NRC FORM 658
(9-1999)

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Project ~~Docke~~t Number(s)	702
Vendor ~~Plant/Fac~~ility Name	Siemens Power Corporation
TAC Number(s) (if available)	MB0575
Reference Meeting Notice	ML010170105
Purpose of Meeting (copy from meeting notice)	SPC is making a presentation to support the staff's review of topical report EMF-2403(P) Rev.0, Duplex Dx (DxD4) Cladding for PWRs.

NAME OF PERSON WHO ISSUED MEETING NOTICE: N. Kalyanam

TITLE: Project Manager

OFFICE: NRR/DLPM/PDIV-2

DIVISION:

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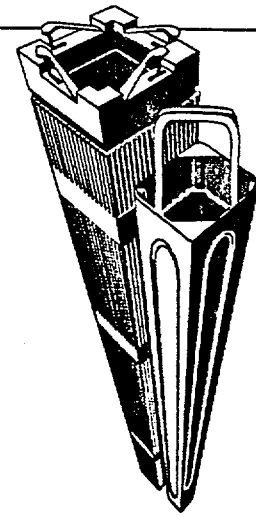
Duplex D4 (DXD4) Cladding for PWRs



Presented by: Jerry Holm
Charlie Brown
Richard Perkins

U.S. Nuclear Regulatory Commission
January 31, 2001

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Duplex D4 (DXD4) Cladding for PWRs

• Introduction and Summary	Jerry Holm
• Description of DXD4 Cladding	Charlie Brown
• DXD4 Evaluation Against SRP 4	Charlie Brown
• Corrosion at Normal Operating Conditions	
• Hydrogen	
• Fuel Rod Growth	
• Cladding Stress Evaluation	
• Fuel Performance Code Applicability	
• LOCA Items for DXD4 Cladding	Rich Perkins
• High Temperature Oxidation	
• High Temperature Creep	
• Conclusions	Jerry Holm

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Duplex D4 (DXD4) Cladding for PWRs

Introduction and Summary

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Topical Report EMF-2403(P)

- Describes the manufacture, physical characteristics, and operational performance of Duplex D4 fuel rod cladding
- Provides the technical bases and justification for the use of DXD4 cladding in PWR fuel reloads
- Requests approval for use of the cladding in PWR reload fuel up to a rod-average burnup of 62 GWd/MTU

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Duplex Cladding

- The two layer (Duplex) cladding concept allows independent optimization of mechanical performance and corrosion properties
- The mechanical performance is defined by a thick inner layer of Zircaloy-4
- The corrosion performance is defined by a thin outer layer of low tin zirconium alloy

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Summary

- Extensive Duplex clad operational experience
  - 580,000 Duplex rods in 15 PWRs
  - 21,000 Duplex rods with D4 outer layer
  - DXD4 experience up to [81] MWd/kgU rod-average
- Revised analysis model for fuel cladding corrosion
- Revised analysis model for fuel rod growth
- Confirmed applicability of Zircaloy models for other criteria
- Maximum, 95/95 confidence level, corrosion [45] microns at 62 MWd/kgU rod burnup

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Duplex D4 (DXD4) Cladding for PWRs

General Description

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Chemical Composition of Duplex D4 Cladding

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Duplex Cladding Fabrication Process Outline

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Through-Wall Treatment of Properties

- Tensile and hoop properties tested and evaluated on a section average basis
- Bending properties evaluated to show relative margin between circumferential and axial properties
- Creep properties evaluated on an average section basis confirmed by code benchmarks
- High temperature properties (for LOCA) defined by Zircaloy-4 inner layer after D4 layer is consumed by oxidation

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Duplex Cladding Operational Experience

Operating Experience of Siemens PWR Fuel with Duplex B (ELS0.8B) Cladding (April 2000)

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Duplex D4 Cladding Operational Experience

Operating Experience of Siemens PWR Fuel with Duplex D4 Cladding (April 2000)

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Duplex D4 (DXD4) Cladding for PWRs

DXD4 Cladding Evaluation Against SRP Chapter 4

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DXD4 Cladding Evaluation - Fuel System Damage

1. Design Stress	• confirm through-wall methodology
2. Design Strain	• confirm RODEX2 applicability
3. Strain Fatigue	• use Zircaloy properties
4. Fretting Wear	• no effect
5. Oxidation, Hydrogen Pick-up	• revise model
6. Rod Bow	• no effect
7. Axial Growth	• revise model
8. Rod Internal Pressure	• no effect
9. Assembly Lift-off	• no effect
10. Control Rod Reactivity	• no effect

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DXD4 Cladding Evaluation - Fuel Rod Failure

1. Hydriding (Internal)	• no effect
2. Cladding Collapse	• confirm Zircaloy model conservatism
3. Overheating of Cladding	• no effect
4. Overheating of Fuel Pellets	• no effect
5. Pellet-Cladding Interaction	• no effect
6. Clad Rupture and Ballooning	• confirm equivalence to Zircaloy
7. Fuel Rod Mechanical Fracturing	• no effect
8. Excessive Enthalpy	• no effect

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DXD4 Cladding Evaluation - Fuel Coolability

1. Fragmentation of Embrittled Cladding	• confirm equivalence to Zircaloy
2. Violent Expulsion of Fuel	• no effect
3. Cladding Ballooning	• confirm equivalence to Zircaloy
4. Assembly Structural Damage from External Forces	• no effect

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Duplex D4 (DXD4) Cladding for PWRs

Corrosion at Normal Operating Conditions

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DXD4 CORROS II Corrosion Model

- DXD4 oxidation is fitted with a second transition model with increased corrosion rate above [25] microns
- Model is incorporated in RODEX2
- Oxide data is well predicted to [72] MWd/kgU
- Design limit is changed from [130 microns peak to 118 microns maximum running average]

DXD4 Cladding Oxide Thickness Data

Oxide Measurement Techniques

- Spiral trace
  - Data reduced as maximum running average over 40 mm
  - Majority of DXD4 data
- Side insertion point measurements
  - Four sides of each rod measured twice
  - Measurement at center of maximum oxide span
  - Data averaged around rod circumference
- Linear trace
  - Data reduced as peak at maximum location
  - Correlation developed to relate peak to maximum running average used in DXD4 evaluation

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Peak to Max Running Average Oxide Adjustment

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Fuel Rod Power History

DXD4 Standard Siemens Model Oxide Thickness Prediction

DXD4 Axial Oxide Profile

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Oxide Thickness Prediction of DXD4 Cladding

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CORROS II Calculated Oxide Thickness Profiles

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Corrosion Behavior of DXD4 Cladding

- Conclusions:
  - Corrosion model accurately predicts the oxide thickness of DXD4 cladding up to [ ] MWd/kgU
  - Model includes a second-transition subroutine that models the increase in oxide growth occurring late in life
  - The following parameters have been established for the corrosion of DXD4
    - Corrosion parameter
    - Second-transition multiplier
    - Oxide thickness at second transition

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Duplex D4 (DXD4) Cladding for PWRs

Hydrogen

Hydrogen Pick-up

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Hydride Distribution in Zircaloy-4 Cladding

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Hydride Distribution in DXD4 Cladding

[ ]

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Duplex D4 Hydrogen Pick-up

- Conclusions:
  - The hydrogen pick-up fraction of DXD4 is approximately [ ]
  - Hydrides accumulate in the coldest part of the cladding wall similar to the accumulation observed for Zircaloy-4 cladding
  - The hydrides in DXD4 precipitate mainly in the tangential direction

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Duplex D4 (DXD4) Cladding for PWRs

Fuel Rod Growth Model

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DXD4 Clad Growth Summary

- DXD4 axial growth to high burnup is less than the Zircaloy design bound
- Optimized Zircaloy-4 growth is less than the design bound
- Combined projection of optimized and DXD4 clad covers projected batch variation on growth and is conservative relative to DXD4 data

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Optimized Zircaloy-4 Fuel Rod Growth

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Duplex D4 Fuel Rod Growth

Upper Bound Zircaloy-4 and DXD4 Fuel Rod Growth

Fuel Rod Axial Growth

- Conclusions:
  - DXD4 and Optimized Zircaloy-4 rod axial growth results are combined in a single correlation
  - There is an improvement of [ ] (less growth) for DXD4 clad maximum growth projections relative to standard Zircaloy-4 rods
  - The correlation is conservative relative to the high-burnup DXD4 data

Duplex D4 (DXD4) Cladding for PWRs

Cladding Stress Evaluation

Clad Stress Evaluation

- Stress limits are based on minimum specified through-wall tensile strength
- Stresses evaluated assuming through-wall properties
  - For measurement convenience
  - To use existing evaluation methods
- Conservatism in circumferential strength relative to tensile test accommodates reduced bending strength due to Duplex outer layer

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Deformed Tube Samples Between Plates

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Load - Deflection of DXD4 Tubes at 382°C

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Duplex and Through-Wall Strength Ratios

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Summary of Stress Evaluation

- Stress criteria specified on same tensile test basis as Zircaloy
- Duplex clad stresses calculated on through-wall basis compared to specified through-wall strength
- Conservatism in circumferential strength relative to tensile test accommodates reduced bending strength due to Duplex outer layer

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Duplex D4 (DXD4) Cladding for PWRs

Fuel Performance Code Applicability

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Fuel Performance Code Applicability for DXD4

- RODEX2 is applied as for Zircaloy-4 Clad PWR fuel
  - Strain
  - Gas pressure
  - Corrosion (CORROS II model implemented)
  - Temperature
  - Initial conditions for LOCA
- COLAPX is applied as for Zircaloy-4 PWR fuel

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Summary of Performance Code Applicability to DXD4 Fuel Rods

- Pellet models are unaffected by DXD4 clad
- Clad modulus, strength, creep and conductivity models are equal to Zircaloy-4
- Measured thermal creep is within Zircaloy parameters
- Calculated irradiated creep strain using Zircaloy properties is verified against rod measurements
- Nominal RODEX2 growth for Zircaloy and DXD4 growth are about equal
- Clad corrosion model is revised per DXD4 correlation
- Creep ovality is confirmed

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Thermal Creep of DXD4

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RODEX2 Measured and Calculated DXD4 Strain

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Summary of RODEX2 Application to DXD4 Rods

- RODEX2 models for PWR analysis remain applicable for rods with DXD4 cladding
- Sample problem results show very small differences between existing Zircaloy-4 and DXD4 rod analysis due to lower DXD4 oxidation resulting in slightly lower temperatures
- Corrosion design margins improve substantially

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Duplex D4 (DXD4) Cladding for PWRs

LOCA Items for DXD4 Cladding

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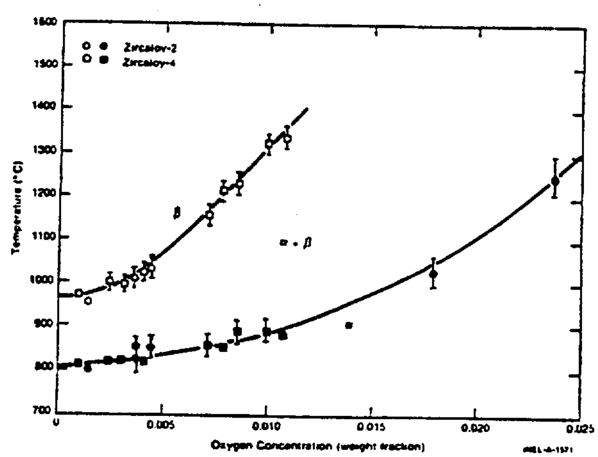
Introduction

- High Temperature Steam Oxidation
  - During a LOCA event, the cladding temperature shall remain less than 2200°F (1204°C)
  - Less than 17% Equivalent Cladding Reacted (ECR) shall be experienced
  - The behavior of Duplex cladding should be equivalent to Zircaloy-4 through-wall cladding
- High Temperature Cladding Creep Rupture
  - Cladding will balloon at high temperature in a Loss-of-Coolant Accident (LOCA)
  - Ballooning (hoop strain) will affect the cooling of the core
  - Time-to-failure of Duplex cladding should be equivalent to that of Zircaloy-4 through-wall cladding (time-to-failure)

High-Temperature Oxidation (LOCA Conditions)

- Reaction of zirconium alloy cladding with steam above 800°C
  - ZrO_2 oxide layer is formed at the outer surface
  - An oxygen stabilized α-Zr layer is formed beneath the oxide layer
  - The inner portion of the cladding remains in the β or α + β phase
- The mechanical strength of the cladding is provided by the inner portion

Phase Diagram for Oxygen in Zircaloy



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Mechanical Strength of the Oxidized Cladding is Dependent Upon the Unreacted Material

- Outer oxide layer provides no strength
- α-Stabilized Zircaloy layer has a high oxygen solubility, so it is brittle and provides no strength
- β-Zircaloy has a lower oxygen solubility, so it remains ductile
- The Duplex layer will be consumed in the oxide and α-Zircaloy layer
- β and $\alpha + \beta$ phase material will be Zircaloy-4 for DXD4

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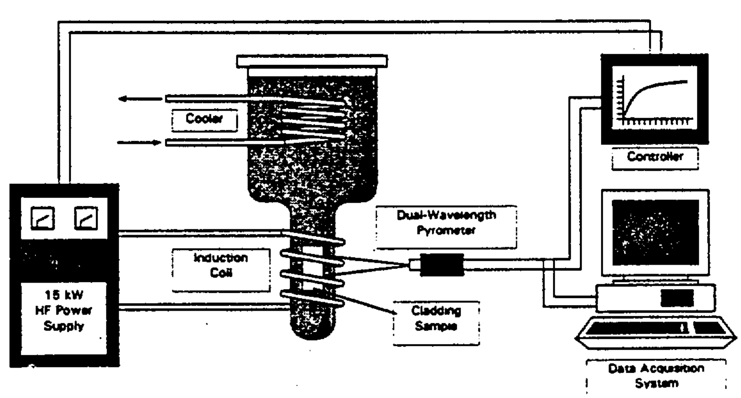
High-Temperature Steam Oxidation Apparatus



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Oxidation of Throughwall Zircaloy-4 Cladding

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Oxidation of DXD4 Cladding

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Comparison of Oxygen-Stabilized α-Layer on Inner and Outer Surfaces of DXD4 Cladding

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Oxidation Layers on DXD4 Cladding for 10 Minutes at 1050°C

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Comparison of Through-wall Zircaloy-4 and DXD4 Cladding Oxidation

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Comparison of Oxide on the Inner and Outer Surfaces of DXD4 Cladding

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Oxidation Layers on DXD4 Cladding for 10 Minutes at 1150°C

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Oxidation Layers on DXD4 Cladding for 1 Minute at 1150°C

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Conclusions for High Temperature Steam Oxidation

- Comparable weight gains (corrosion) and oxygen penetration are obtained for through-wall Zircaloy-4 and Duplex DXD4 cladding during high temperature (1050-1250°C) oxidation
- No differences in quench behavior (fracture) between Zircaloy-4 and DXD4 cladding are seen
- Applicability of the 2200°F (1200°C) and 17% ECR criteria of 10 CFR 50.46 to DXD4 cladding have been confirmed
- High-temperature metal-water reaction correlations established for Zircaloy-4 can be used for DXD4 cladding

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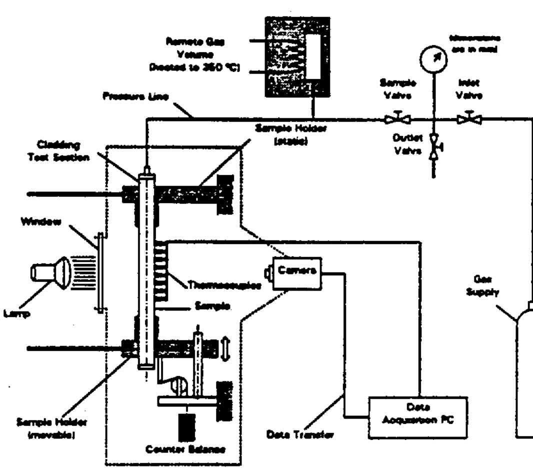
High Temperature Creep Rupture Performance

- Ballooning (hoop strain) of DXD4 cladding must be similar to that of Zircaloy-4 through-wall cladding to maintain the same ability to cool the fuel during a LOCA event
- Time-to-rupture for DXD4 cladding must be equivalent to or greater than that of Zircaloy-4 cladding so that the number of failed rods does not increase during a LOCA event

Characteristics of the Creep Rupture Test

- Internally pressurized cladding samples are maintained at a constant pressure during the test after about a 15 second ramp up
- Constant pressure is maintained by using a heated gas reservoir
- Hoop strain rate is slow for most of the test but increases rapidly late in the test
- Zircaloy goes through a phase change at about 800°C
  - α-Zircaloy exists up to about 800°C
  - $\alpha + \beta$ phase range exists between about 800 and 950°C

Creep Rupture Test Apparatus



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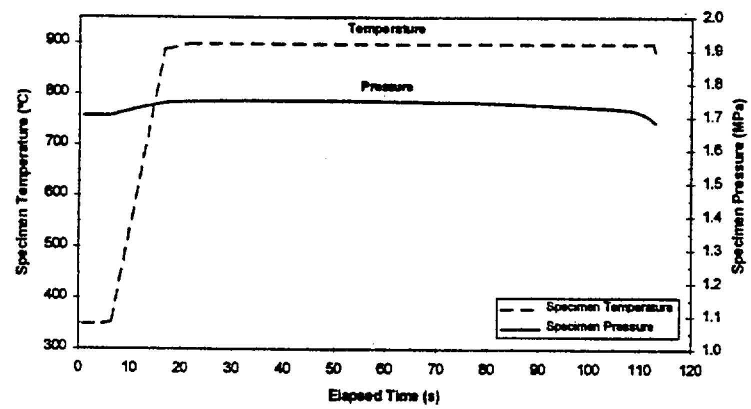
Temperature and Pressure versus Time in Creep Rupture Test



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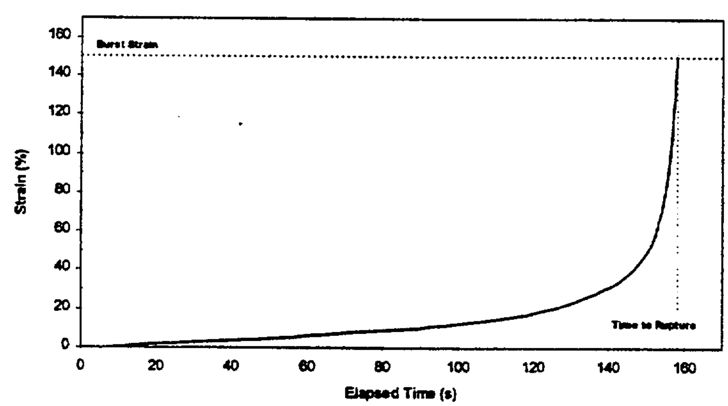
Circumferential Strain versus Time During a Creep Rupture Test



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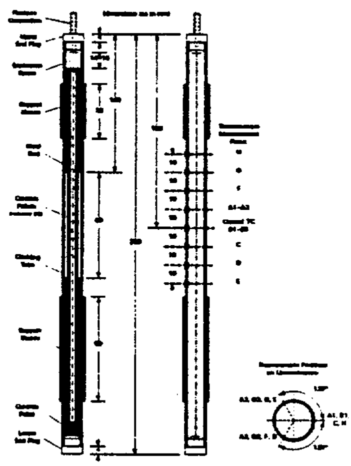
Creep-Rupture Test Apparatus



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Time to Rupture of Low-Tin Zircaloy-4 Cladding

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Hoop Strain at Rupture of Std-Tin Zircaloy-4 Cladding

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Hoop Strain at Rupture of Low Tin Zircaloy-4 Cladding

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Time to Rupture Tests of Std-Tin and Low-Tin Zircaloy-4 Cladding

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Time to Rupture of Duplex Cladding (DXD4 and Other Duplex Variants)

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Hoop Strain at Rupture of DXD4 and DXB Cladding

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Conclusions for Creep Rupture Performance

- Time-to-rupture of DXD4 cladding over the testing temperature range of 600-900°C is identical to the time-to-rupture of Zircaloy-4 cladding
- The hoop strain at rupture of DXD4 cladding samples is the same or smaller than the rupture strain of through-wall Zircaloy-4 cladding
- It is conservative to model the rupture behavior of DXD4 cladding with the same parameters as used for Zircaloy-4 cladding in LOCA analyses

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Conclusions

- Siemens has demonstrated the acceptability of DXD4 cladding for PWRs
- Siemens has a significant amount of operating experience with Duplex cladding
- DXD4 cladding can be treated as Zircaloy-4 for most criteria
- DXD4 has improved behavior for:
  - Corrosion at normal operating conditions
  - Fuel rod growth