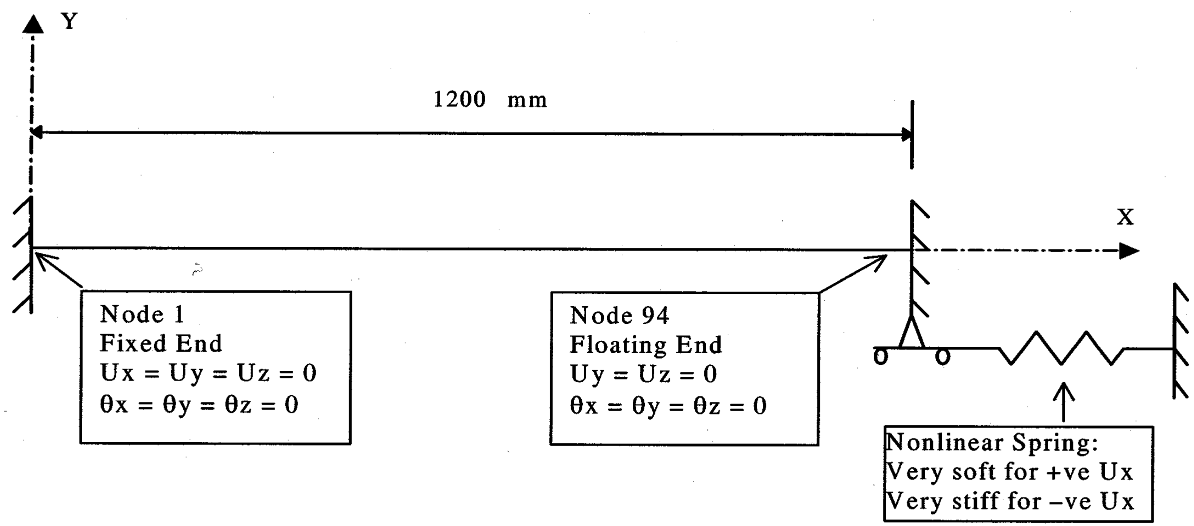
Selected Tests for Model Development

Test No.	Max. Temp. at mid-point (°C)	Hold-time at Max. Temp. (s)	Total time from 800°C(*) to Max. Temp. (s)	Transient Max. Sag (mm)	Permanent Sag (mm)	Heatup Rate from 800°C (°C /s)
CD-7	1307	2670	5695	120	111	0.09
CD-9	1390	0	11500	132	123	0.048

ABAQUS Beam Model

- Full channel length modeled as 93 Beam Elements and 94 Nodes
- Bundle-to-Bundle Gap Element size 1mm
- Small element sizes near gap selected to simulate variation in stress/strain concentration near gap region
- One end fixed, restrained against displacements and rotations (Fixed End)
- Other end allowed to move freely in horizontal direction outward (Floating End), but restrained to move back beyond the original location by attaching that node to a non-linear spring with a small stiffness in positive direction and a relatively high stiffness in the negative direction
- Longitudinal Creep Equation for Zr-2.5 Nb used
- Localized accelerated creep deformation observed at bundle junctions represented by a stress concentration factor in the creep equation

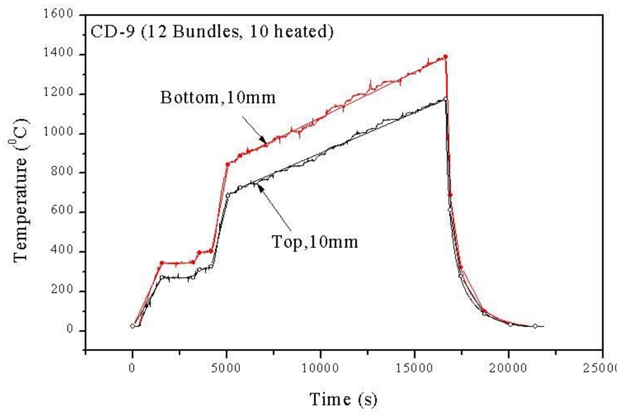
ABAQUS Beam Model

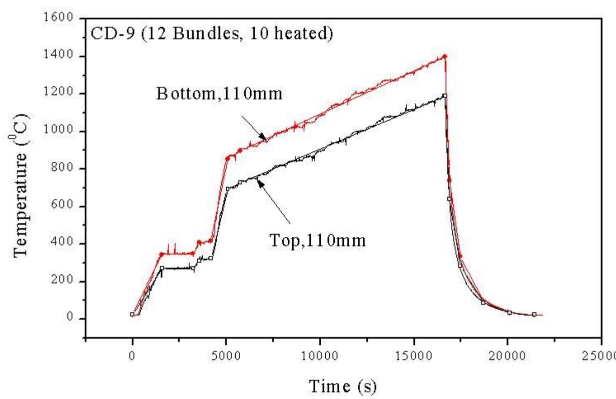


(a) Geometry and Boundary Conditions

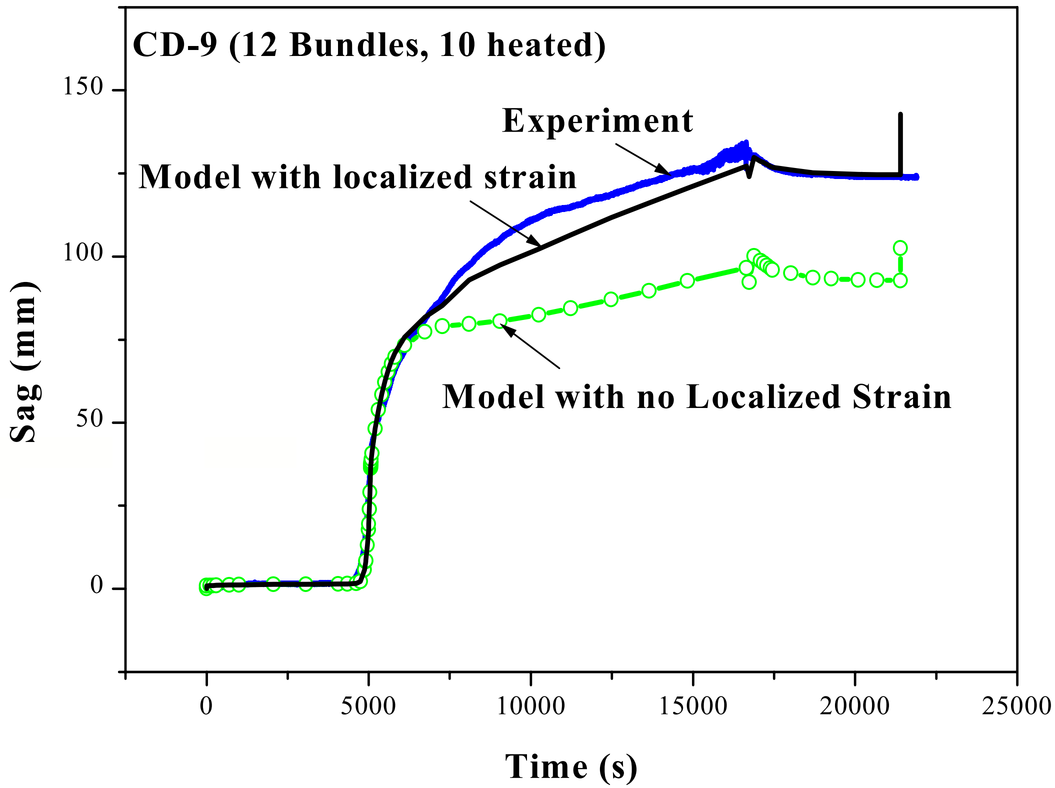
(b) Nodes (from 1 to 15) in the Finite Element Model

Sample Input Temperatures (CD-9)

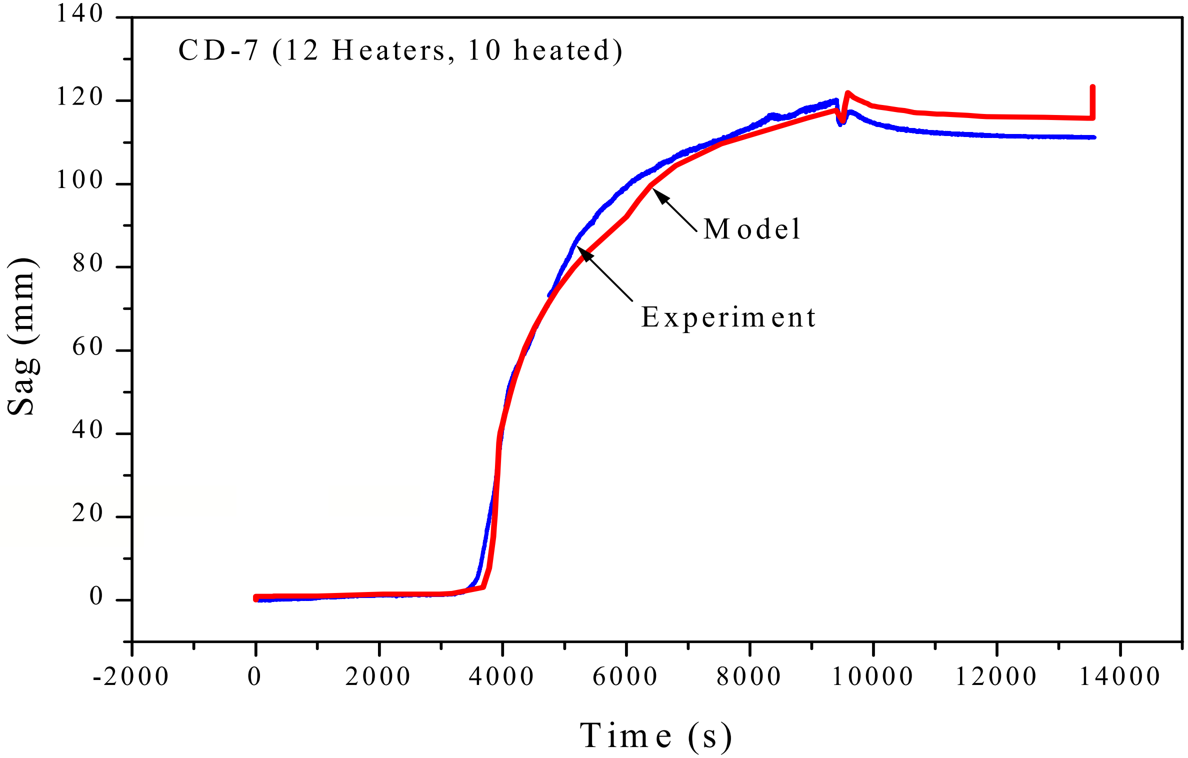




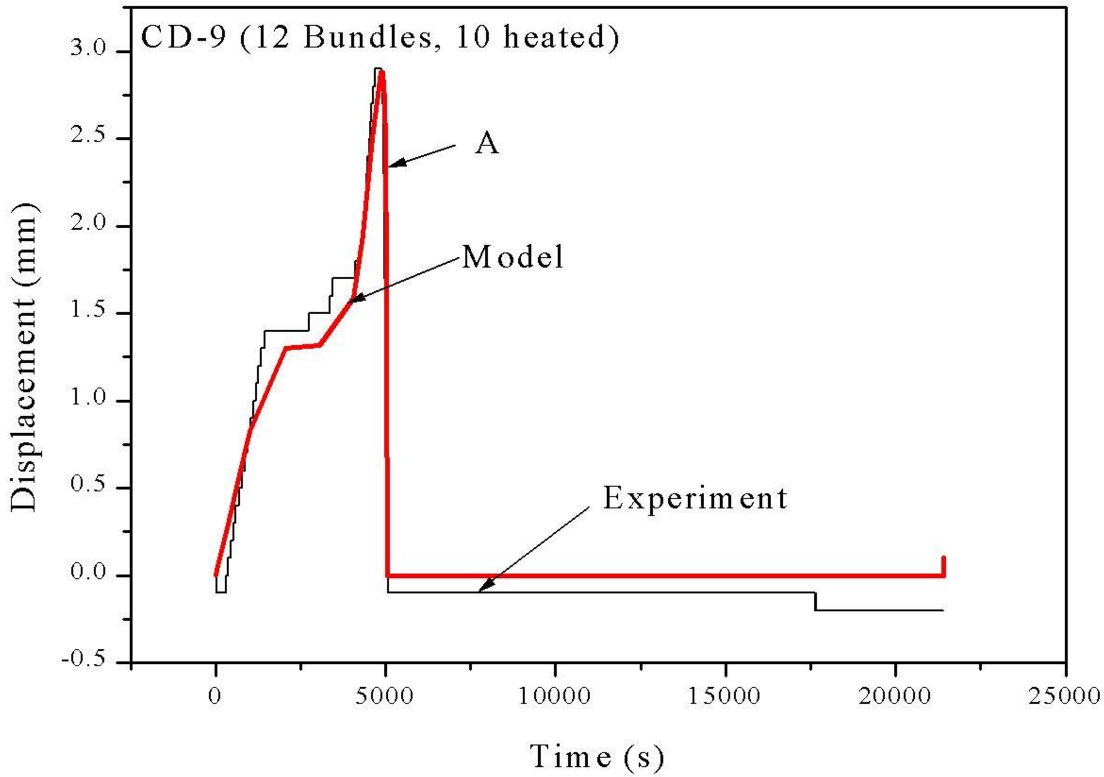
Comparison of Measured Sag at Channel Midpoint with and without Localized Strain Model (CD-9)



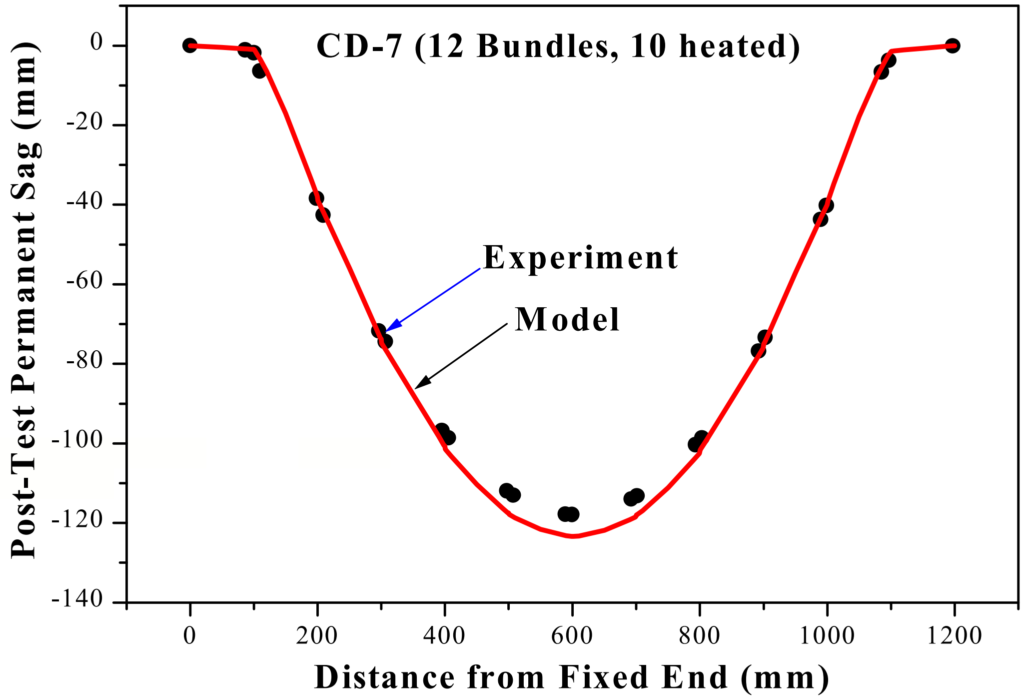
Comparison of Measured Sag at Channel Midpoint with Localized Strain Model (CD-7)



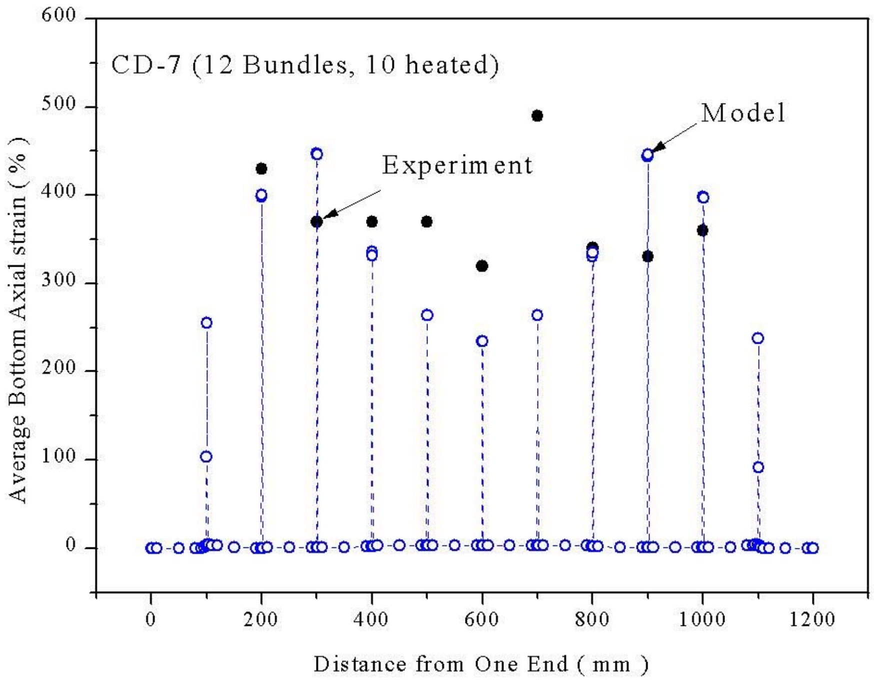
Axial Displacement for Test CD-9



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



Comparison of Post-test Permanent Axial Strain with Model (CD-7)



Conclusions from Tests

- Sag at channel mid-point increases with heated length, significant sag for T > 800 °C
- Sag is time-dependent, so channel deformation by creep mechanism
- Multiple channel tests suggest coarse debris formation, debris as long as 10 bundles long
- 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.

Future Work

- Effect of oxidation
  - Dissolved oxygen in channel material will strengthen the channel (slower creep rate)
  - Growing oxide layer will decrease the load-bearing cross-section
- Develop models to explain the findings
- Implement findings in MAAP4 CANDU
  - Temperature for Debris Formation
  - Size of Debris

Summary

- Understand phenomena leading to CANDU core disassembly
- The 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
- ACR channel sag behavior is expected to be driven by creep and the debris are expected to be coarse

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