Conf-9105173-3-Extd.Abst.

In-Vessel Phenomena - CORA

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BWR Core Melt Progression Phenomena Program*

Oak Ridge National Laboratory

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In-Vessel Phenomena - CORA

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ABSTRACT

Experiment-specific models have been employed since 1986 by Oak Ridge National Laboratory (ORNL) severe accident analysis programs for the purpose of boiling water reactor experimental planning and optimum interpretation of experimental results. The large integral tests performed to date, which start from an initial undamaged core state, have involved significantly different-from-prototypic boundary and experimental conditions because of either normal facility limitations or specific experimental constraints. These experiments (ACRR: DF-4, NRU: FLHT-6, and CORA) were designed to obtain specific phenomenological information such as the degradation and interaction of prototypic components and the effects on melt progression of control-blade materials and channel boxes.

Applications of ORNL models specific to the KfK CORA-16 and CORA-17 experiments are discussed and significant findings from the experimental analyses such as the following are presented:

1) applicability of available Zircaloy oxidation kinetics correlations,
2) influence of cladding strain on Zircaloy oxidation,
3) influence of spacer grids on the structural heatup, and
4) the impact of treating the gaseous coolant as a gray interacting medium.

The experiment-specific models supplement and support the systems-level accident analysis codes. They allow the analyst to accurately quantify the observed experimental phenomena and to compensate for the effect of known uncertainties. They provide a basis for the efficient development of new models for phenomena that are currently not modeled (such as material interactions). They can provide validated phenomenological models (from the results of the experiments) as candidates for incorporation in the systems-level "whole-core" codes.

The BWR Core Melt Progression Phenomena Program At ORNL Is Currently Performing Posttest Analyses Of The CORA BWR Experiments

- CORA-16, underway
- CORA-17, underway
- CORA-18, to be done this fiscal year

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Experiment-Specific Features Dramatically Influence Test Behavior

- Must consider test geometry when interpreting the data
- Difficult to control boundary conditions (especially heat losses)
- Additional phenomena must be treated

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Experiment Structural Thermal Response Must Be Accurately Modeled

- Requires very detailed approach
  - to predict phenomena after melting begins
  - to interpolate between data points
  - to extrapolate when thermocouples fail at high temperature
- System codes represent the reactor vessel and do not have this level of modeling

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By Excluding Extraneous Considerations Experiment-Specific Modeling And Analysis Yields

- Thorough understanding of key phenomena of interest
- Data with reduced uncertainties
- A verified database that can be used to formulate and validate models for the system-level codes

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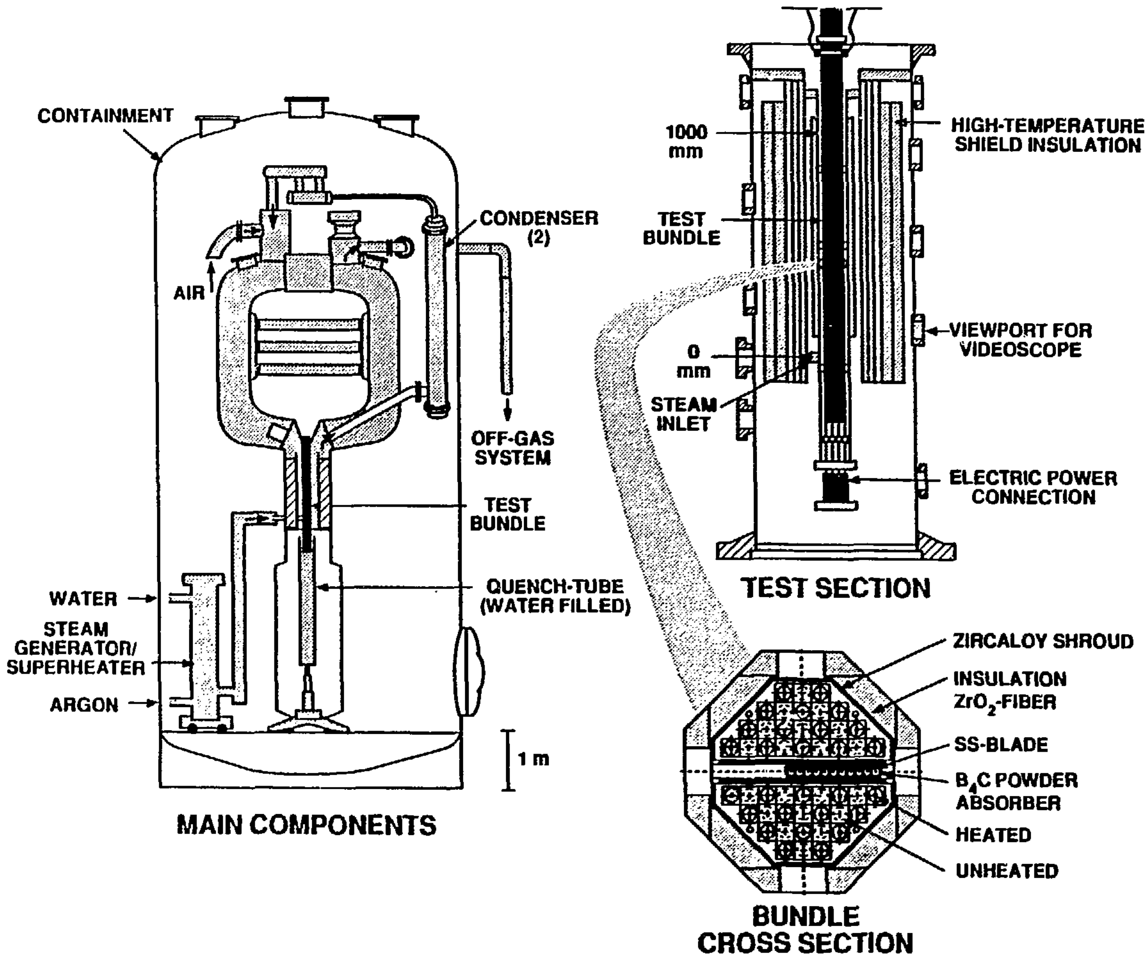
CORA Severe Fuel Damage Test Facility



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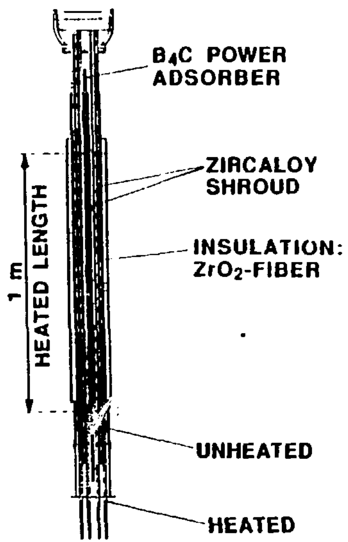
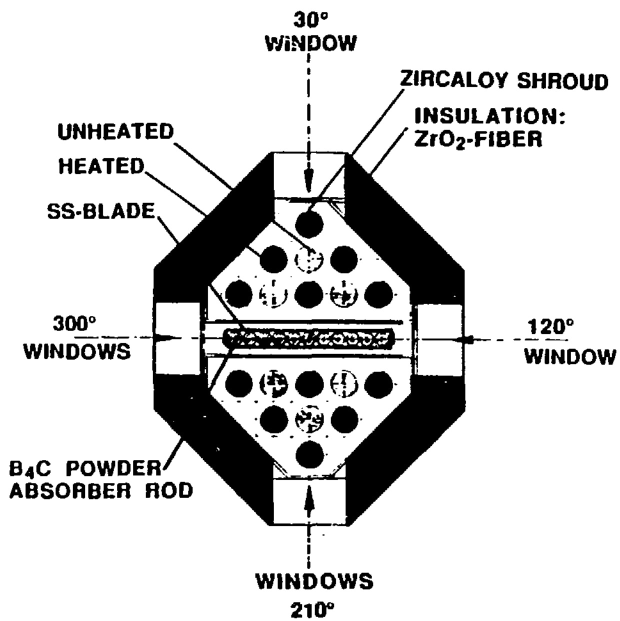
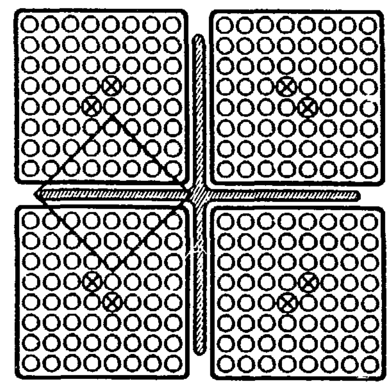
CORA BWR Experimental Cross-Sections And The Portion Of A BWR Core Unit Cell That Is Represented In The Experiment







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CORA BWR Experiments

(include representative section of B_4C filled control blade)

Test No.	Bundle Size	Description	Date of Test
16	18 rods	~1.0 k/s heatup rate, slow cooling	Nov. 24, 1988
17	18 rods	~1.0 k/s heatup rate, ~1 cm/s quench rate	June 29, 1989
18	48 rods	~1.0 k/s heatup rate, slow cooling	June 21, 1990
31	18 rods	slow initial heatup rate (~ 0.3 k/s), ~1 cm/s quench rate	planned for June 1991

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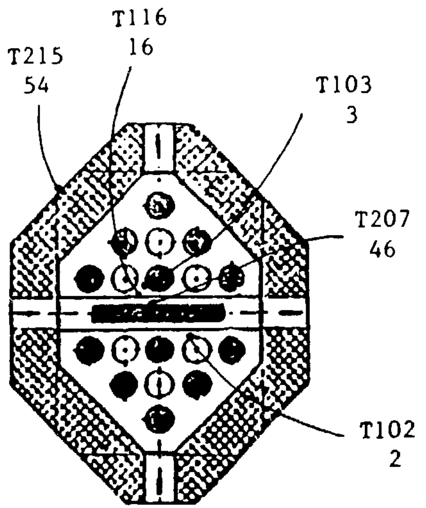
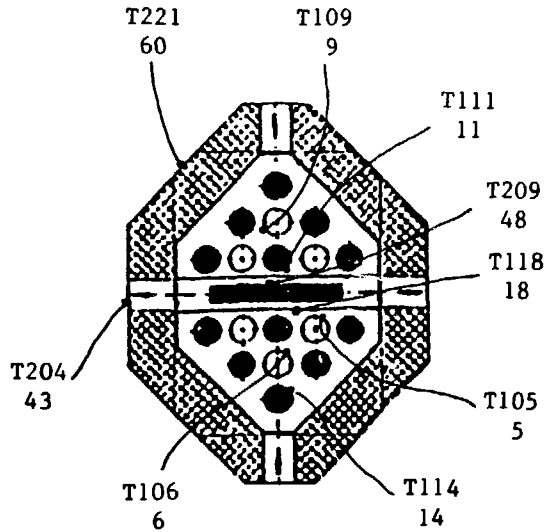
Analytical Simulations Of The CORA-16 And CORA-17 Experiments Accurately Predict The Thermal Response Of The Experimental Structures Through Early Phase Melt Relocation

Examples

- CORA-16, 950 mm Elevation



- CORA-17, 550 mm Elevation (location of spacer grid)



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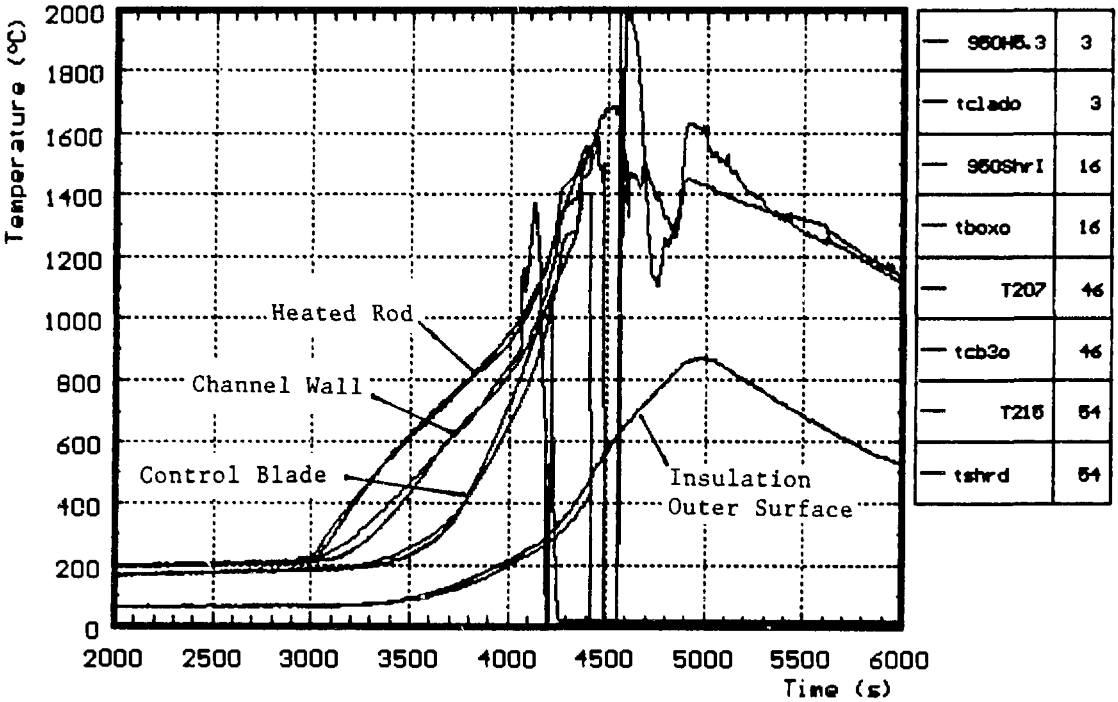
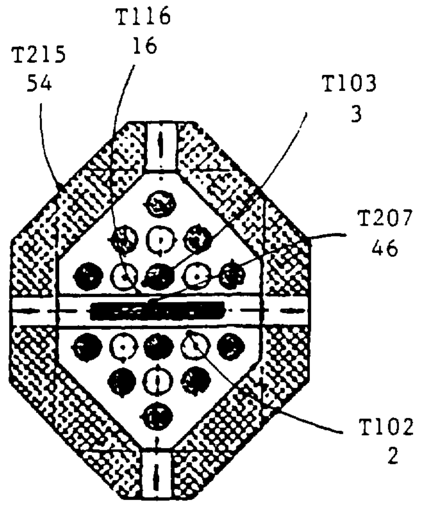
CORA-16 Structural Thermal Response At The 950 mm Elevation





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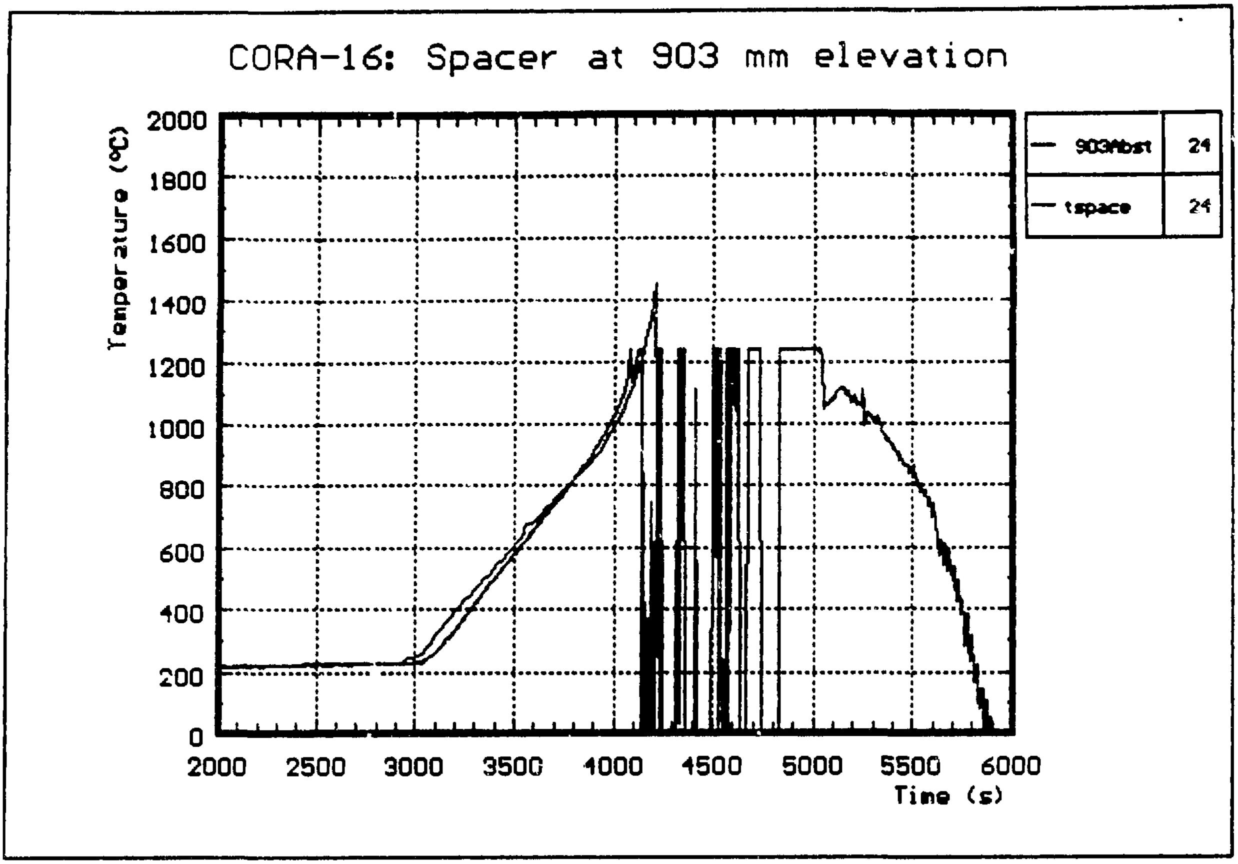
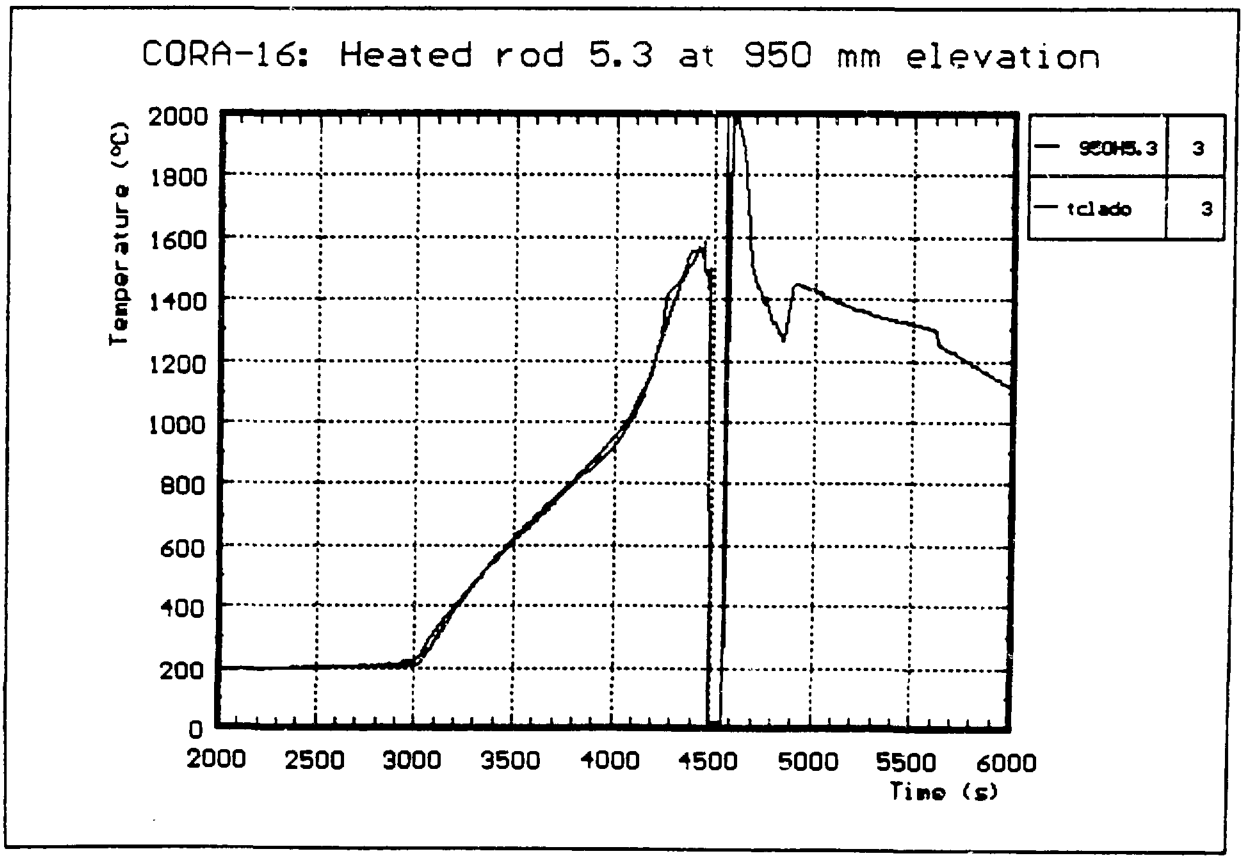
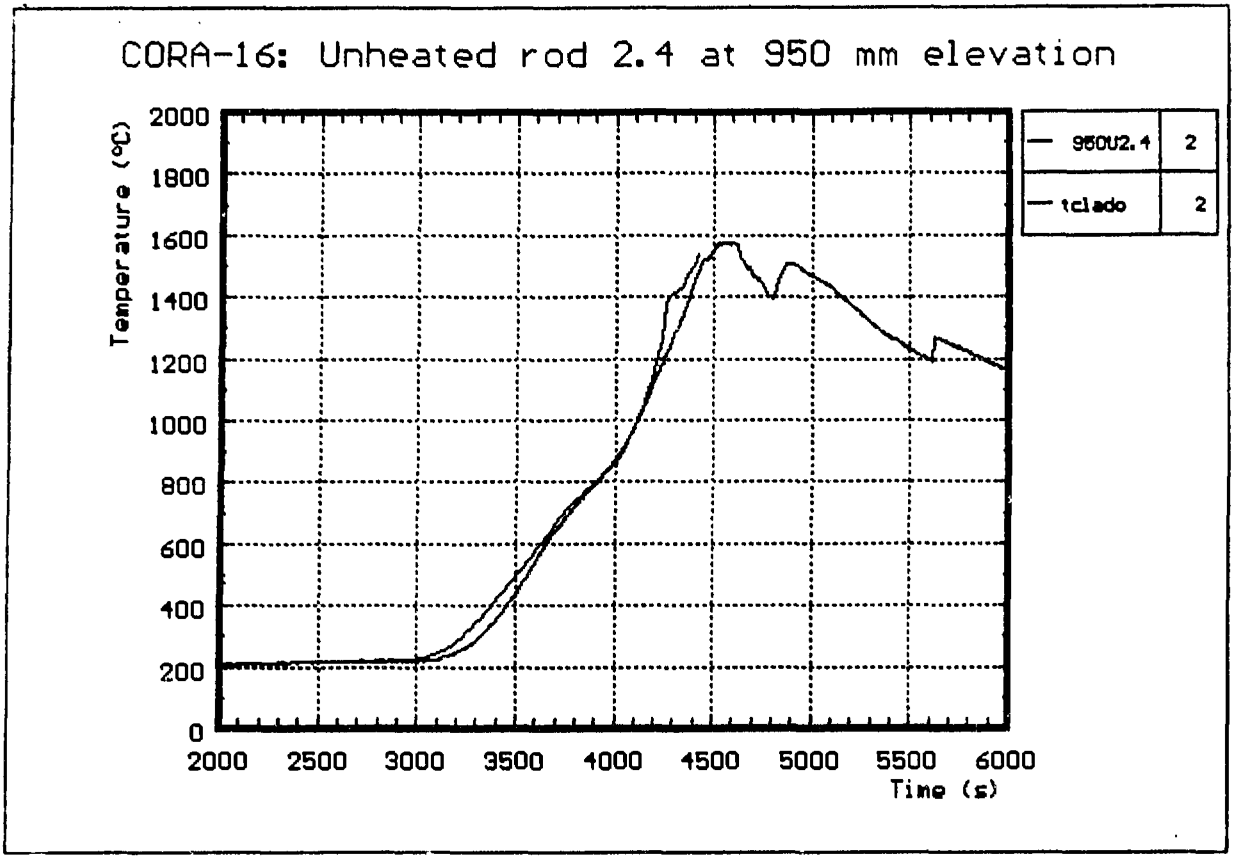
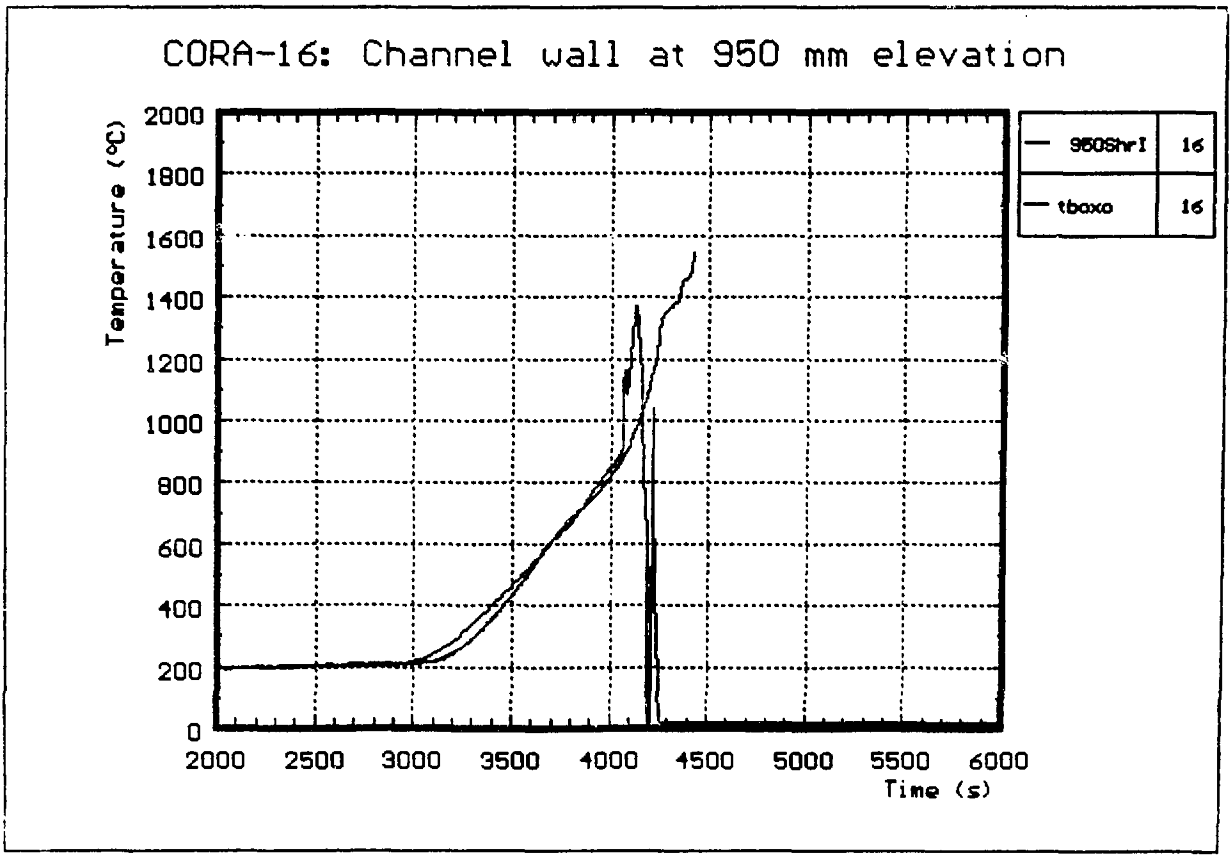


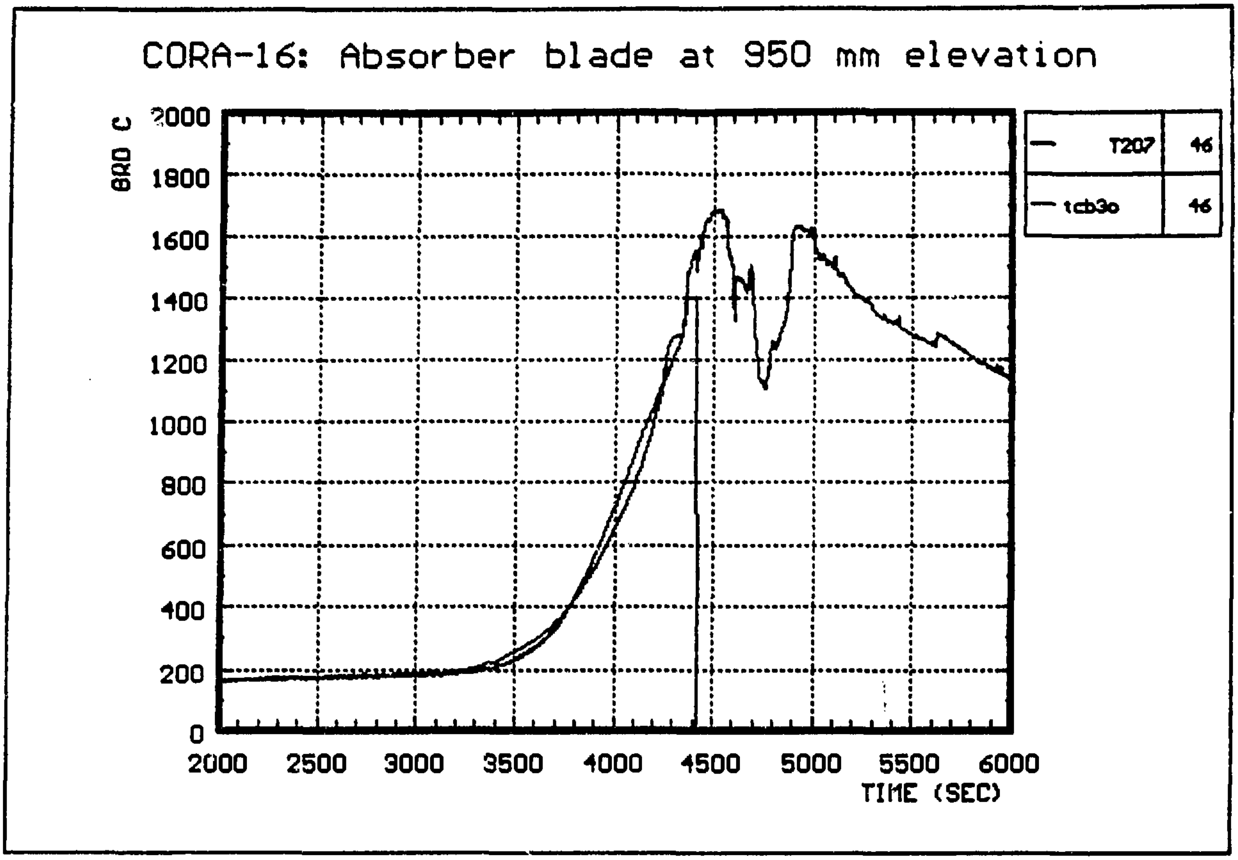
CORA-16: Spacer at 903 mm elevation
Temperature (°C)
Time (s)
903Abst 24
tspace 24



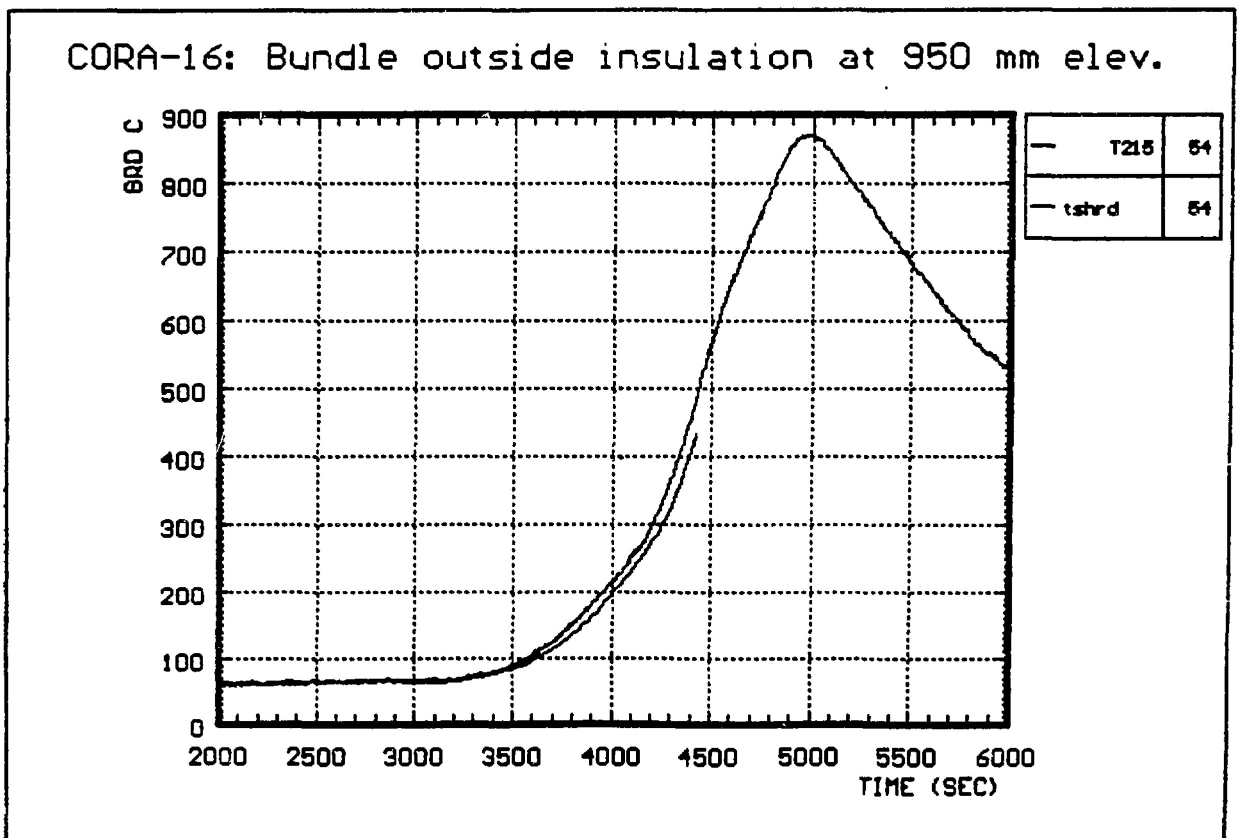
CORA-16: Heated rod 5.3 at 950 mm elevation
Temperature (°C)
Time (s)
950H5.3 3
tclado 3


CORA-16: Unheated rod 2.4 at 950 mm elevation
Temperature (°C)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
2000
2500
3000
3500
4000
4500
5000
5500
6000
Time (s)
950U2.4
2
tclado
2

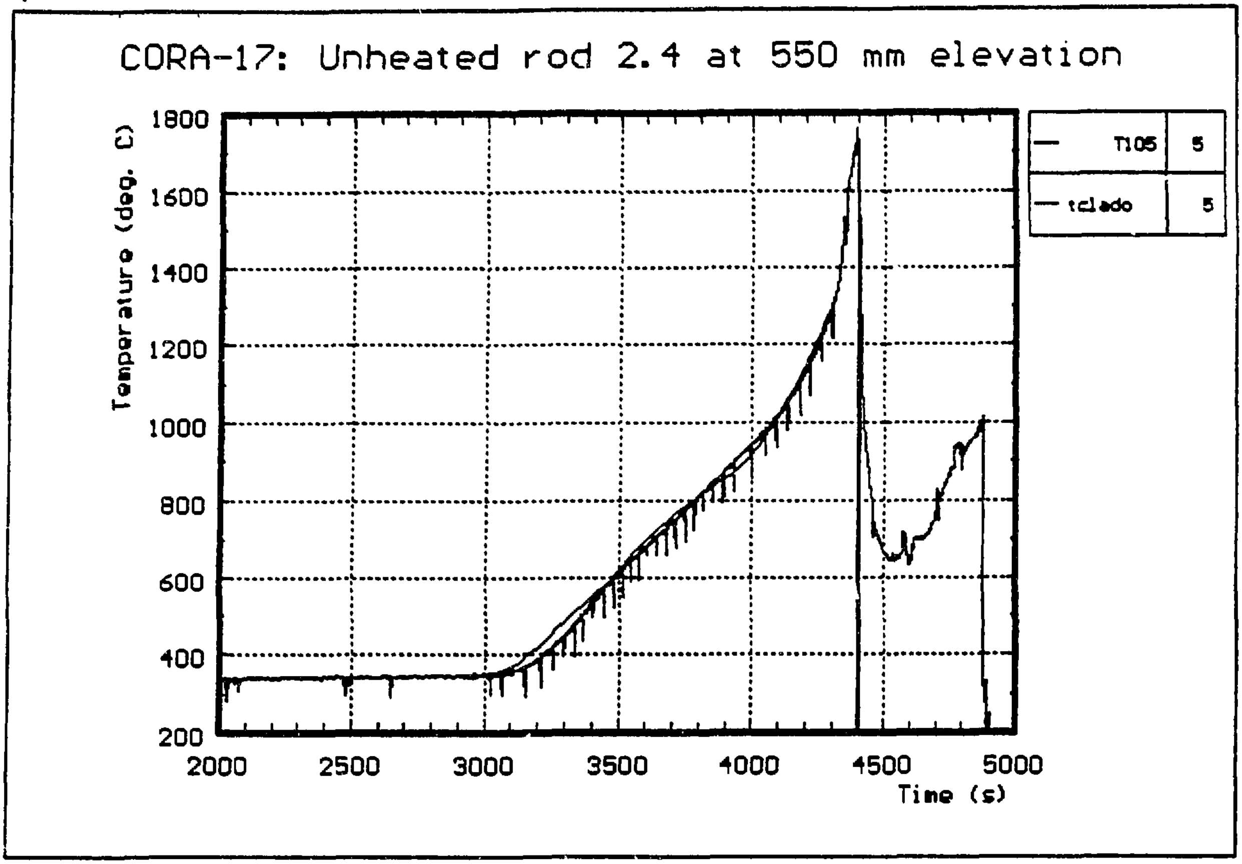

CORA-16: Channel wall at 950 mm elevation
Temperature (°C)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
2000
2500
3000
3500
4000
4500
5000
5500
6000
Time (s)
950ShrI
16
tboxo
16

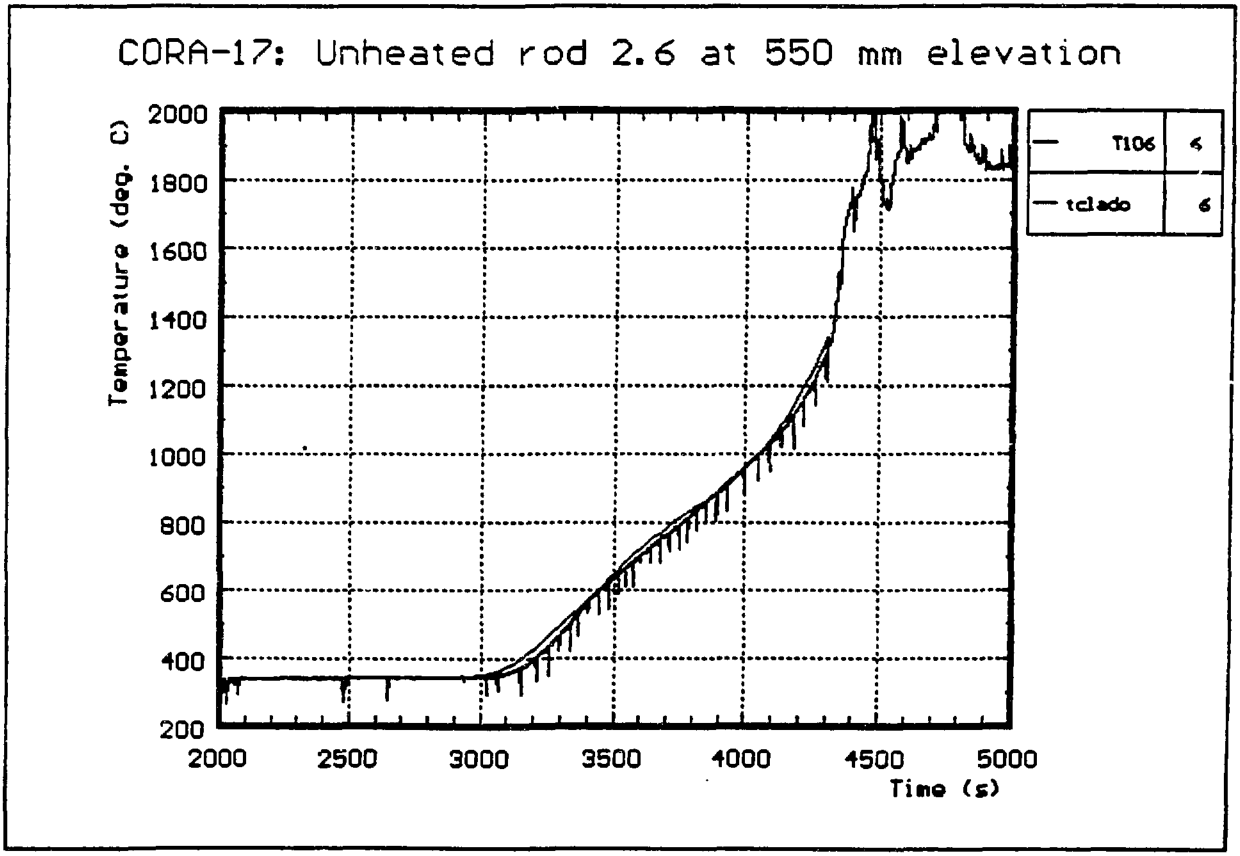


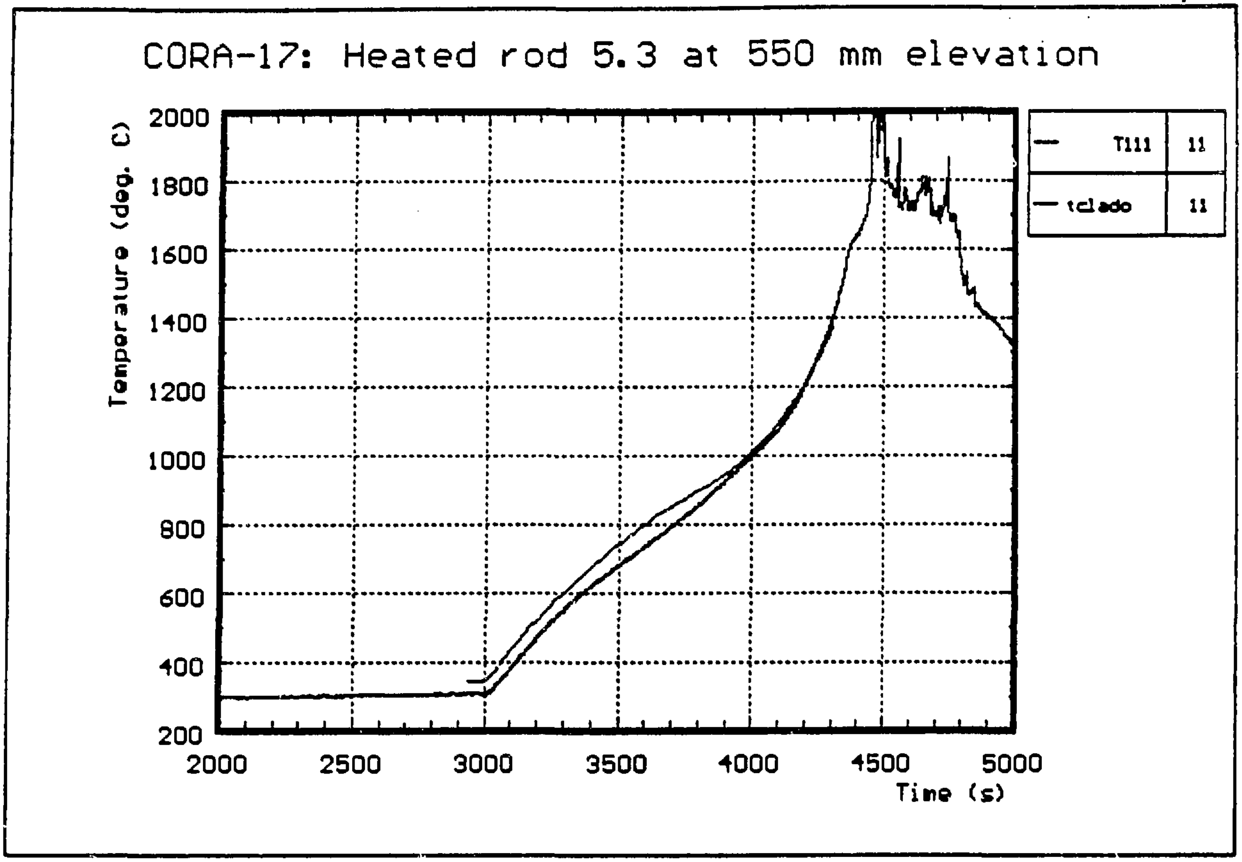
CORA-16: Absorber blade at 950 mm elevation
GRD C
TIME (SEC)
T207 46
tcb3o 46
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2000
2500
3000
3500
4000
4500
5000
5500
6000

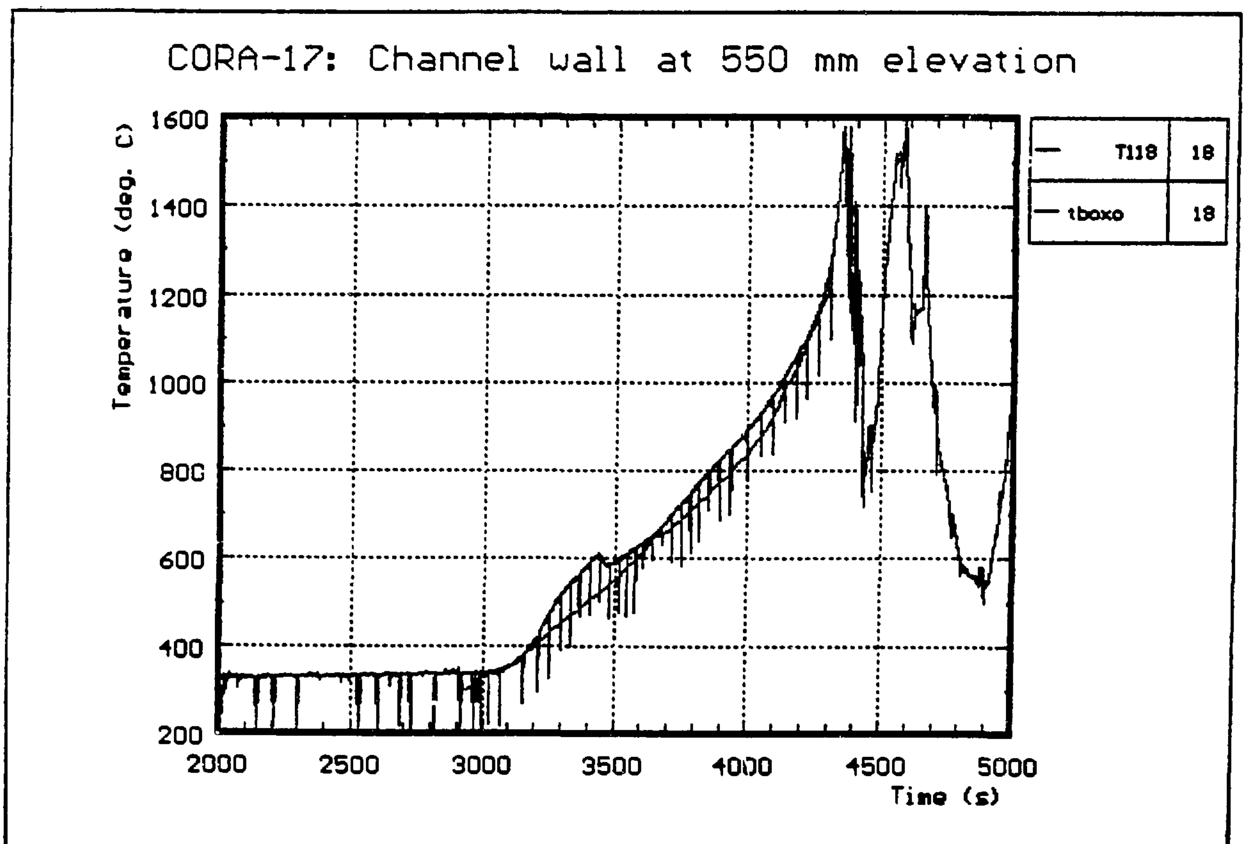


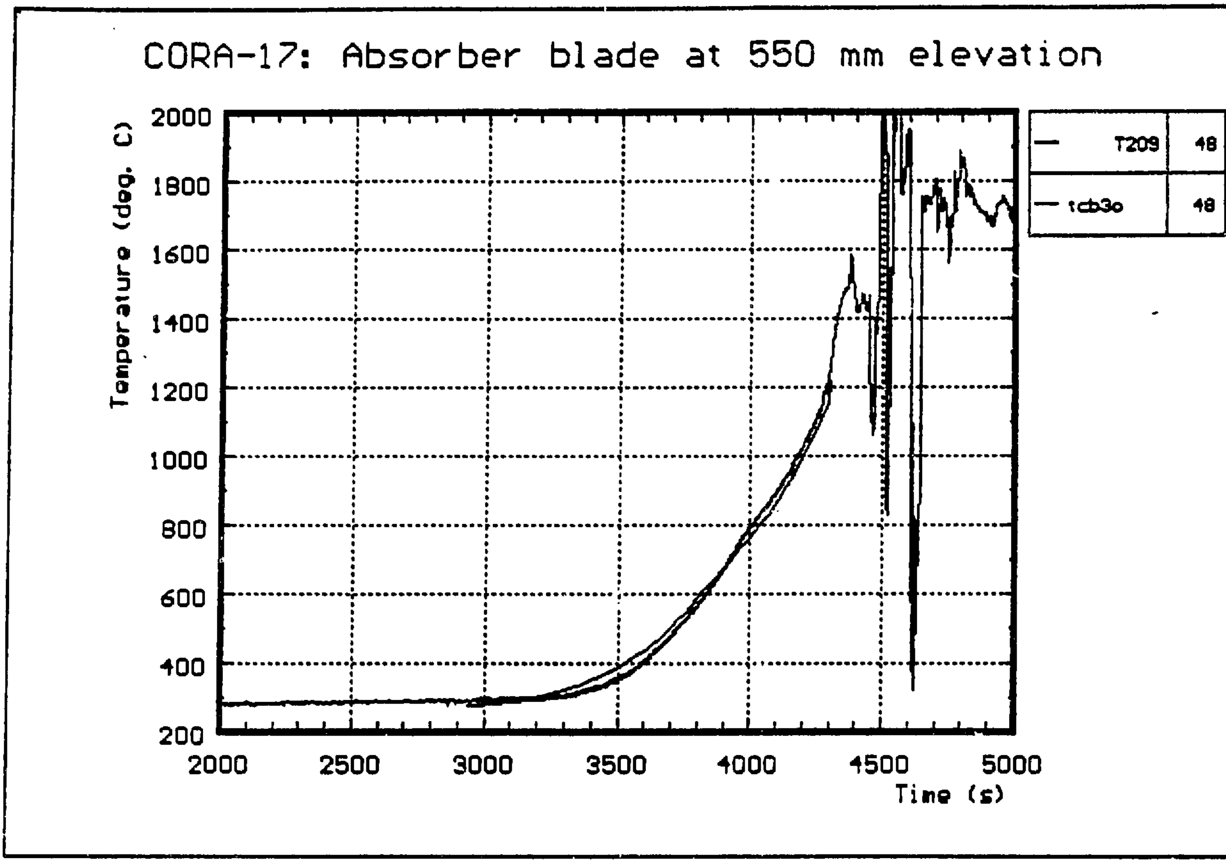
CORA-16: Bundle outside insulation at 950 mm elev.
GRD C
TIME (SEC)
T215 54
tshrd 54
0
100
200
300
400
500
600
700
800
900
2000
2500
3000
3500
4000
4500
5000
5500
6000

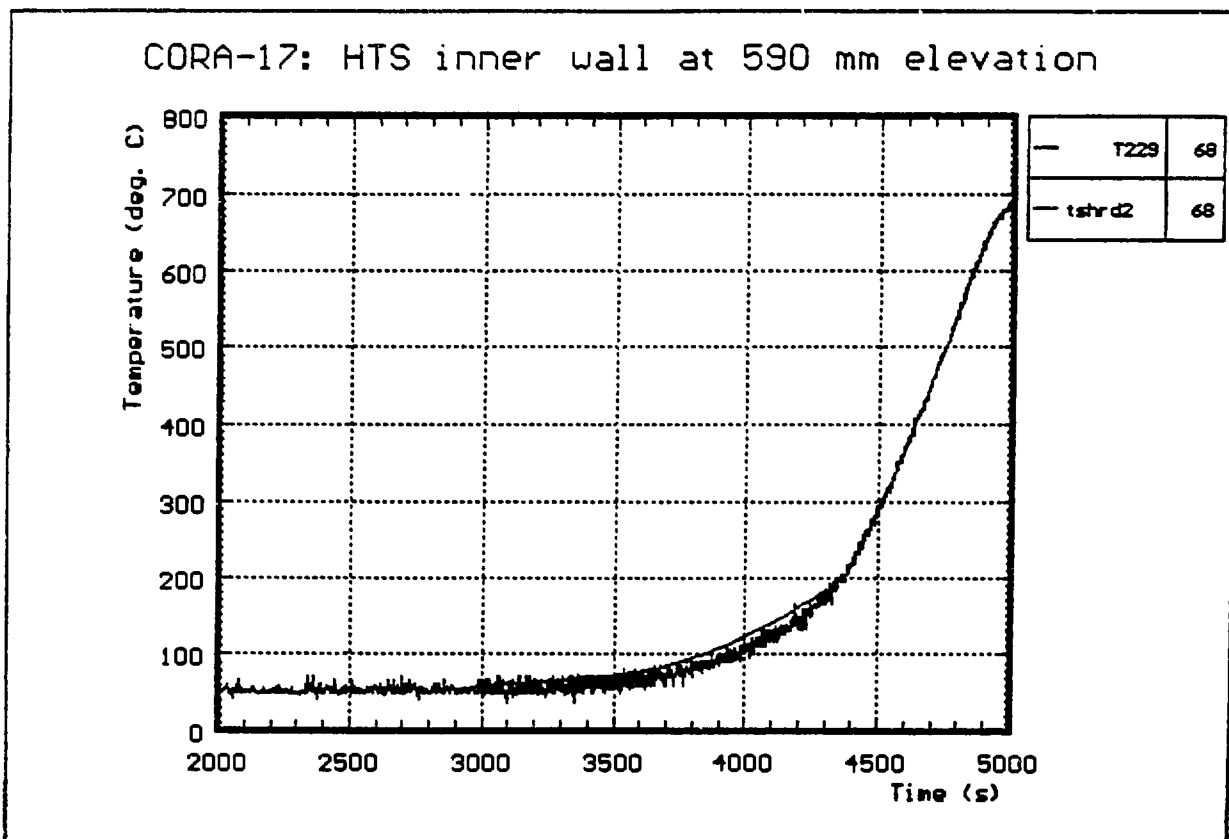

CORA-17: Unheated rod 2.4 at 550 mm elevation
Temperature (deg. C)
1800
1600
1400
1200
1000
800
600
400
200
2000
2500
3000
3500
4000
4500
5000
Time (s)
T105
5
tclado
5


CORA-17: Unheated rod 2.6 at 550 mm elevation
Temperature (deg. C)
2000
1800
1600
1400
1200
1000
800
600
400
200
2000
2500
3000
3500
4000
4500
5000
Time (s)
T106
6
tclado
6


CORA-17: Heated rod 5.3 at 550 mm elevation
Temperature (deg. C)
2000
1800
1600
1400
1200
1000
800
600
400
200
2000
2500
3000
3500
4000
4500
5000
Time (s)
T111
11
tclado
11


CORA-17: Channel wall at 550 mm elevation
Temperature (deg. C)
1600
1400
1200
1000
800
600
400
200
2000
2500
3000
3500
4000
4500
5000
Time (s)
T118
18
tboxo
18


CORA-17: Absorber blade at 550 mm elevation
Temperature (deg. C)
2000
1800
1600
1400
1200
1000
800
600
400
200
2000
2500
3000
3500
4000
4500
5000
Time (s)
T209 48
tcb3o 48


CORA-17: HTS inner wall at 590 mm elevation
Temperature (deg. C)
800
700
600
500
400
300
200
100
0
2000
2500
3000
3500
4000
4500
5000
Time (s)
T229 68
tshrd2 68

Important Results Learned From The Posttest Analyses Of The CORA-16 And CORA-17 Experiments:

- The gaseous coolant (at 2.2 bar) can be treated as a transparent non-interacting medium
- Spacers should be explicitly treated in the experimental analysis
- Available solid-state Zircaloy oxidation kinetics (Haste, Harrison, and Hindle, 'Zircaloy oxidation kinetics in the temperature range 700-1300 °C,' IAEA-TC-657/4.7, Sept. 1988) give reasonable results for CORA-17
- Cladding strain enhanced the Zircaloy oxidation in CORA-16
- Analytical simulations indicate no influence of hydrogen blanketing on Zircaloy oxidation, but do indicate steam starvation as the experiment progresses
- Thermocouple response flags material interaction
- Fuel (UO_2) electrically conducts at elevated test temperatures

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ORNL Modeling Treats The Gaseous Stream As A Gray, Interacting Medium:

- Uses Ludwig's (NASA-SP-3080) emissivity/temperature/optical length tables
- Applicability demonstrated previously:
  DF-4 experimental analyses
  ORNL BDHT experimental analyses
- Augments convective transfer
  $$h_{conv_{effective}} = h_{conv} + h_{rad}$$
- Affects structure-to-structure radiation heat transfer

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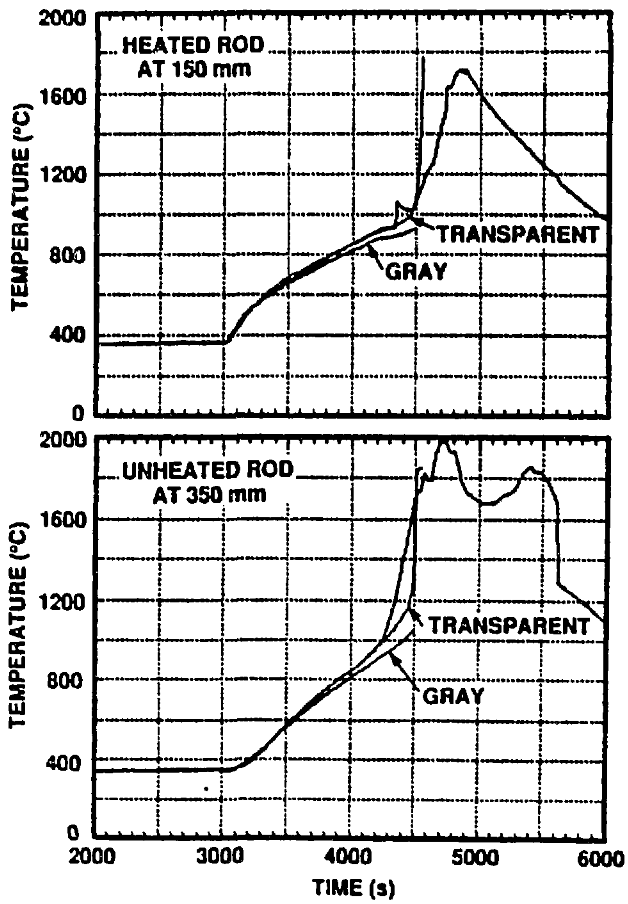
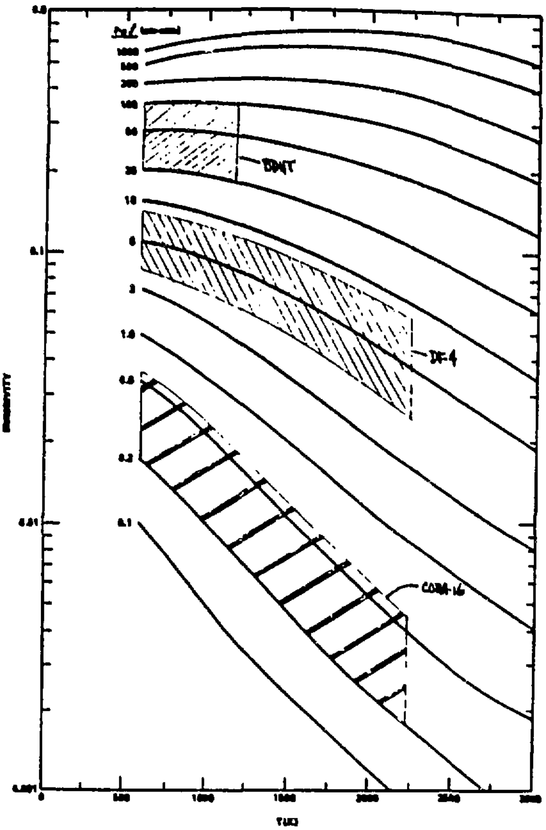
Treating The Gas Stream As A Gray, Interacting Medium Overpredicts The Convective Heat Transfer In CORA-16



Reviewing The Emissivity Data Indicates That The CORA-16 Test Conditions Are At The Low End Of The Original Ludwig Data Range:

- Computed optical lengths for CORA-16: 0.2 - 0.6 cm•atm



- For CORA-16, the gas is essentially transparent and non-interacting
- For CORA-16, Sozer's correlation adequately predicts the convective heat transfer

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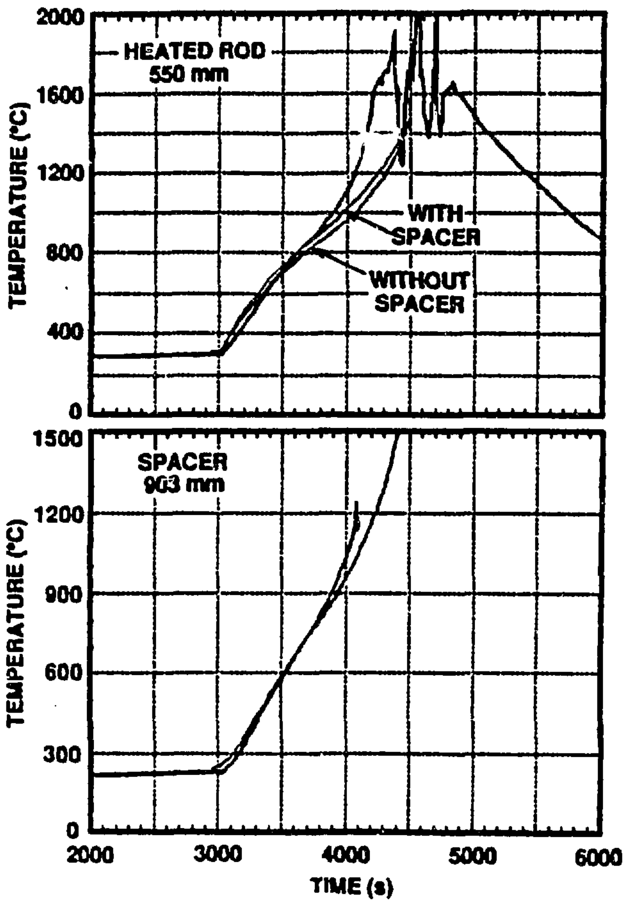
Spacers In CORA-16 Had To Be Explicitly Modeled To Achieve Reasonable Calculational/ Experimental Comparisons At The 550 mm And 903 mm Levels



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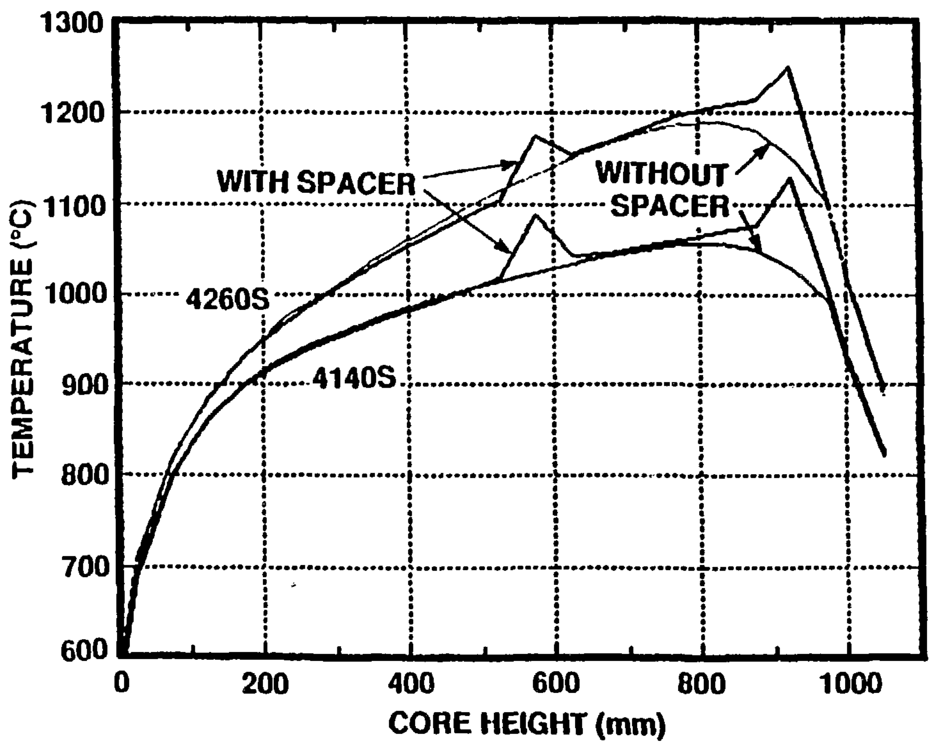
Apparently, The Spacers Act As Radiation Shields Causing Higher Local Rod Temperature



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Cladding Strain Was Not A Factor In The CORA-17 Experiment:

- 2.2 bar test section pressure
- Rod pressurization range of 3.0 - 4.8 bar
- Estimated cladding strain (using the Erbacher model)
  - at 4200s, cladding temperatures of ~ 1200 °C, ϵ_{max} ~ 0.0004
  - at 4280s, incipient structural melting occurs, ϵ_{max} ~0.004

Cladding oxidation accurately predicted by available correlations

Cladding Strain Was A Factor In The CORA-16 Experiment

- 2.2 bar test section pressure
- Rod pressurization range of 4.6 - 6.1 bar
- Estimated cladding strain (using the Erbacher model)
  - at 4200s, clad temperature range of 1000 - 1300 °C, ϵ range of 0.005 - 0.11
  - estimated cladding failure (4240 - 4320s)
- Observed cladding failure (4215 - 4310s)
- Cladding temperature at failure > 1400 °C
- Cladding strain and significant oxidation occurred simultaneously

Cladding oxidation was not accurately predicted by available correlations

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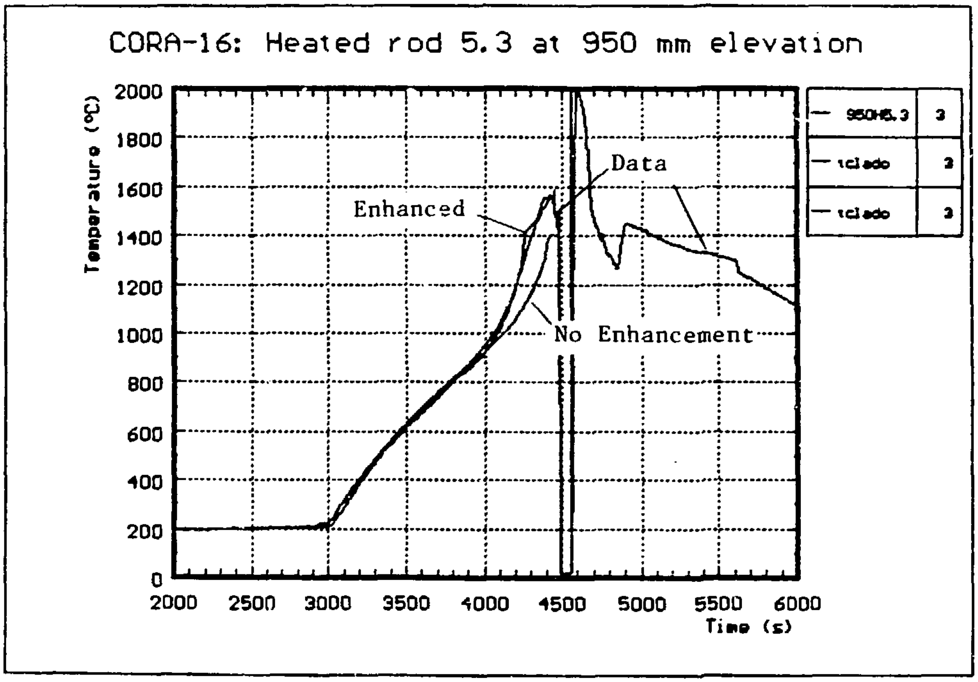
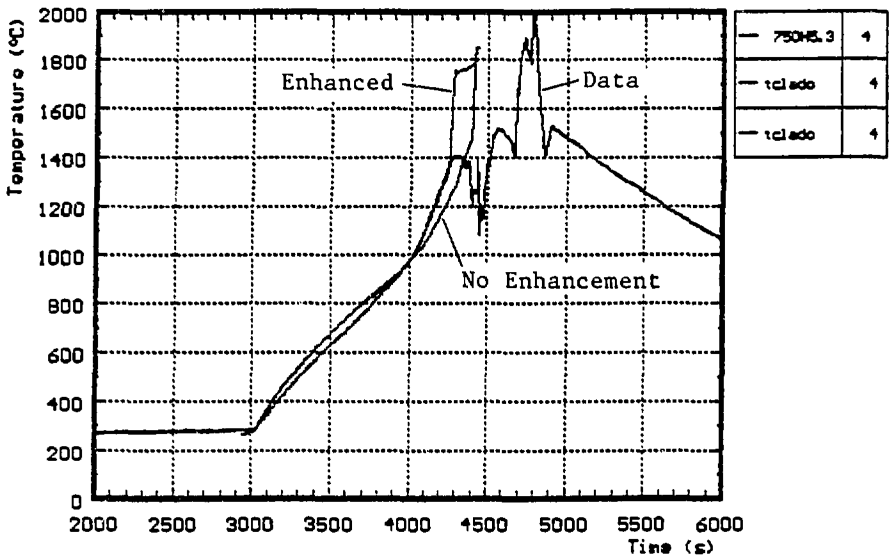
Use Of A Simple Multiplicative Factor (Function Of Strain) To Enhance The Zircaloy Oxidation Yields Reasonable Predictions For CORA-16

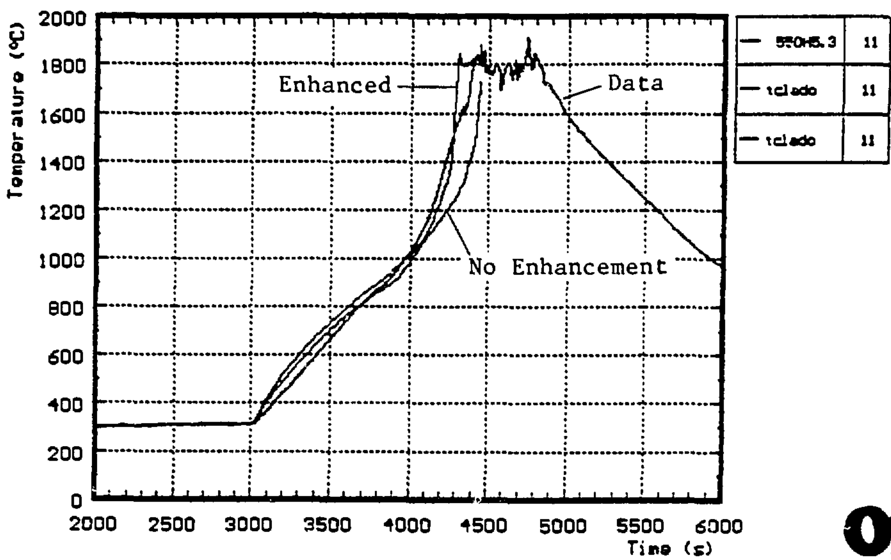


Strain Enhanced Zircaloy Oxidation
(Continued)

CORA-16: Heated rod 5.3 at 750 mm elevation



CORA-16: Heated rod 5.3 at 550 mm elevation



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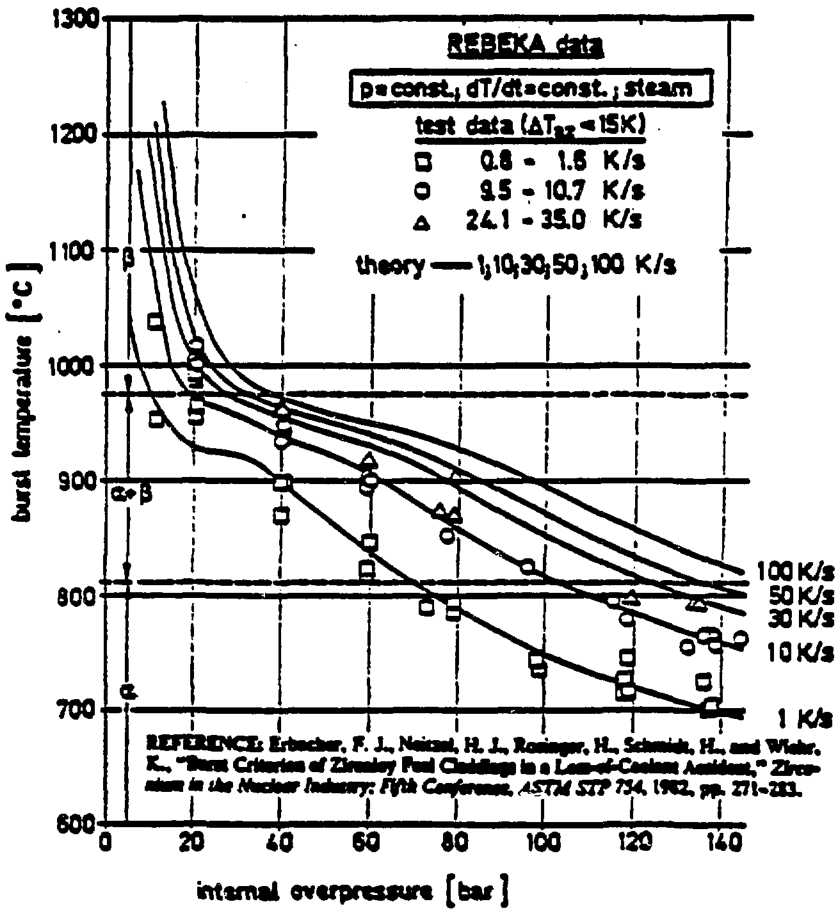
In Commercial LWR's Rod Clad Burst Would Be Anticipated For The α And $\alpha + \beta$ Zircaloy Phase Regimes



However, concurrent strain and oxidation in the β phase regime must be considered in the experimental analysis

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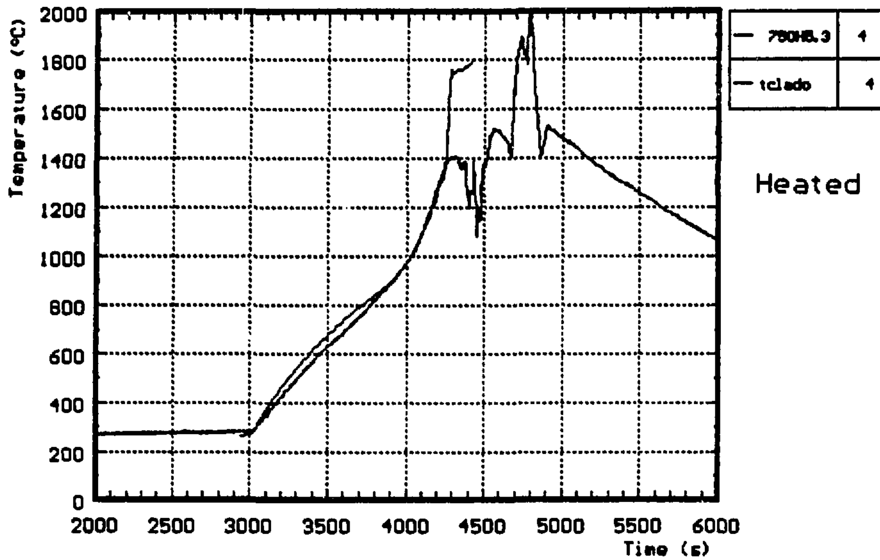
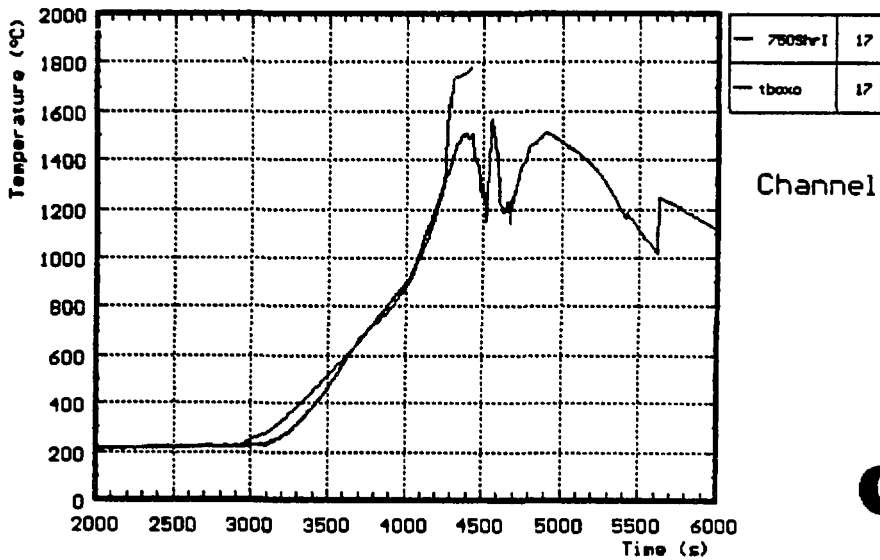
Thermocouple Response Is Sufficient To Indicate Material Relocation/Interaction; Therefore, This Data Could Be Used To Develop And Validate Material Interaction And Blockage Models

CORA-16: 750 mm elevation



Heated rod 5.3



Channel wall

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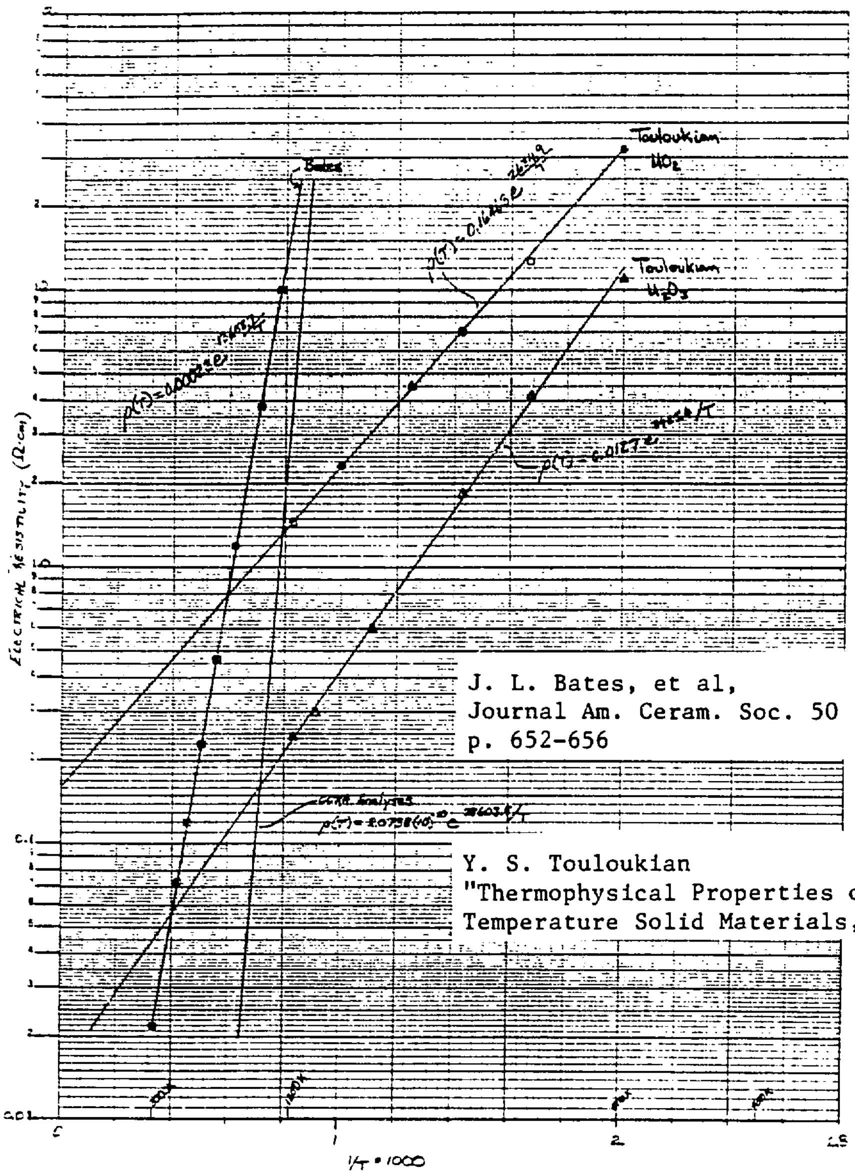
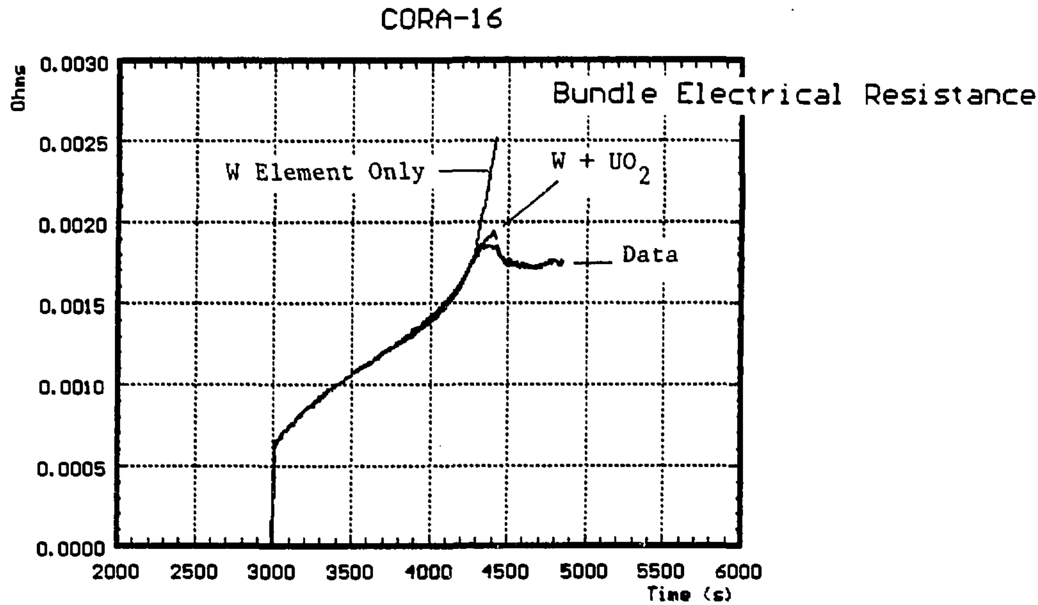
Fuel (UO_2) Electrically Conducts At Elevated Temperatures

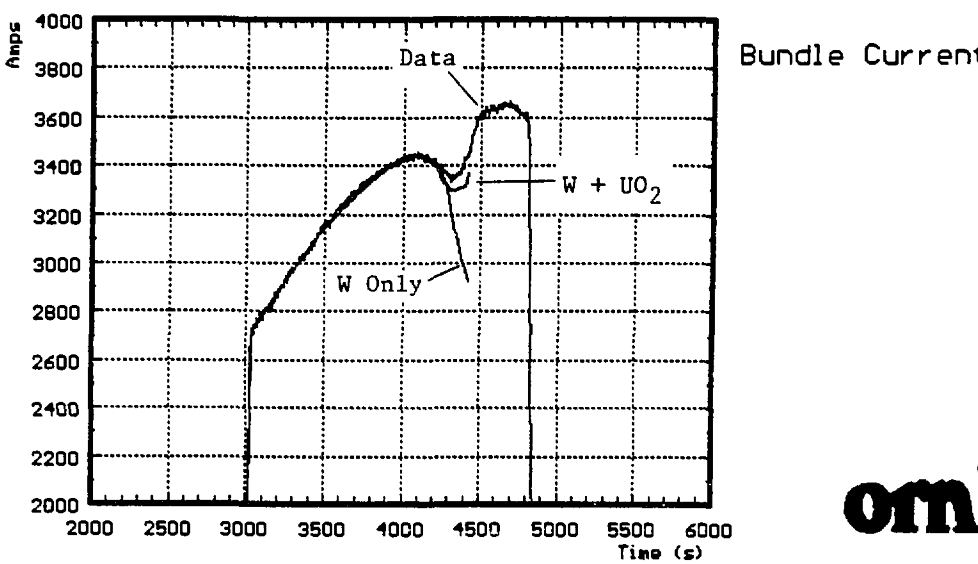


J. L. Bates, et al,
Journal Am. Ceram. Soc. 50 (12), 1967
p. 652-656

Y. S. Touloukian
"Thermophysical Properties of High Temperature Solid Materials," 1967

To Properly Account For The Spatial And Temporal Power Generation Within The Electrically Heated CORA Bundle, The Electrical Conductivity Of The Fuel Should Be Included In The Analytical Simulation





A Major Role Of Experiment-Specific Analytical Simulation Is To Provide Physics Guidance To Integrated Code Development

- Not biased by geometric modeling considerations
- Clarifies the experimental phenomena and timing of events
- Indicates what needs to be modeled and what does not, or which models work and which do not
- Provides a platform for developing and validating models that can be incorporated into integrated codes

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