Attachment 2
NRC Slides

High Burnup (HBU) Fuel Overview

U.S. Nuclear Regulatory Commission
Washington D.C.
March 5, 2002

High Burnup (HBU) Fuel Overview

- December, 1999 NRC/NEI Meeting on Generic Issues
- HBU #1 on Generic Issues Priority List
- NRC/NEI Conducted Several Public Meetings
- Staff Revised ISG 11 in May 2000
- Staff Requested Additional Data to Support ISG Revision
- Staff Has Approved HBU > 45 Gwd/MTU
- NEI Submittals in December 1999 and January 2000
- Staff Feedback In A Meeting on 4/18/2001
- NEI Submittals in August 2001 and November 2001

NRC Staff Review of NEI/EPRI Reports On Creep of High Burnup Zircaloy SNF Cladding

NRC/NEI-Industry Meeting on High Burnup Fuel Dry Storage Issues

March 5, 2002

Scope of Discussion

1. NEI's response of 8/16/2001
   a) Response to NRC's RAI letter, dated May 18, 2001.
   b) Attachment 2, "Creep as the governing mechanism of spent fuel in dry storage", Y.R. Rashid and A.J. Machiels
2. NEI's response of 10/2/2001

   "Creep modeling and analysis methodology for spent fuel in dry storage", Y.R. Rashid and R.S. Dunham, EPRI Report No: 1003135
3. Status of staff effort on potential revisions to ISG-11/15

NEI's Response to NRC Staff's RAI

NEI's response of 8/16/2001 to NRC's RAI letter, dated May 18, 2001

- **The answers to majority of the RAI questions are acceptable**
- **Questions remain with respect to the role of zirconium hydrides in ensuring cladding reliability.**
  - **Thermodynamics and kinetics of hydrides in zircaloy**
  - **The strength of spalled cladding - the role of hydrides**
  - **Influence of burnup on hydrides - the extent of reorientation achievable**

Discussion on Attachment 2

"Creep as the governing mechanism of spent fuel in dry storage", Y.R. Rashid and A.J. Machiel

The salient points:

- Both strain and stress should be defined for acceptance criterion formulation
- Heat decay analysis – input for peak cladding temperature

  Fuel rod parameters – input for cladding stress

  Cladding creep model – post-irradiation

  Fluence effects, Hydrogen effects, Irradiation-damage annealing
- Fuel rod behavior (finite element/difference) code – FALCON

  "Bench-marked" using ABAQUS

Discussion on Attachment 2 (Continued)

"Creep as the governing mechanism of spent fuel in dry storage", Y.R. Rashid and A.J. Machiel

Staff's observations:

- No additional creep data, other than those contained in earlier report, relevant to dry storage of HBF were considered
- Major focus seems to be plastic instability near yield strength of the material for failure
- The theoretical predictions (FALCON) of Figure 4 needs support from experiments with similar hydride concentration and creep conditions
- Staff did not conduct a methodology review of the computer models and code in Attachment 3

NEI's Response of 10/2/2001

"Creep modeling and analysis methodology for spent fuel in dry storage", Y.R. Rashid and R.S. Dunham, EPRI Report No: 1003135

The salient points:

- Both strain and stress should be defined for acceptance criterion formulation
- Thermal analysis – input for peak cladding temperature

  Fuel rod parameters – input for cladding stress

  Cladding creep model – post-irradiation

  Fluence effects, Hydrogen effects, Irradiation-damage annealing
- Fuel rod behavior (finite element/difference) code - FALCON

Comments on EPRI Report No: 1003135

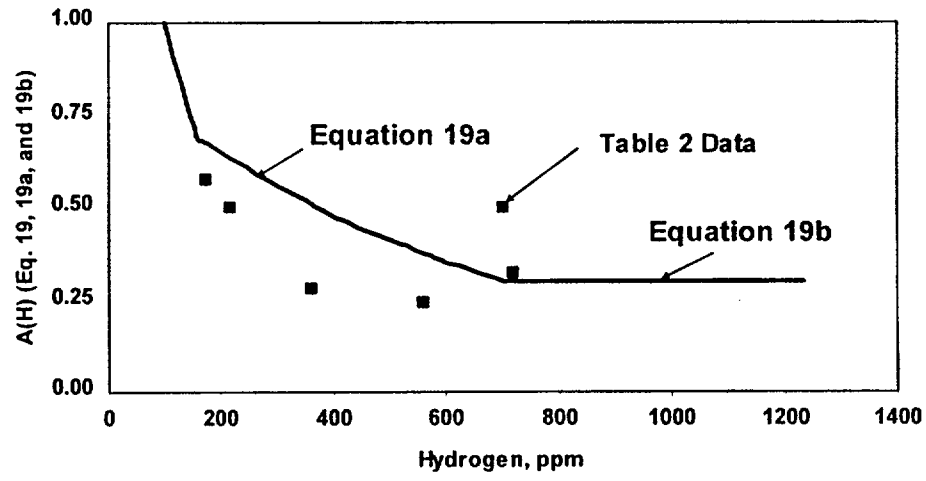
Strengths

- **Potentially comprehensive creep model that encompasses the effects of**
  - **Post-irradiation (fluence)**
  - **Hydrogen**
  - **Oxidation**
  - **Irradiation-damage annealing during creep**
- **Additional and concurrent criterion - relative stress (Cladding stress/Yield stress)**
- **Development of concept for estimating expected relative damage during dry storage (pseudo-probabilistic)**

Creep Modeling

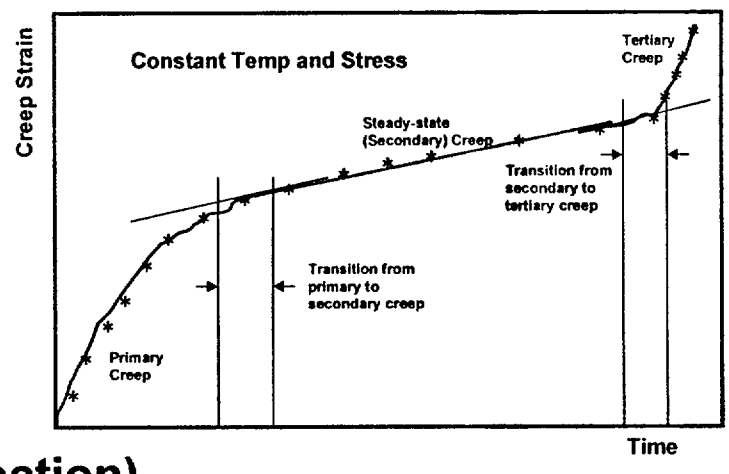
EDF-CEA Model (3) has been chosen

- Role of primary creep
- Role of hydrogen
- Role of potential annealing – MATPRO and FALCON



Modeling Creep Rupture

- Understanding terminology (plastic instability and damage due to creep)
  - Nominally constant stress (secondary stage)
  - Rapidly increasing stress (tertiary stage)
  - Failure potentially possible without (considerable) necking (reduction in cross section)

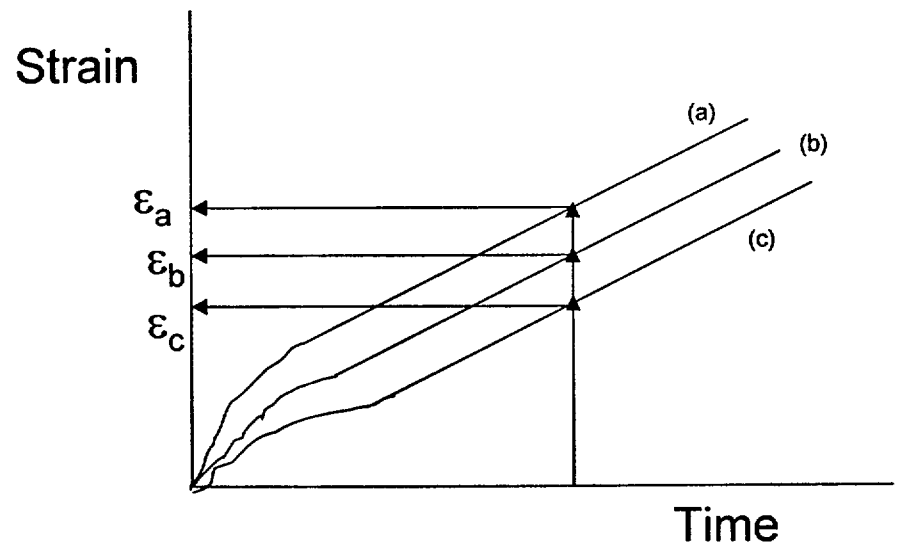


- Role of flaws
  - Failure well below yield (fracture mechanics)

Estimating Damage Due to Creep

The model to estimate damage index, likely, needs additional development

- **The life fraction rule does not consider primary stage strain contribution, which could be substantial for dry storage**



Estimating Damage Due to Creep (Continued)

- There is recognition (page 19 of the report) that:
  - Strain hardening due to creep will increase rupture time significantly (Leading to uncertainties in rupture models)
  - Role of defects (stress concentrations)
- Potential contradiction to damage index estimation assumptions, which uses life fraction rule
- Substitution of "time-to-failure" with "time-to-yield" (Changes in operating mechanisms)

Stress Limit For the Cladding

NEI/EPRI propose limiting the cladding stress be limited to less than 2/3 of the irradiated yield strength

- Is it tensile or burst yield strength?
- What is the relationship between the two? Which is more appropriate for the dry storage conditions?
- How should the scatter in strength be considered?
  - Origin of scatter (Flaws versus "true" strength)
  - Hydrogen effects
  - Specimen volume effects
  - Statistical treatment

FALCON – Finite Element Creep Model

The staff did not conduct any methodology review of the creep or other models in the report, including any code verification or calculation.

Summary of Staff's Review

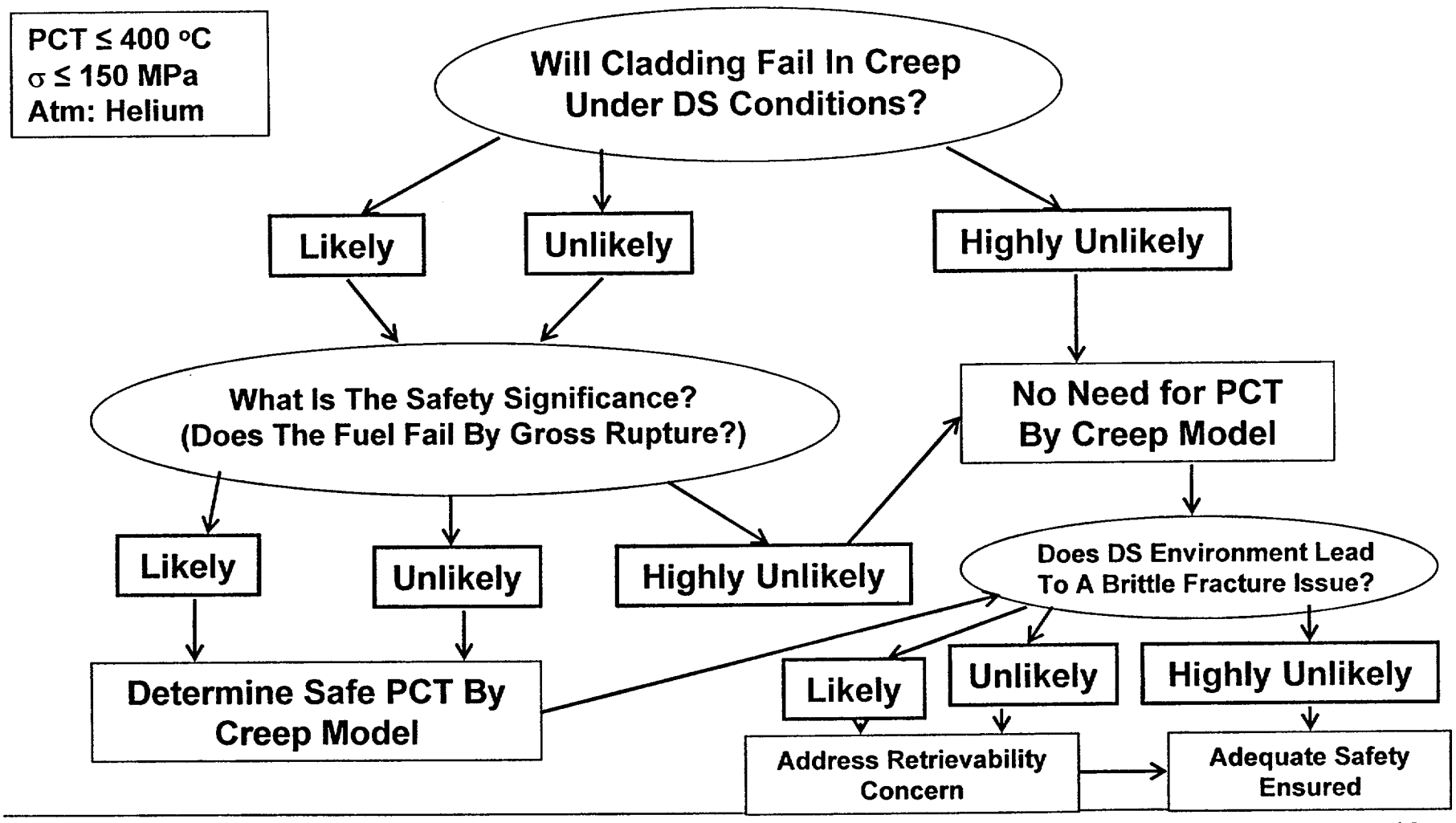
- The EDF-CEA creep model, which has been used in FALCON, attempts to make a comprehensive consideration of the effects of (a) irradiation (fluence), (b) hydrogen, and (c) potential annealing during dry storage
- Damage index estimation needs further development

Status of Staff Efforts On Potential Revision to ISG-11/15 on High Burnup Fuel

Based on recently available creep literature on high burnup fuel, NEI/EPRI reports, and Industry topical reports, the staff is reviewing the relevance and need for:

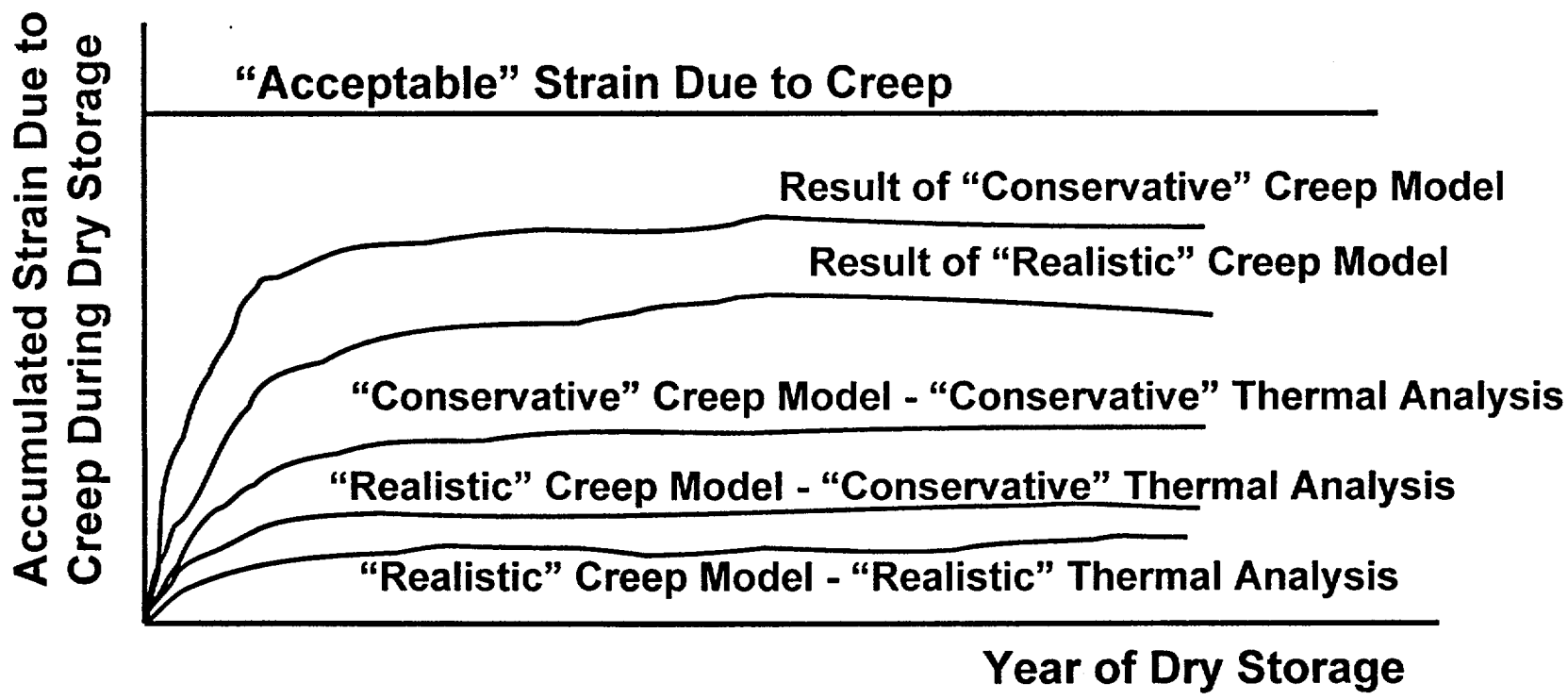
- Calculating peak cladding temperature for zircaloy cladding limiting the cumulative creep strain during dry storage to 1 percent
- Oxide thickness limitations
- Evaluation of operative mechanisms during dry storage
- Understanding potential changes in cladding properties during dry storage that will affect subsequent retrieval of the fuel

What Is the Safety Concern for HBF?



How "Conservative"/"Realistic"? How Much "Safety Margin"?

Schematic Behavior Only

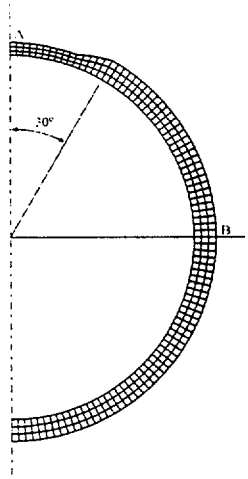


Attachment 3

EPRI Slides

(Machiels/Rashid)

Behavior of High Burnup Fuel in Dry Storage Applications



Presentation to:

Spent Fuel Project Office

Washington, DC

March 5, 2002

Albert Machiels, EPRI

Joe Rashid, ANATECH

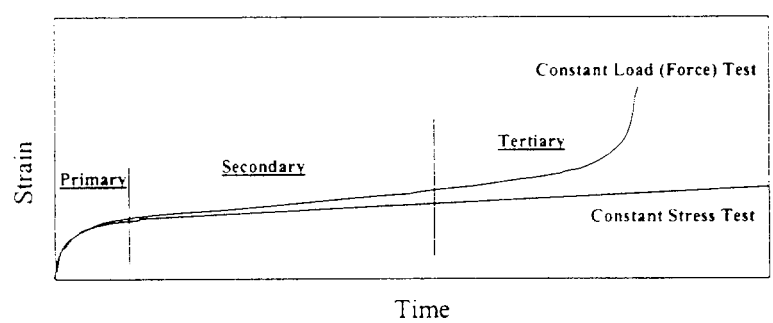
Documents Submitted to NRC

- EPRI Documents submitted to SFPO by NEI
  - "*Creep as the Limiting Mechanism for Spent Fuel Dry Storage*" [1001207] provided to NRC on December 4, 2000
  - "*Fracture Toughness Data for Zirconium Alloys -- Application to Spent Fuel Cladding in Dry Storage*" [1001281] submitted to NRC on January 6, 2001
  - Responses to NRC's Request for Additional Information submitted to NRC on August 16, 2001
  - "*Creep Modeling and Analysis Methodology for Spent Fuel in Dry Storage*" [1003135] submitted to NRC on October 2, 2001

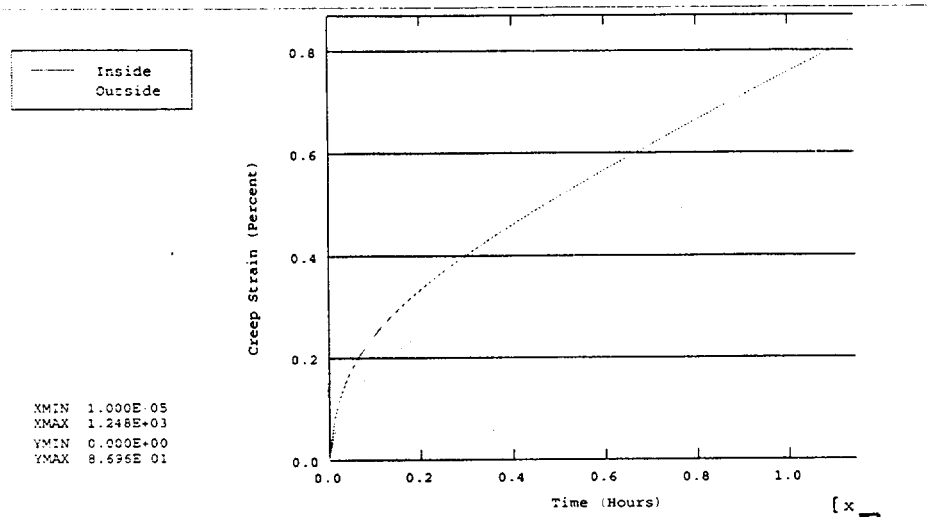
Results from these Documents

- Creep is the limiting mechanism
- Occurrence of creep rupture during dry storage is a remote possibility as long as cladding hoop stresses remain below cladding yield strength throughout the storage duration (avoid plastic instability associated with "tertiary" creep)
  - Cladding strain is not a particularly useful figure-of-merit when this criterion is maintained
- Should excessive creep occur, ruptures would not be classified as "gross degradation"

Creep Testing Under Constant Load (Force) and Constant Stress Conditions



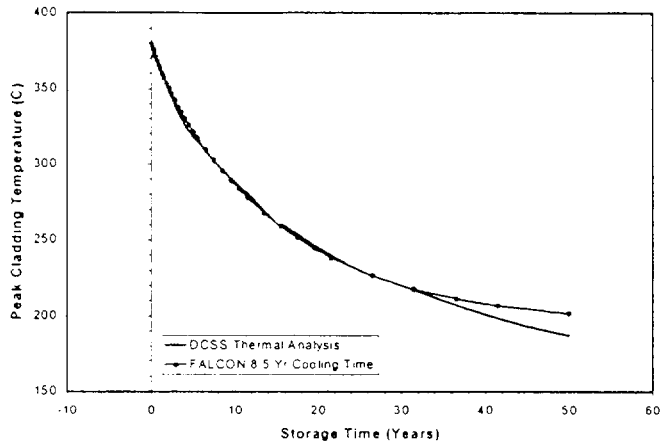
ANL Creep Testing 400°/190 MPa



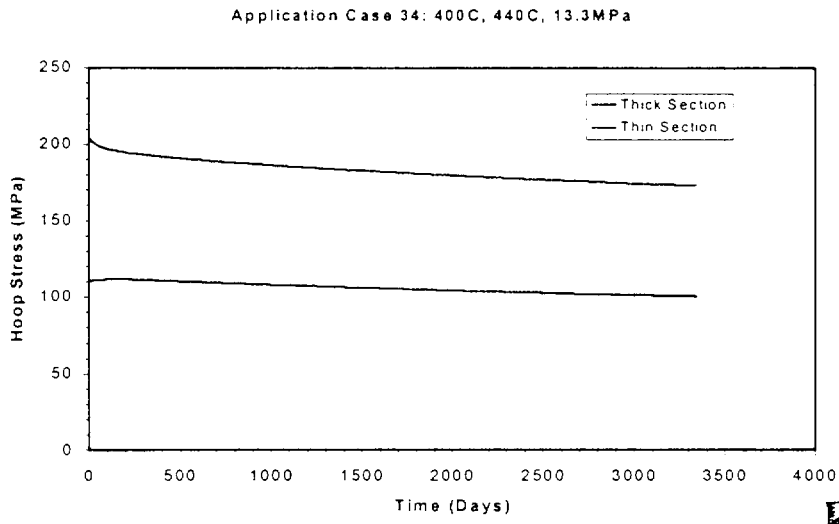
Results (continued)

- Calculations using bounding parameters for cladding condition and state-of-the-art creep model (EDF-CEA) and fuel-rod code (FALCON) show that initial temperatures of 380-400°C can be accommodated for 60 GWd/MTU, 8.5-year cooled fuel (including a 24-hr drying cycle with 8-hr at 420-440°C).
  - Details in EPRI Report 1003135
  - Dr. Rashid's Presentation

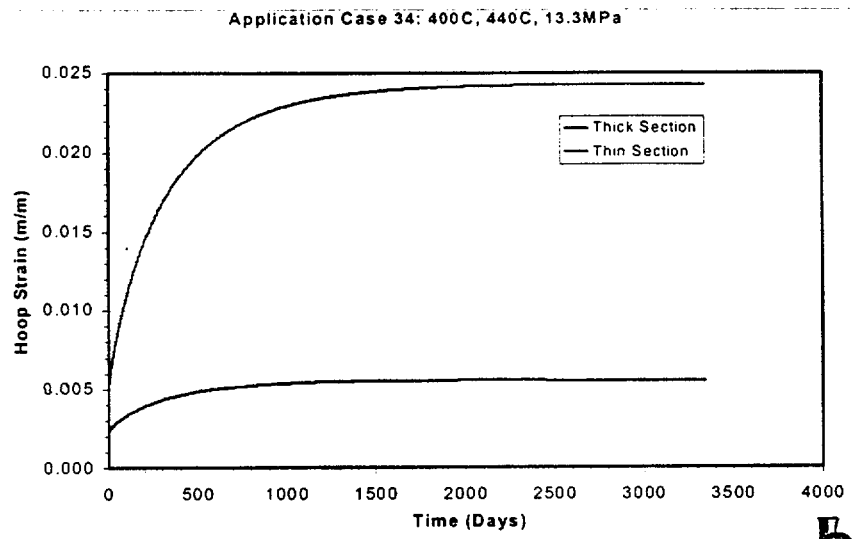
Temperature Time History for 8.5-Year Cooled 60 GWd/MTU rod



Case 34: 400°C/440°C/13.3 MPa



Case 34: 400°C/440°C/13.3 MPa



Results (continued)

- Results obtained so far support
  - Elimination of zirconium oxide thickness limits as they appear in ISG-11, Rev. 1
  - Elimination of the need for spent fuel examinations given that the acceptance criterion is robust, i.e., applicable even for rods with thick hydride lenses (loss of 1/2 of wall thickness resulting from severe spalling) on the outer surface of the cladding
- In addition
  - Creep strain calculations based on calculated temperatures (margin)
  - Ruptures due to excessive creep (unlikely) do not fit the "gross degradation" classification

Attachment 4

EPRI Slides

(Rashid/Machiels)

Behavior Evaluation of Spent Fuel Creep in Dry Storage

Presented By

Joe Rashid and Albert Machiels

to the Staff of the

United States Nuclear Regulatory Commission

Washington D C, March 5, 2002

Spent Fuel Creep in Dry Storage *(Phenomena and Applications)*

Outline

- General Description of the Creep Phenomenon as a Deformation Mechanism in Dry Storage
- State of the Art of Post-Irradiation Creep Data for Spent Fuel Cladding
- Summary and Conclusions of the Recent EPRI Report *(EPRI-1003135)*

Creep Deformation Mechanism in Dry Storage - Follows Three Steps

- *Step 1*: Experimental Characterization to Obtain Creep Data
- *Step 2*: Step-1 Data is Recast in a Constitutive Rate Law, Transformed to a Fuel Rod Analysis Code, and Case Analyses are Performed
- *Step 3*: Analysis Results are Compared to an Acceptance Criterion and/or a Failure Model

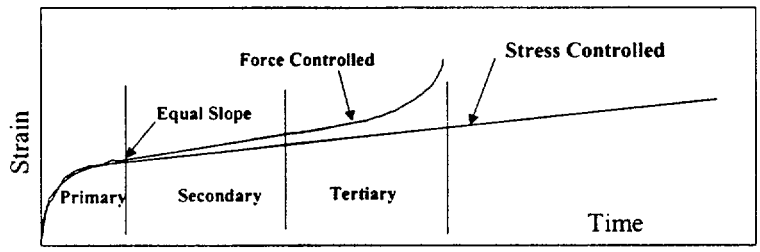
Step 1: Experimental Characterization

- Constant Force Test (the Usual Approach): Easy to Conduct, Difficult to Interpret - Creep Strain is Partitioned into Three Regimes:
  - Primary (Transient) Creep
  - Secondary (Steady State) Creep
  - Tertiary (Accelerated) Creep
- Constant Stress Test (Rarely Performed): Difficult to Conduct, Easy to Interpret
  - Primary and Secondary Creep Regimes Only

Step 1: Experimental Characterization (Cont.)

- Stress Controlled

Graphical Representation of Constant Force & Constant Stress Tests



Step 1: Experimental Characterization Constant Force/Pressure Tests

- Tests Conducted under Constant Temperature
- Creep Data is Obtained in the Form of Creep Strain vs. Time Curves for Different Initial Stresses and Temperatures
- Irradiation Effects Treated as:
  - Single Constant Multiplier on Total Creep

    or
  - Separate Multipliers, Functions of Fast Fluence, for Primary and Secondary Components

Step 2: From Data to Analysis

- Develop a "Time-Hardening" Creep Model:
  - Cast Data (Creep Curves) in the Form of an Equation Giving Creep Strain vs. Time as Function of:
    - Test Variables: Initial Stress and Temperature
    - Material Variables: Fast Fluence, Hydrogen, CW
- Convert Model To Strain-Hardening Creep-Rate Law with the following Independent Variables:
  - von Mises Stress
  - Temperature
  - Cumulative Primary-Creep Strain
  - Effective Fast Fluence, CW and Hydrogen

Step 2: From Data to Analysis (Cont.)

- Implement Strain-Hardening Creep-Rate Law in 3D Stress-Strain Constitutive Formulation
  - Combines Elastic, Instantaneous-Plastic and Viscoplastic (Creep) Relations: $\sigma_{ij} = (\varepsilon_{ji}^{e}, \varepsilon_{ij}^{p}, \varepsilon_{ij}^{c})$
- Implement in:
  - Fuel Behavior Code with Finite-Strain Capability: (FALCON)
  - Structural Analysis Code, Neglect Fuel Behavior: (ABAQUS)
- Carryout Fuel Rod Analyses in Dry
  - Temperature Decay: Deform Independent
  - Rod Pressure Decay: Temperature & Deformation Dependent

Step 3: Compare Results to Failure Criteria

- **Two Empirical Time-to-Rupture Criteria in Literature**
  - **Larson-Miller Parameter (LMP)**
    - **Temperature Dependent:** $LMP = 0.0018(20 + \log_{10} t_r)T$
    - **LMP as Function of Initial Stress:** $LMP = a \ln(\sigma_0 / b)$
  - **Monkman-Grant Correlation**
    - **Temperature Independent:** $\log t_r + m \log(\dot{\varepsilon}_{sc}) = c$
    - **m ≈ 1:** $t_r \dot{\varepsilon}_{sc} = const.$ **(Implies Equal Ductility for All Materials)**
    - **Possible Error of a factor of 10 in Rupture Time?**
- **Physically Based Model - EPRI 1003135 Report**
  - **Cumulative Damage Model Based on Plastic Instability**

$$D = \sum \Delta t_i / \left[-\ln\left(\sigma_i / \sigma_{yi} \right) / a \dot{\varepsilon}_{si} \right] \le 1$$

State of the Art of Post-Irradiation Creep Data

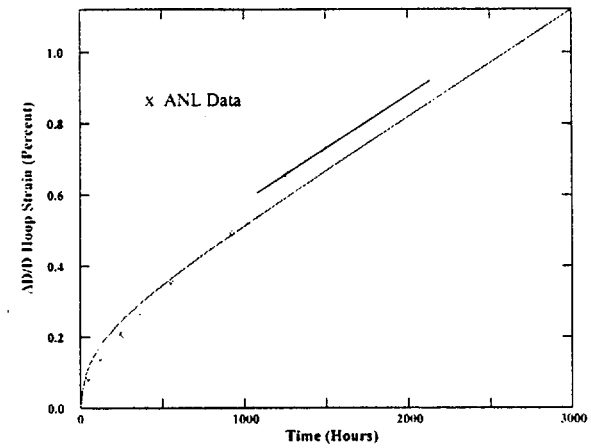
- **Creep Tests: 23 Cases 250-16,000 hours - (France)**
  - **Unirradiated, Hydrided (175-560ppm)**
  - **80-200 MPa, 350°C- 470°C**
  - **1, 2 and 4 Cycles of Irradiation**
- **Creep Rupture Tests - (France and Germany)**
  - **7 Creep Rupture Cases - (France)**
    - **As-received, Hydrided (215-1040ppm): 350-386 MPa, 350- 400°C**
    - **One 4-Cycle Case : 226 MPa, 420°C**
  - **12 Creep/Creep-Rupture Cases, High Burnup - (Germany)**
    - **54-64 GWD/MTU Burnup**
    - **400-622 MPa, 300°C-370°C**
  - **Failure Occurs at Stress Levels Above Yield Strength**

Post-Irradiation Creep Data (cont.)

- ANL Program for Surry
  - 1 Creep Case so Far
  - 3 Cycles
  - 190 MPa, 400°C
  - < 0.9% Strain after 1490 hours
- Available Data Indicates a Fairly Robust Data Base
  - Sufficient to Support the Development of the Creep Methodology Described in Steps 2 and 3
  - Allows Analytical Evaluation, Conservatively, of High-Burnup Induced Defects, e.g. Oxide Spallation and Hydride Lenses

Summary and Conclusions of EPRI-1003135 Report

- The EDF/CEA Time-Hardening Creep Equations were Transformed to a Strain-Hardening Creep-Rate Model
  - Modified Fluence Dependence of the Secondary Creep Term
  - Introduced Hydrogen Dependence
  - Introduced Annealing of Iradiation-Damage & Cold-work
- Implemented Model in FALCON
  - Combines Elastic, Instantaneous-Plastic & Viscoplastic-Creep Relations in Finite-Strain Constitutive Formulation
- Validated the Modified Model Against the Data Base
  - See Appendix A of EPRI-1003135
  - ANL's Creep Test Next Slide



Analysis of the ANL 190MPa/400°C Creep Test Using the EDF Creep Model as Modified in EPRI-1003135

Summary and Conclusions of EPRI-1003135 Report *(cont.)*

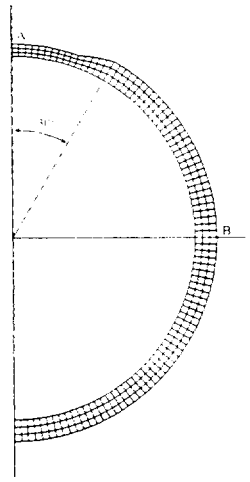
- **Developed, from First Principles, a Damage Model Based on Plastic Instability** $D = \sum \Delta t_i / \left[-\ln\left(\sigma_i / \sigma_{yi} \right) / \dot{\varepsilon}_{si} \right]$
  - **D: Damage Index**
  - **Δt_i: Time Step Size**
  - **σ_i , σ_{yi}: Stress and Yield Strength at Time Step t_i**
  - **$\dot{\varepsilon}_{si}$: Secondary Creep Rate at Step t_i**
  - **A value of D=1 Implies 50% Failure Probability**
  - **This Model Led to the Acceptance Criterion: *Local Stress Must Remain Below 2/3rd of the Yield Strength***
  - **Validated by the Fact that Creep Rupture Data Conclusively Shows No Failure at Stress Levels Below the Yield Strength**

Summary and Conclusions of EPRI-1003135 Report *(cont.)*

- Application of the Model to Spalled Cladding with Hydride Lens as a Bounding Condition
- Consider Application Case 31and 32 in the Report:

  120μm Oxide and a Hydride Lens 50% of Thickness, 60° wide

  - Case 1: Initial Storage Temperature: 400°C
    Vacuum Drying Temperature: 440°C
    Initial Storage Pressure: 19.1 MPa
  - Case 2: Initial Storage Temperature: 380°C
    Vacuum Drying Temperature: 420°C
    Initial Storage Pressure: 18.6 MPa



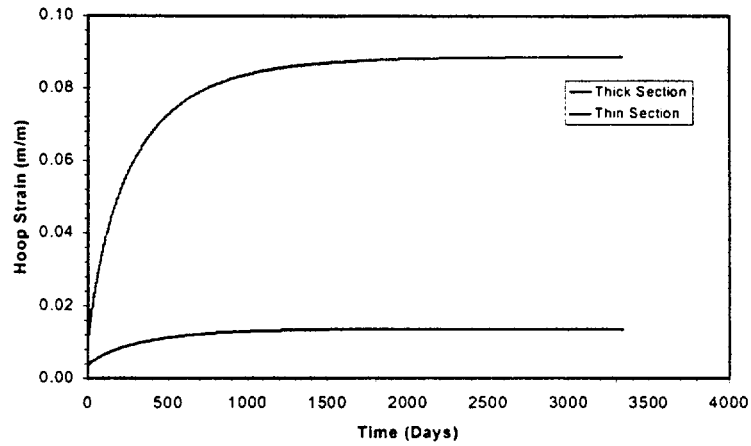
Line of Symmetry

FALCON's Finite Element Model of a Cladding with a Hydride Lens

120μm Oxide and a Hydride Lens 50% of Thickness, 60° wide

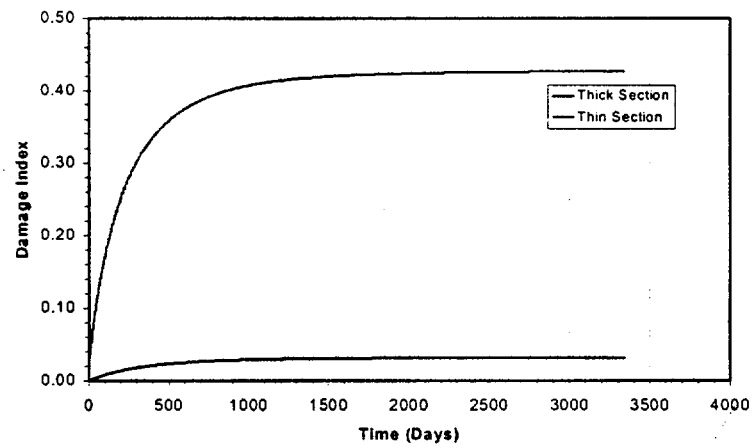
Case 1 - Strain Response

Application Case 31: 400C, 440C, 19.1MPa



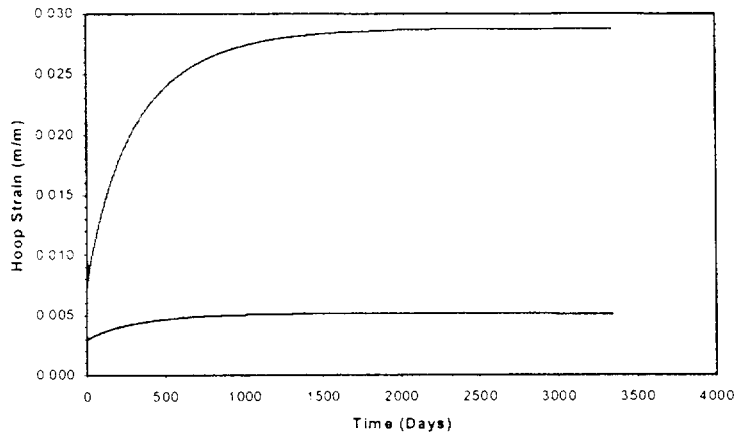
Case 1 - Damage Index

Application Case 31: 400C, 440C, 19.1MPa



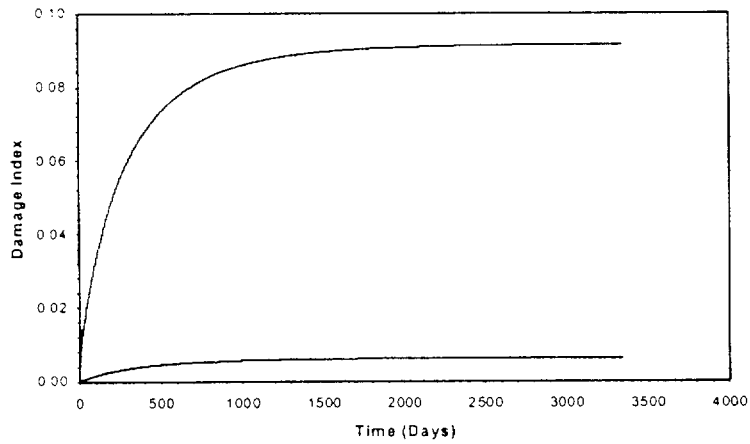
Case 2 - Strain Response

Application Case 32: 380C, 420C, 18.6MPa



Case 2 - Damage Index

Application Case 32: 380C, 420C, 18.6MPa



Attachment 5

NEI Slides

(Supko/Vincent)

High Burnup Spent Nuclear Fuel Storage Analysis

Eileen M. Supko
Energy Resources International, Inc.
John A. Vincent
Nuclear Energy Institute

Overview

- Spent fuel storage statistics
- Projected discharge burnup distributions
- SNF projection assumptions
- 6 PWR spent fuel storage case studies
- 2 BWR spent fuel storage case studies
- Observations

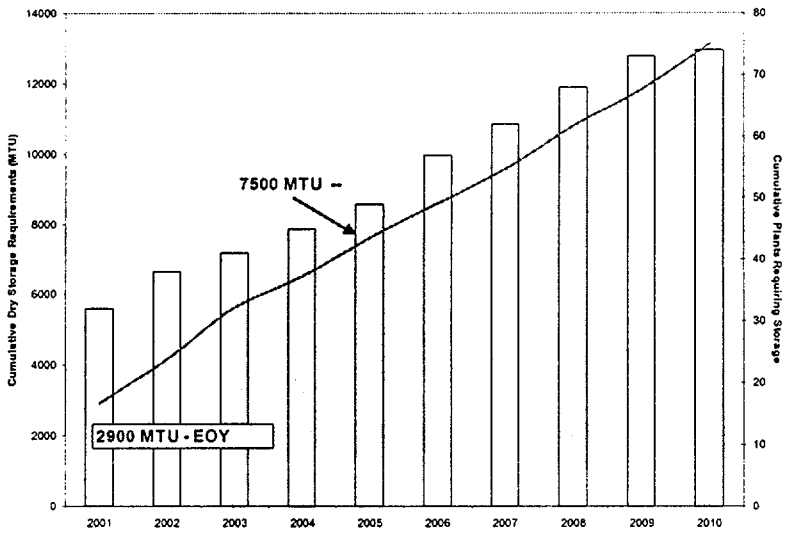
Where are we now?

- Approximately 45,000 MTU of spent fuel has been discharged as of 12/31/01
- 18 commercial sites have implemented dry storage for 32 nuclear power plants
- Approximately, 2,900 MTU of spent fuel in storage as of 12/31/01

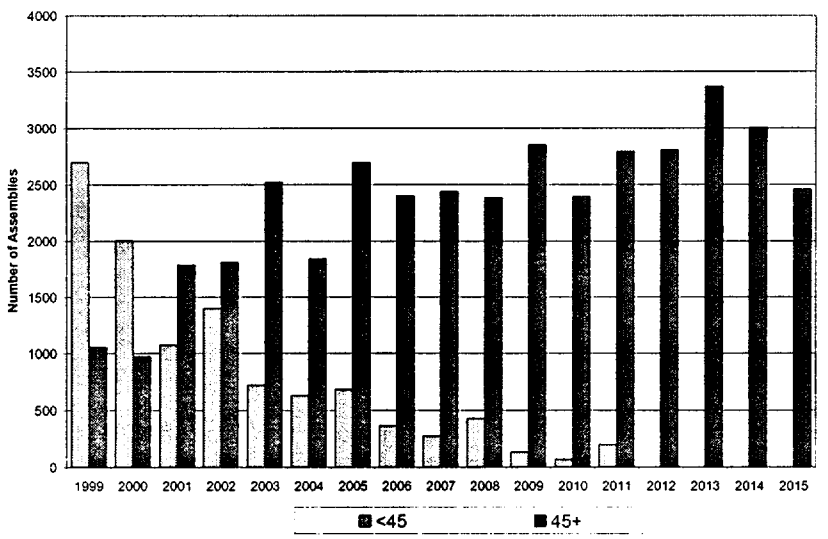
Where are we going?

- The number of plants requiring dry storage will double to 60 plants by 2006
- The cumulative SNF in dry storage will more than double by 2005
  - This includes shutdown plant plans to implement dry storage
- By 2010, more than 12,000 MTU of spent fuel will require dry storage

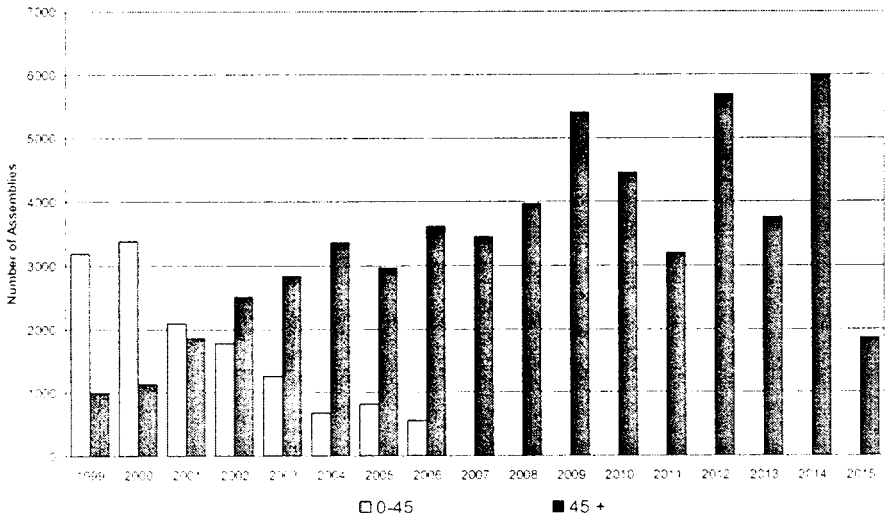
Projected Dry Storage Requirements



PROJECTED PWR BURNUP DISTRIBUTION THROUGH 2015



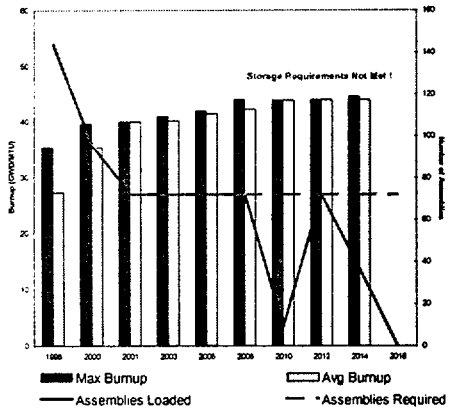
PROJECTED BWR BURNUP DISTRIBUTION THROUGH 2015



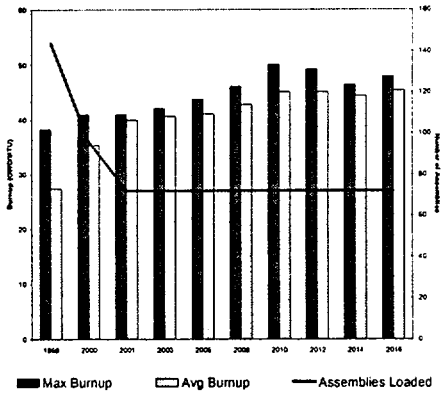
PWR1 - Dry Storage Mid 1990s

- Commercial operation -- mid 1970s
- 2 Loading Profiles Run
  - 24 PWR Cask, <45 GWD/MTU, uniform loading
  - 24 PWR Cask, High Burnup, regional loading
- Results
  - 24 PWR Cask, <45 GWD/MTU -- could not fully load beginning in 2010
  - 24 PWR Cask, High Burnup -- had no loading problems through 2016

24 PWR, <45 GWD/MTU,
Uniform Loading



24 PWR, High Burnup,
Regional Loading

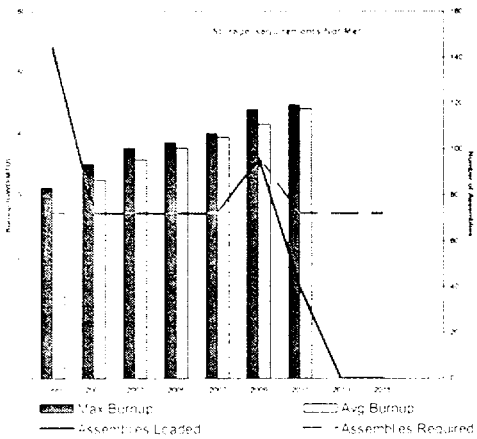


PWR 1

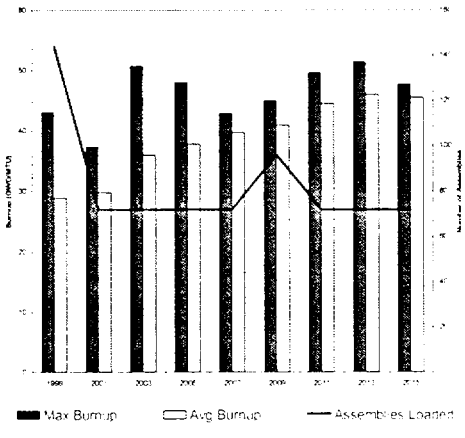
PWR2 - Dry Storage Mid 1990s

- Commercial operation -- mid 1970s
- 2 Loading Profiles Run
  - 24 PWR Cask, <45 GWD/MTU, uniform loading
  - 24 PWR Cask, High Burnup, regional loading
- Results
  - 24 PWR Cask, <45 GWD/MTU -- could not fully load beginning in 2009
  - 24 PWR Cask, High Burnup -- had no loading problems through 2016

24 PWR, <45 GWD/MTU,
Uniform Loading



24 PWR, High Burnup,
Regional Loading

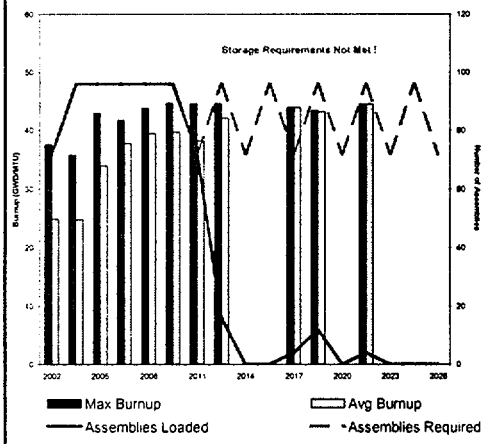


PWR 2

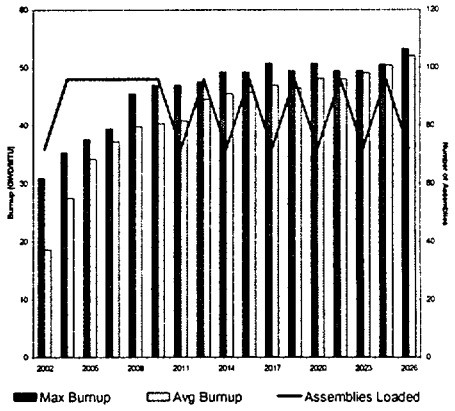
PWR3 - Dry Storage 2002

- Commercial operation -- Mid 1980s
- 3 Loading Profiles Run
  - 24 PWR Cask, <45 GWD/MTU, Uniform Loading
  - 24 PWR Cask, <45 through 2007, 24 PWR Cask, High Burnup, Regional Loading thereafter
  - 24 PWR Cask, High Burnup, Regional Loading II
- Results
  - 24 PWR Cask, <45 GWD/MTU -- could not fully load beginning in 2013
  - 24 PWR Cask, High Burnup. Regional I-- no problems
  - 24 PWR Cask, High Burnup, Regional II

24 PWR, <45 GWD/MTU, Uniform Loading

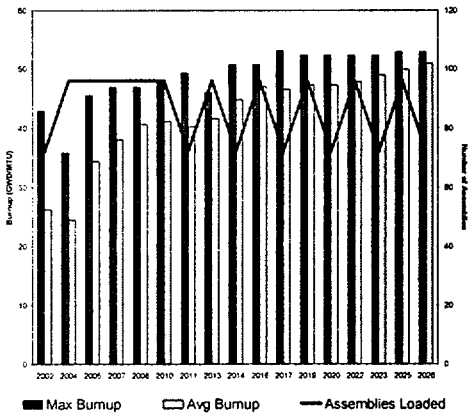


24 PWR, High Burnup, Regional Loading I

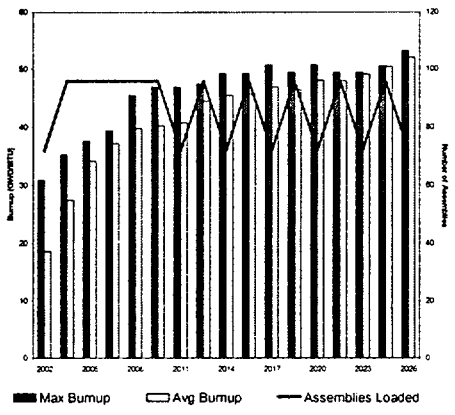


PWR 3

24 PWR, High Burnup Regional Loading II



24 PWR, High Burnup, Regional Loading I

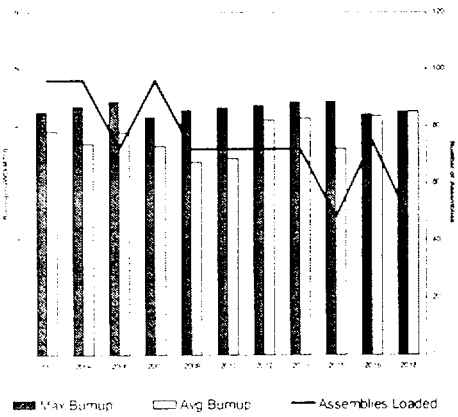


PWR 3

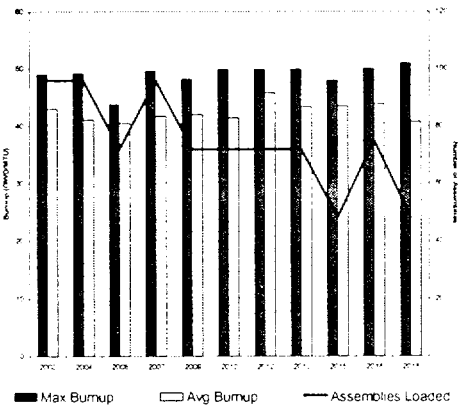
PWR4 - Dry Storage 2003

- Commercial operation -- early 1980s
- 2 Loading Profiles Run
  - 24 PWR Cask, <45 GWD/MTU, Uniform Loading
  - 24 PWR Cask, High Burnup, Regional Loading
- Results
  - 24 PWR Cask, <45 GWD/MTU -- no problems
  - 24 PWR Cask, High Burnup. Regional -- no problems

24 PWR, <45 GWD/MTU, Uniform Loading



24 PWR, High Burnup, Regional Loading

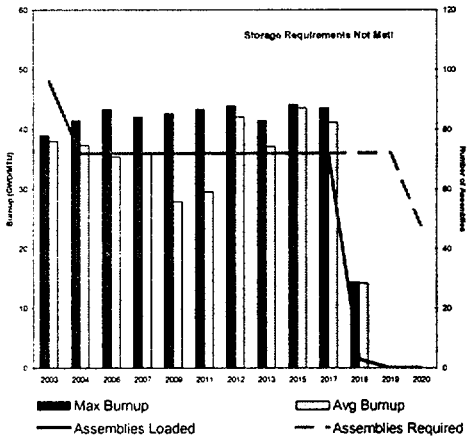


PWR 4

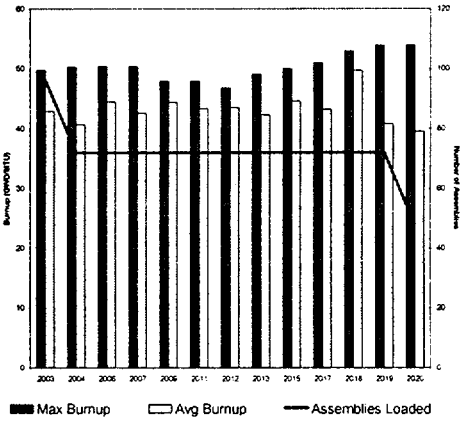
PWR5 - Dry Storage 2003

- Commercial operation -- early 1980s
- 3 Loading Profiles Run
  - 24 PWR Cask, <45 GWD/MTU, Uniform Loading
  - 24 PWR Cask, High Burnup, Regional Loading
  - 32 PWR Cask, High Burnup, Regional Loading
- Results
  - 24 PWR Cask, <45 GWD/MTU -- problems 2018
  - 24 PWR Cask, High Burnup, Regional -- no problems
  - 32 PWR Cask, High Burnup, Regional -- problems 2015 -- not enough "cold" fuel

24 PWR, <45 GWD/MTU, Uniform Loading

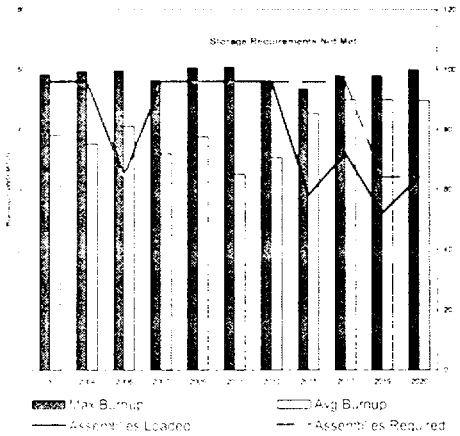


24 PWR, High Burnup, Regional Loading

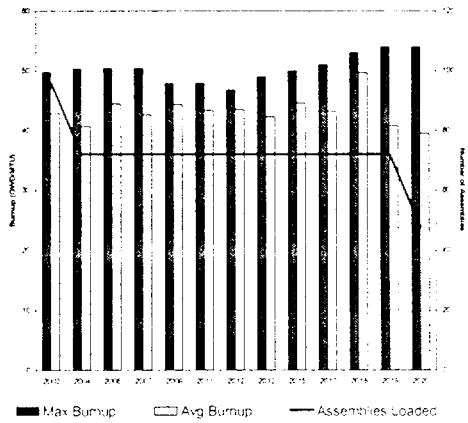


PWR 5

32 PWR, High Burnup
Regional Loading



24 PWR, High Burnup,
Regional Loading



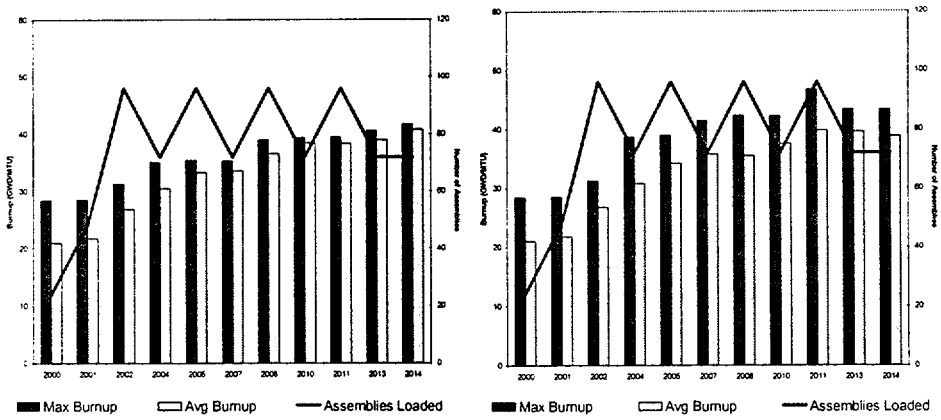
PWR 5

PWR6 - Dry Storage 2000

- Commercial operation -- early 1980s
- 2 Loading Profiles Run
  - 24 PWR Cask, <45 GWD/MTU, Uniform Loading
  - 24 PWR Cask, <45 GWD/MTU, to 2002; High Burnup, Regional Loading thereafter
- Results
  - 24 PWR Cask, <45 GWD/MTU -- no problems
  - 24 PWR Cask, High Burnup, Regional -- no problems

24 PWR, <45 GWD/MTU,
Uniform Loading

24 PWR, High Burnup,
Regional Loading

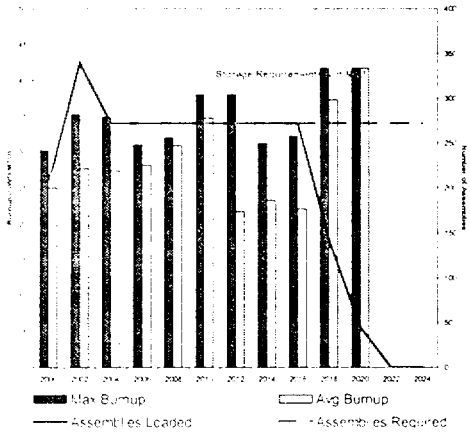


PWR 6

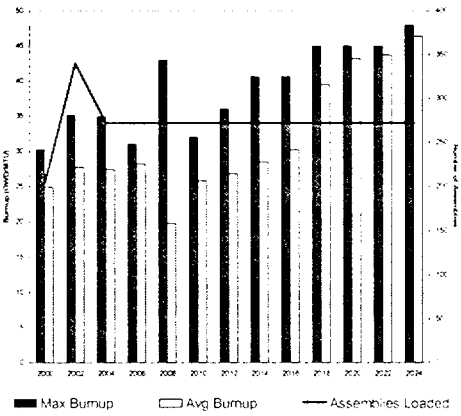
BWR1 - Dry Storage 2000

- Commercial operation -- mid 1970s
- 2 Loading Profiles Run
  - 68 BWR Cask, <42 GWD/MTU, Uniform Loading
  - 68 BWR Cask, <42 GWD/MTU, Through 2006; 68 BWR Cask, High Burnup, Regional Loading thereafter
- Results
  - 68 BWR Cask, <42 GWD/MTU -- problems 2018
  - 68 BWR Cask, High Burnup, Regional -- no problems

68 BWR, <42 GWD/MTU,
Uniform Loading



68 BWR, High Burnup,
Regional Loading

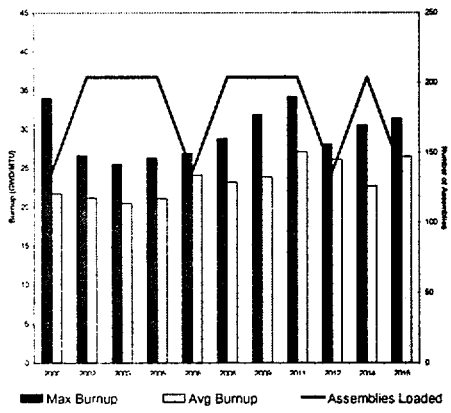


BWR 1

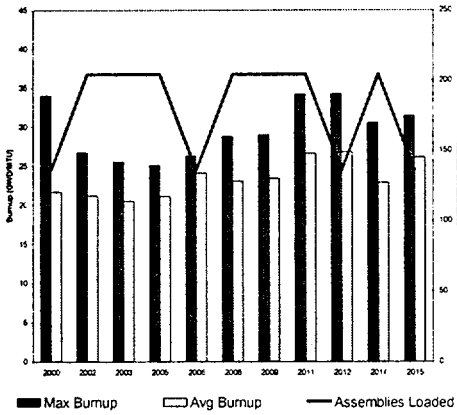
BWR2 - Dry Storage 2000

- Commercial operation -- mid 1970s
- 2 Loading Profiles Run
  - 68 BWR Cask, <42 GWD/MTU, Uniform Loading
  - 68 BWR Cask, <42 GWD/MTU, Through 2002; 68 BWR Cask, High Burnup, Regional Loading thereafter
- Results
  - 68 BWR Cask, <42 GWD/MTU -- no problems
  - 68 BWR Cask, High Burnup, Regional -- no problems

68 BWR, <42 GWD/MTU,
Uniform Loading



68 BWR, High Burnup,
Regional Loading



BWR 2

Observations

- Results may underestimate timing for need to load high burnup SNF due to:
  - Some portion of inventory not suited for current containers (damaged fuel, other considerations)
  - Additional pool storage constraints (boraflex) results in less pool capacity
  - Operational considerations result in higher spent fuel discharges than projected

Observations

- Near-term need to load high burnup SNF will be site specific and will depend upon:
  - Age of plant
  - Spent fuel storage pool capacity
  - Spent fuel inventory burnup profile, capacity factors
  - Number of years of dry storage required
  - Type of plant (PWR, BWR)
- PWRs tend to have nearer term needs for spent fuel management flexibility
- BWRs also have near term needs

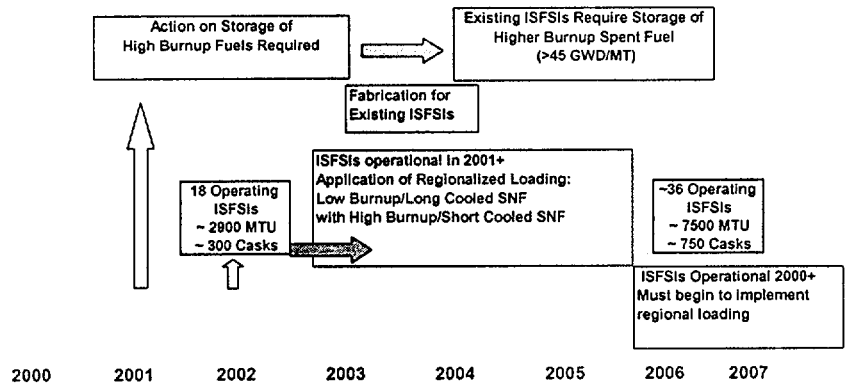
Observations

- PWRs that began operation in mid 1980s
  - Greater percentage of inventory will be high burnup spent fuel;
  - Will have smaller inventory of older, colder spent fuel; therefore regional loading is needed ASAP
  - Need flexibility to load a variety of container capacities, e.g., 24 PWR and 32PWR containers to maximize loading of high burnup spent fuel

Observations

- Eventually will require container designs capable of storing all high-burnup fuel
  - Higher heat transfer capabilities
  - Different basket configurations
  - Different, possibly lower capacity
- Transport issues associated with high burnup fuel
  - dose rates, heat load
  - need for burnup credit approval

Timeline



Conclusions

- Regulatory approval of high burnup designs needed to support near term needs
- Storage of high burnup SNF important to both existing and planned dry storage facilities
- Regional loading important to provided SNF management flexibility
  - Allows storage of low burnup/longer cooled SNF and high burnup/shorter cooled SNF in same container

Attachment 5

NEI Slides

(Supko/Vincent)

High Burnup Spent Nuclear Fuel Storage Analysis

Eileen M. Supko
Energy Resources International, Inc.
John A. Vincent
Nuclear Energy Institute

Overview

- Spent fuel storage statistics
- Projected discharge burnup distributions
- SNF projection assumptions
- 6 PWR spent fuel storage case studies
- 2 BWR spent fuel storage case studies
- Observations

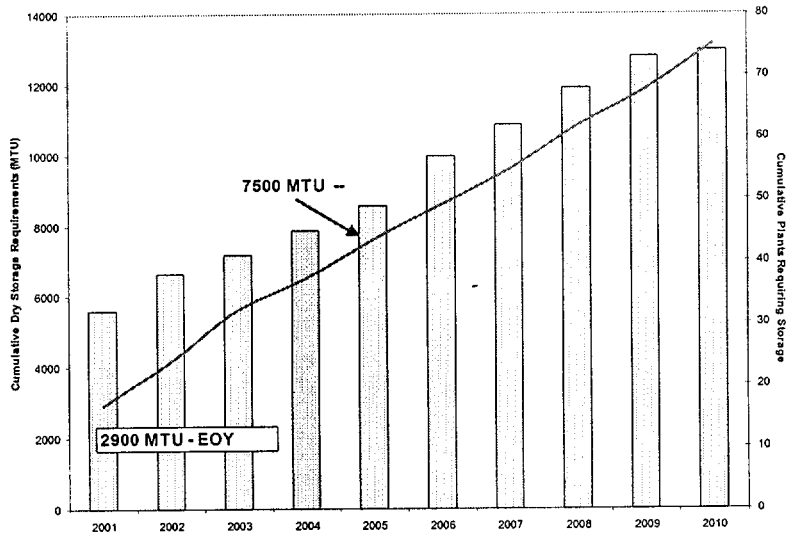
Where are we now?

- Approximately 45,000 MTU of spent fuel has been discharged as of 12/31/01
- 18 commercial sites have implemented dry storage for 32 nuclear power plants
- Approximately, 2,900 MTU of spent fuel in storage as of 12/31/01

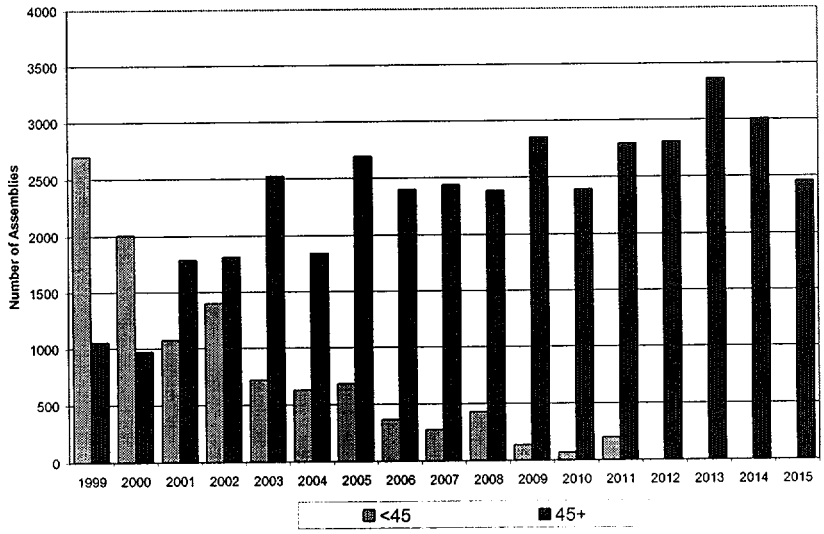
Where are we going?

- The number of plants requiring dry storage will double to 60 plants by 2006
- The cumulative SNF in dry storage will more than double by 2005
  - This includes shutdown plant plans to implement dry storage
- By 2010, more than 12,000 MTU of spent fuel will require dry storage

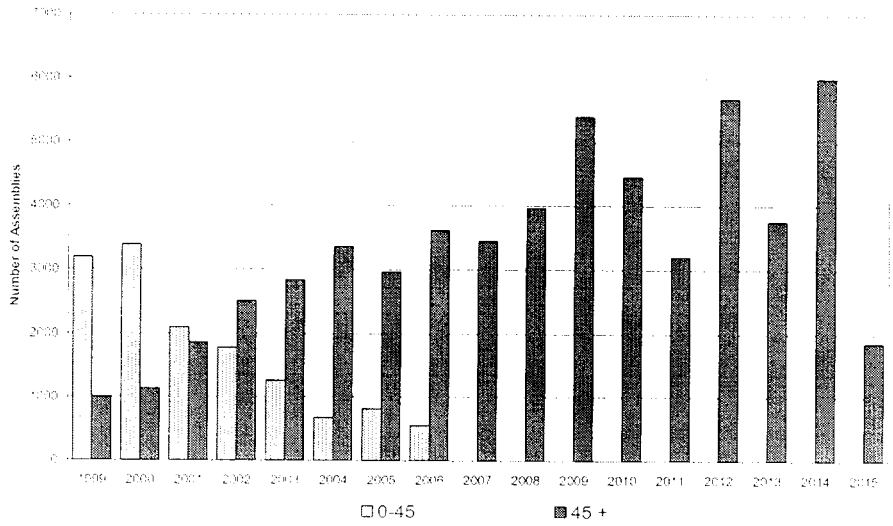
Projected Dry Storage Requirements



PROJECTED PWR BURNUP DISTRIBUTION THROUGH 2015



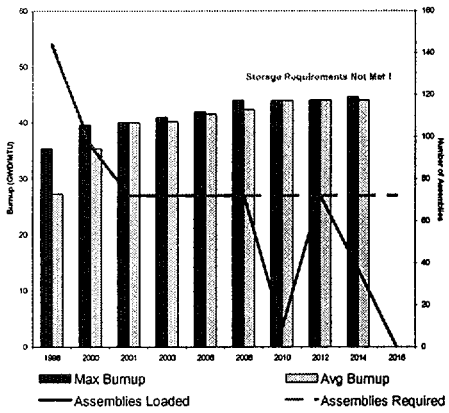
PROJECTED BWR BURNUP DISTRIBUTION THROUGH 2015



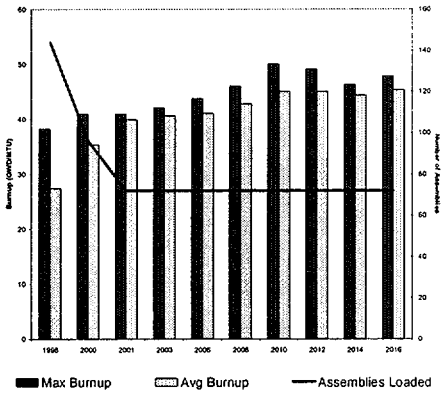
PWR1 - Dry Storage Mid 1990s

- Commercial operation -- mid 1970s
- 2 Loading Profiles Run
  - 24 PWR Cask, <45 GWD/MTU, uniform loading
  - 24 PWR Cask, High Burnup, regional loading
- Results
  - 24 PWR Cask, <45 GWD/MTU -- could not fully load beginning in 2010
  - 24 PWR Cask, High Burnup -- had no loading problems through 2016

24 PWR, <45 GWD/MTU,
Uniform Loading



24 PWR, High Burnup,
Regional Loading

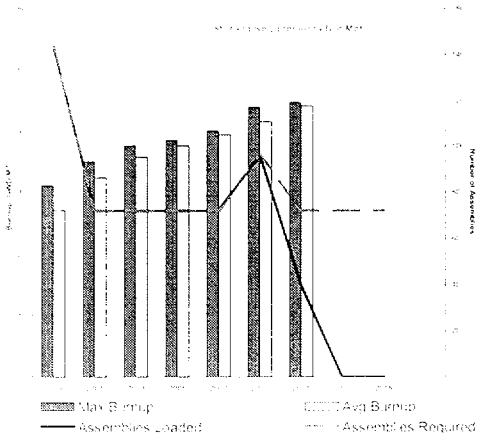


PWR 1

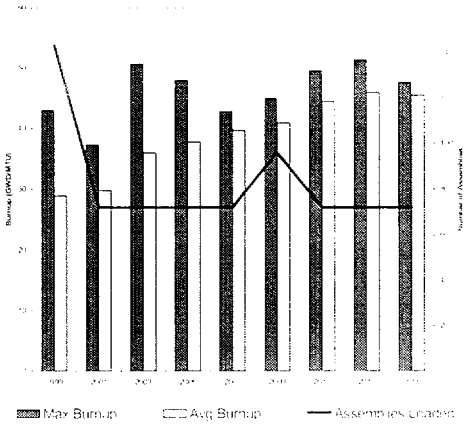
PWR2 - Dry Storage Mid 1990s

- Commercial operation -- mid 1970s
- 2 Loading Profiles Run
  - 24 PWR Cask, <45 GWD/MTU, uniform loading
  - 24 PWR Cask, High Burnup, regional loading
- Results
  - 24 PWR Cask, <45 GWD/MTU -- could not fully load beginning in 2009
  - 24 PWR Cask, High Burnup -- had no loading problems through 2016

24 PWR, <45 GWD/MTU, Uniform Loading



24 PWR, High Burnup, Regional Loading

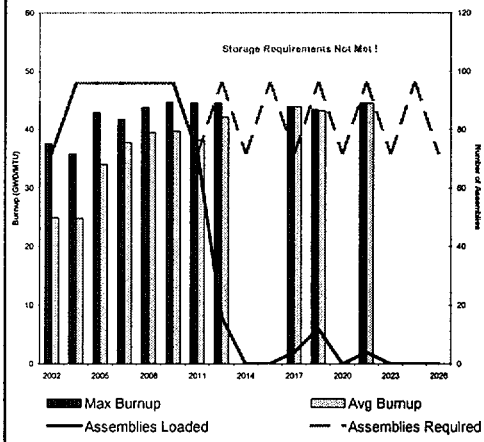


PWR 2

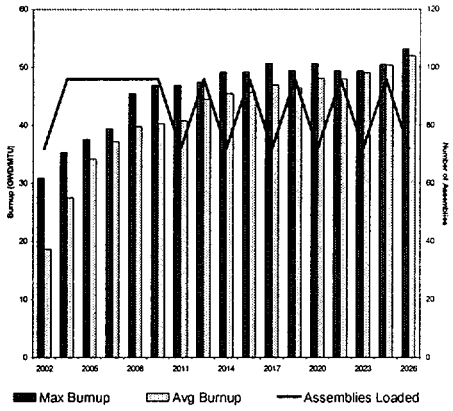
PWR3 - Dry Storage 2002

- Commercial operation -- Mid 1980s
- 3 Loading Profiles Run
  - 24 PWR Cask, <45 GWD/MTU, Uniform Loading
  - 24 PWR Cask, <45 through 2007, 24 PWR Cask, High Burnup, Regional Loading thereafter
  - 24 PWR Cask, High Burnup, Regional Loading II
- Results
  - 24 PWR Cask, <45 GWD/MTU -- could not fully load beginning in 2013
  - 24 PWR Cask, High Burnup. Regional I-- no problems
  - 24 PWR Cask, High Burnup, Regional II

24 PWR, <45 GWD/MTU, Uniform Loading

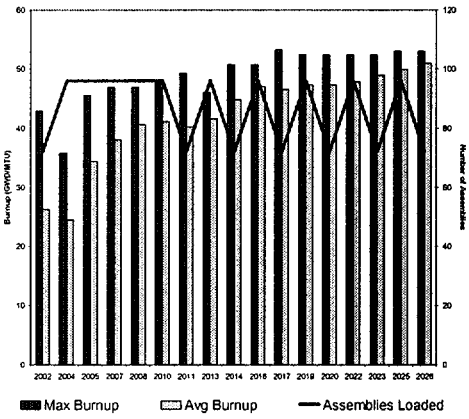


24 PWR, High Burnup, Regional Loading I

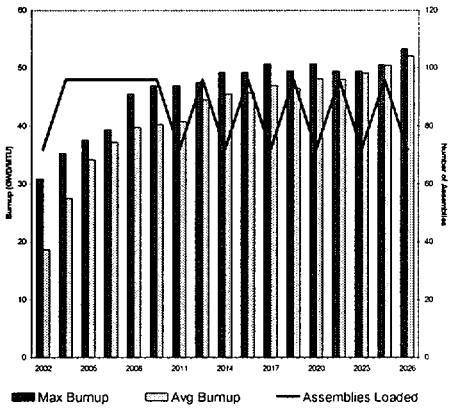


PWR 3

24 PWR, High Burnup Regional Loading II



24 PWR, High Burnup, Regional Loading I

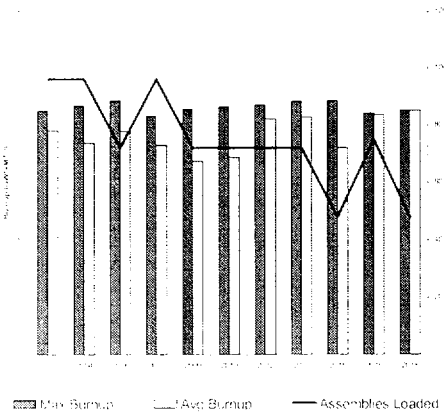


PWR 3

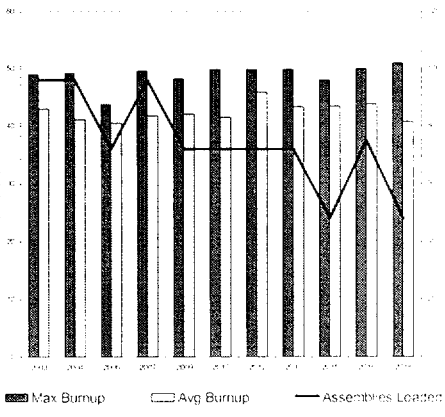
PWR4 - Dry Storage 2003

- Commercial operation -- early 1980s
- 2 Loading Profiles Run
  - 24 PWR Cask, <45 GWD/MTU, Uniform Loading
  - 24 PWR Cask, High Burnup, Regional Loading
- Results
  - 24 PWR Cask, <45 GWD/MTU -- no problems
  - 24 PWR Cask, High Burnup. Regional -- no problems

24 PWR, <45 GWD/MTU, Uniform Loading



24 PWR, High Burnup, Regional Loading

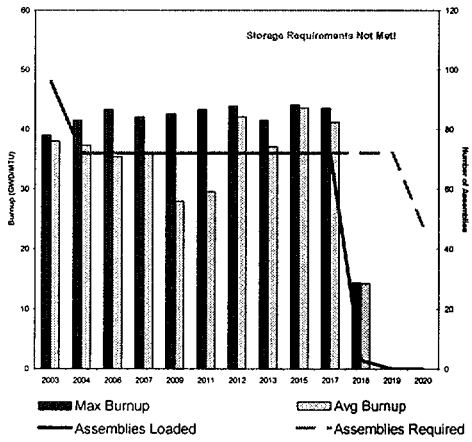


PWR 4

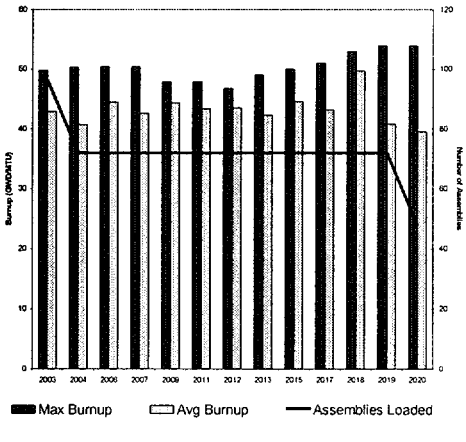
PWR5 - Dry Storage 2003

- Commercial operation -- early 1980s
- 3 Loading Profiles Run
  - 24 PWR Cask, <45 GWD/MTU, Uniform Loading
  - 24 PWR Cask, High Burnup, Regional Loading
  - 32 PWR Cask, High Burnup, Regional Loading
- Results
  - 24 PWR Cask, <45 GWD/MTU -- problems 2018
  - 24 PWR Cask, High Burnup, Regional -- no problems
  - 32 PWR Cask, High Burnup, Regional -- problems 2015 -- not enough "cold" fuel

24 PWR, <45 GWD/MTU, Uniform Loading



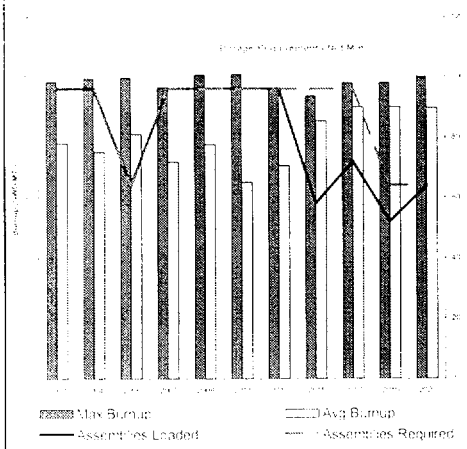
24 PWR, High Burnup, Regional Loading



PWR 5

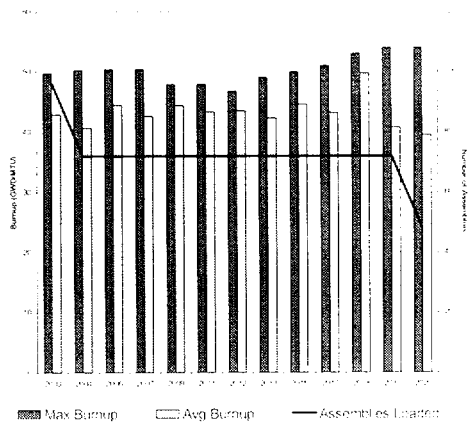
32 PWR, High Burnup

Regional Loading



24 PWR, High Burnup,

Regional Loading



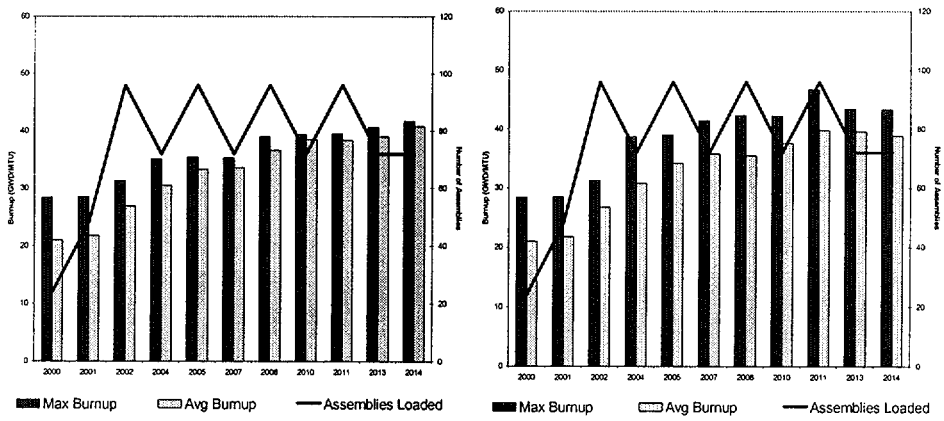
PWR 5

PWR6 - Dry Storage 2000

- Commercial operation -- early 1980s
- 2 Loading Profiles Run
  - 24 PWR Cask, <45 GWD/MTU, Uniform Loading
  - 24 PWR Cask, <45 GWD/MTU, to 2002; High Burnup, Regional Loading thereafter
- Results
  - 24 PWR Cask, <45 GWD/MTU -- no problems
  - 24 PWR Cask, High Burnup, Regional -- no problems

24 PWR, <45 GWD/MTU,
Uniform Loading

24 PWR, High Burnup,
Regional Loading

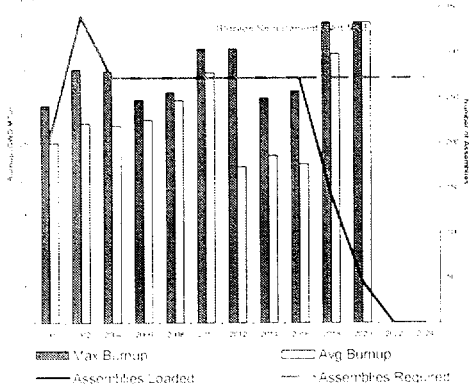


PWR 6

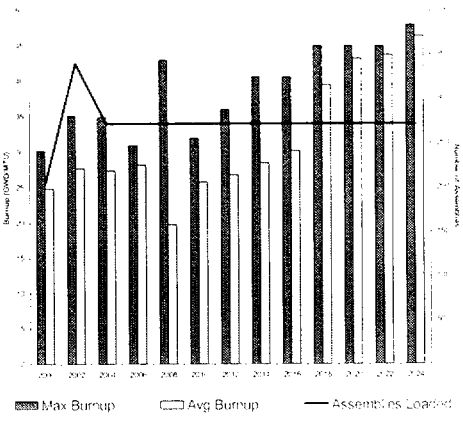
BWR1 - Dry Storage 2000

- Commercial operation -- mid 1970s
- 2 Loading Profiles Run
  - 68 BWR Cask, <42 GWD/MTU, Uniform Loading
  - 68 BWR Cask, <42 GWD/MTU, Through 2006; 68 BWR Cask, High Burnup, Regional Loading thereafter
- Results
  - 68 BWR Cask, <42 GWD/MTU -- problems 2018
  - 68 BWR Cask, High Burnup, Regional -- no problems

68 BWR, <42 GWD/MTU,
Uniform Loading



68 BWR, High Burnup,
Regional Loading

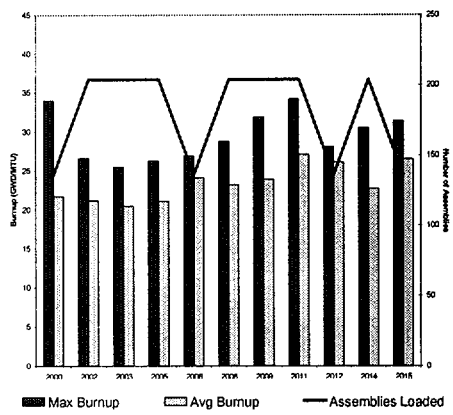


BWR 1

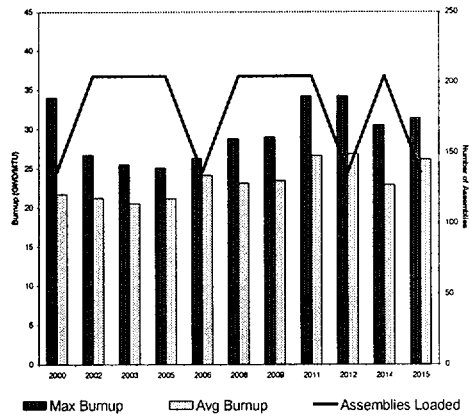
BWR2 - Dry Storage 2000

- Commercial operation -- mid 1970s
- 2 Loading Profiles Run
  - 68 BWR Cask, <42 GWD/MTU, Uniform Loading
  - 68 BWR Cask, <42 GWD/MTU, Through 2002; 68 BWR Cask, High Burnup, Regional Loading thereafter
- Results
  - 68 BWR Cask, <42 GWD/MTU -- no problems
  - 68 BWR Cask, High Burnup, Regional -- no problems

68 BWR, <42 GWD/MTU,
Uniform Loading



68 BWR, High Burnup,
Regional Loading



BWR 2

Observations

- Results may underestimate timing for need to load high burnup SNF due to:
  - Some portion of inventory not suited for current containers (damaged fuel, other considerations)
  - Additional pool storage constraints (boraflex) results in less pool capacity
  - Operational considerations result in higher spent fuel discharges than projected

Observations

- Near-term need to load high burnup SNF will be site specific and will depend upon:
  - Age of plant
  - Spent fuel storage pool capacity
  - Spent fuel inventory burnup profile, capacity factors
  - Number of years of dry storage required
  - Type of plant (PWR, BWR)
- PWRs tend to have nearer term needs for spent fuel management flexibility
- BWRs also have near term needs

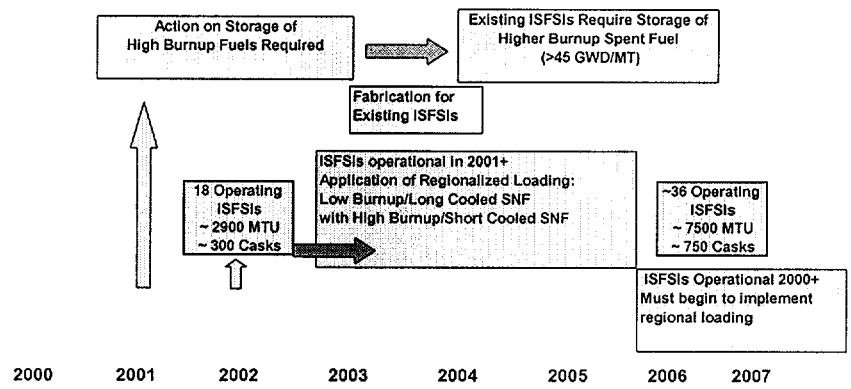
Observations

- PWRs that began operation in mid 1980s
  - Greater percentage of inventory will be high burnup spent fuel;
  - Will have smaller inventory of older, colder spent fuel; therefore regional loading is needed ASAP
  - Need flexibility to load a variety of container capacities, e.g., 24 PWR and 32PWR containers to maximize loading of high burnup spent fuel

Observations

- Eventually will require container designs capable of storing all high-burnup fuel
  - Higher heat transfer capabilities
  - Different basket configurations
  - Different, possibly lower capacity
- Transport issues associated with high burnup fuel
  - dose rates, heat load
  - need for burnup credit approval

Timeline



Conclusions

- Regulatory approval of high burnup designs needed to support near term needs
- Storage of high burnup SNF important to both existing and planned dry storage facilities
- Regional loading important to provided SNF management flexibility
  - Allows storage of low burnup/longer cooled SNF and high burnup/shorter cooled SNF in same container