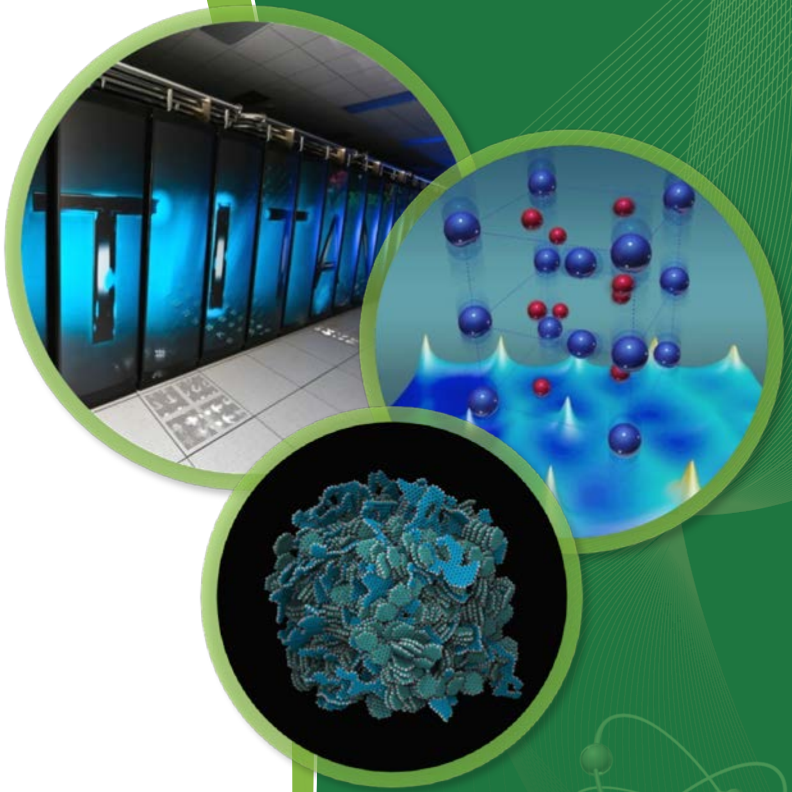
High Burnup Spent Fuel Data Project in the U.S.

Zababakhin Scientific Talks
13th International Conference
Snezhinsk, Chelyabinsk Region, Russia
March 20-24, 2017



Bruce Bevard, Rose Montgomery, John Scaglione

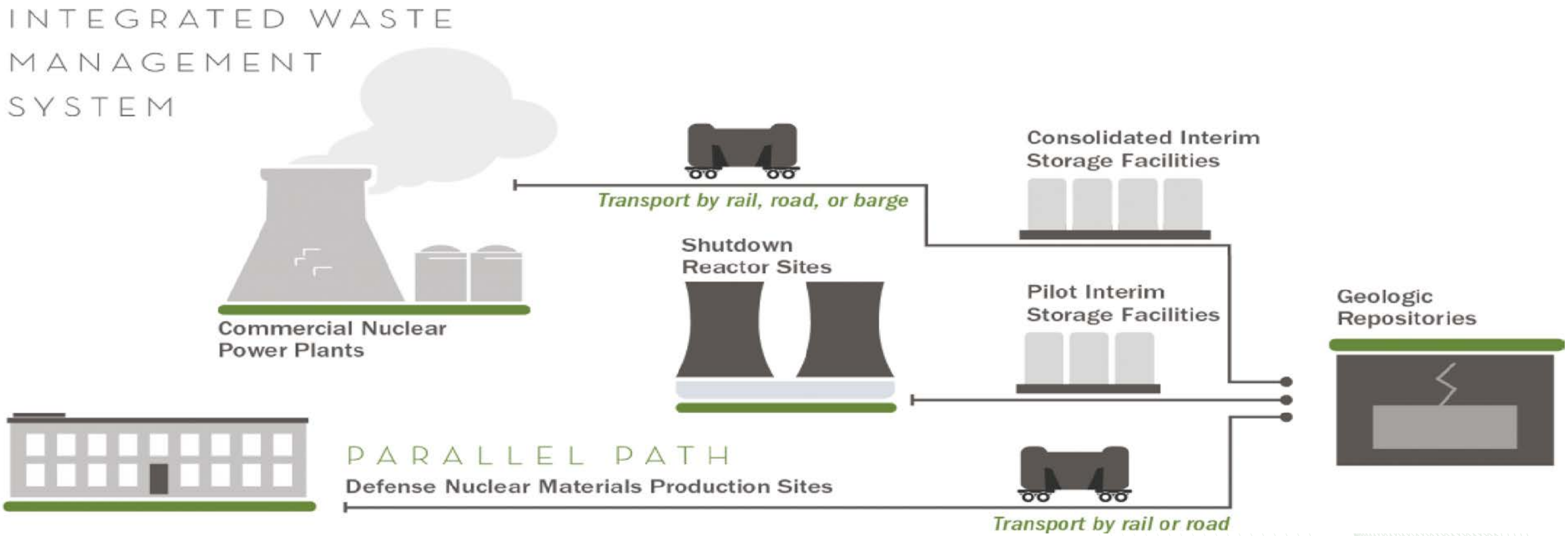
Oak Ridge National Laboratory

This work was sponsored by the Spent Fuel and Waste and Science Technology program in the Office of Nuclear Energy, US Department of Energy with UT-Battelle, LLC.

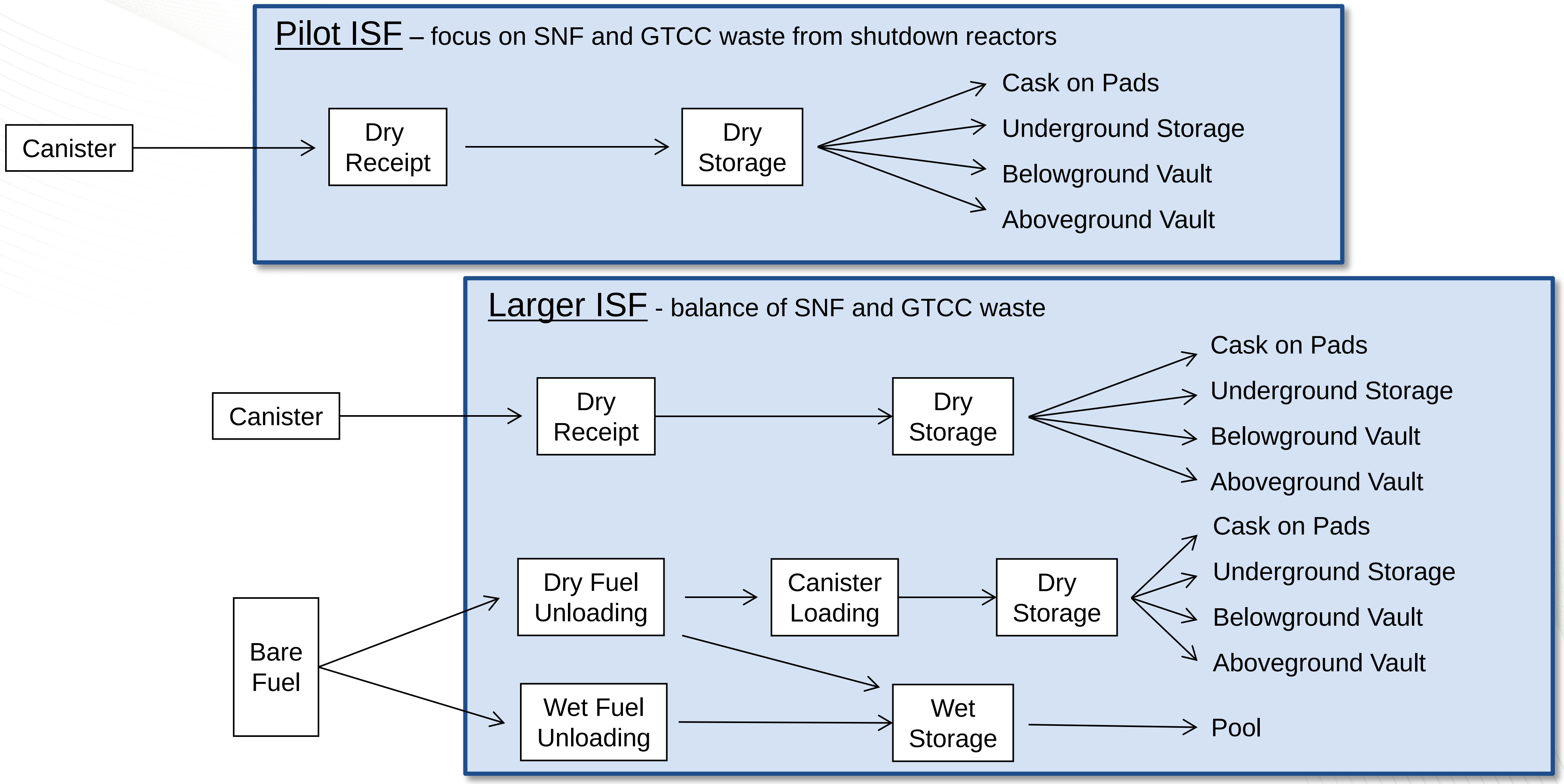
ORNL is managed by UT-Battelle for the US Department of Energy

OAK RIDGE
National Laboratory

DOE is planning for an integrated waste management system to transport, store, and dispose of SNF and HLW



The U.S. is taking a systematic approach – considering multiple design concepts



The U.S. Department of Energy Office of Nuclear Energy is funding efforts to support removal of commercial SNF from utility sites.

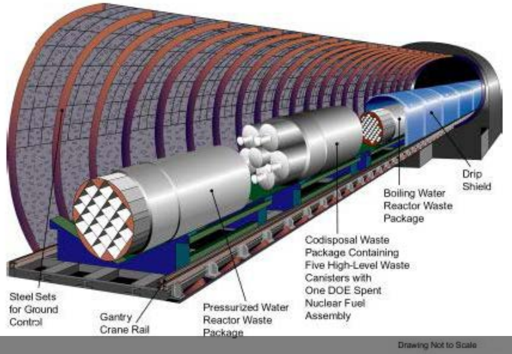
Goal: To identify alternatives and conduct scientific research and technology development to enable storage, transportation and disposal of spent nuclear fuel (SNF) and wastes generated by existing and future nuclear fuel cycles.

Overall DOE goals include:

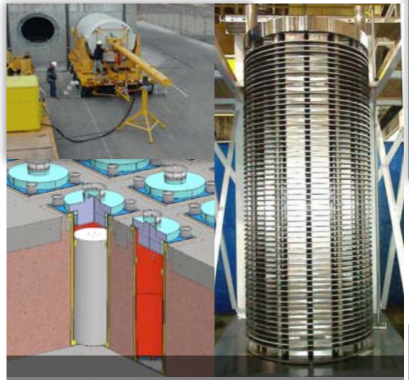
- Improve the overall integration of storage as part of the waste management system;
- Prepare for the large-scale transportation of SNF;

In support of these goals, near-term Storage and Transportation objectives include:

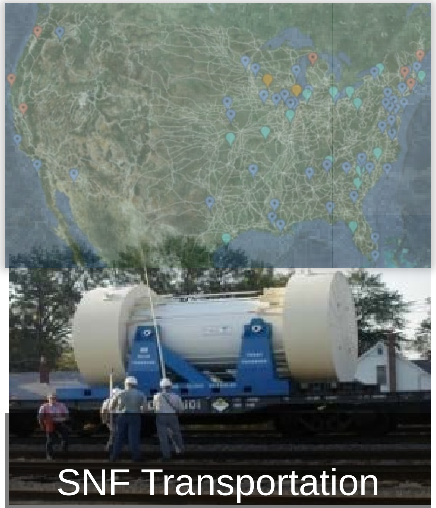
- Support the high-burnup (HBU) spent fuel full-scale storage data project;
- **Develop understanding of how temperature and pressure affect cladding integrity in HBU SNF**
- **Predictive modeling**
- **Experimentation**
- **Characterize external loadings on SNF during normal conditions of transport**



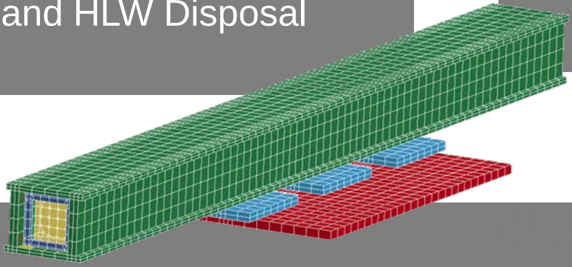
SNF and HLW Disposal



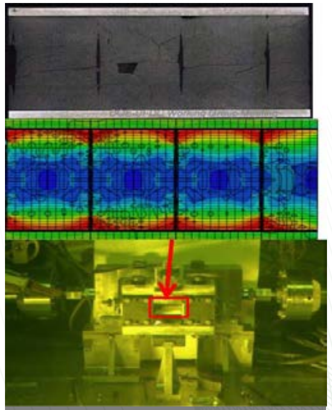
SNF Storage



SNF Transportation



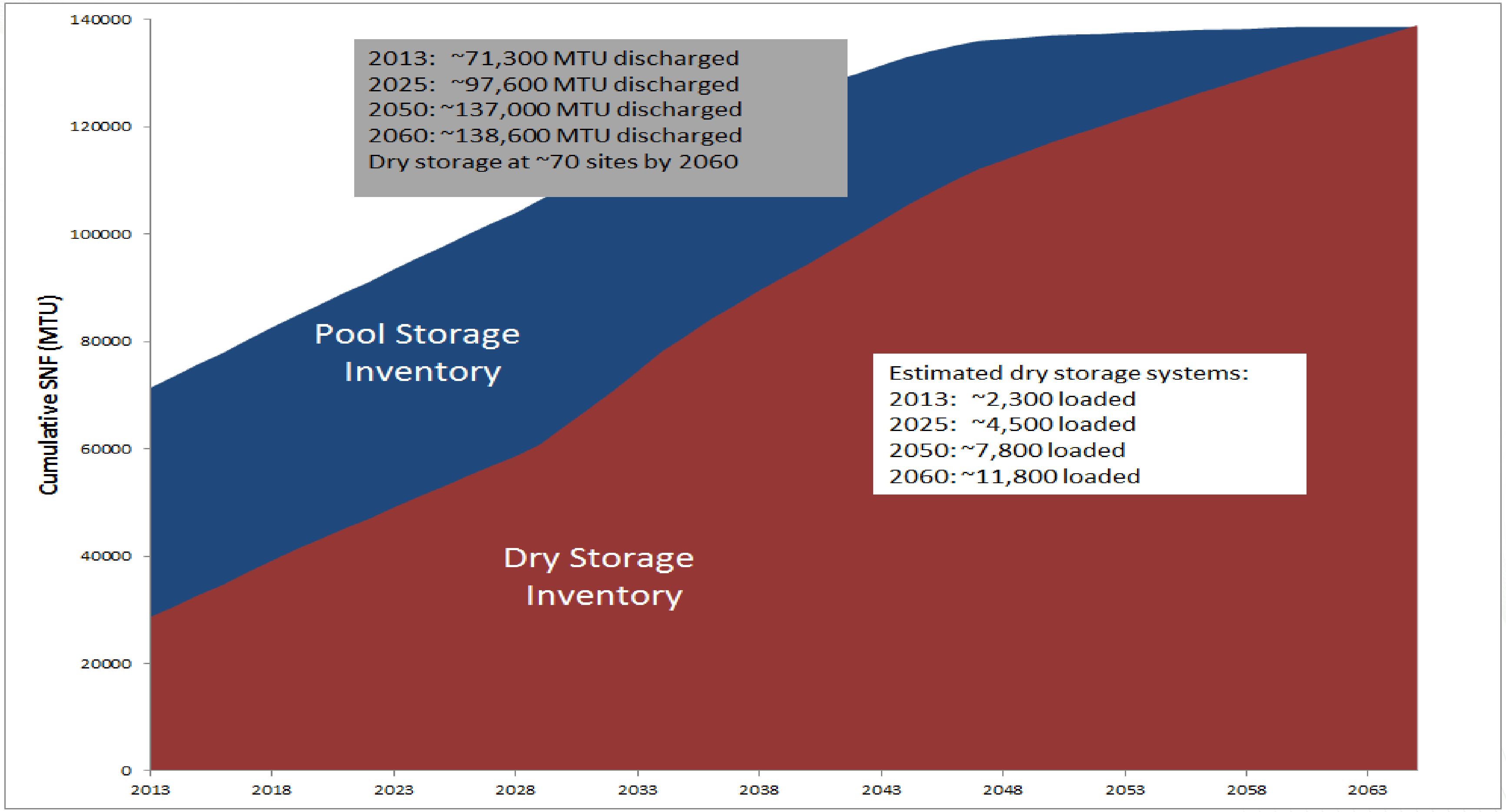
Surrogate Assembly Measurements



Fuel Testing

*

The U.S. is looking at SNF Storage now because commercial SNF in storage continues to increase by ~2,000 MTHM annually; 150 – 200 new dry storage canisters are loaded annually



Current Reactors Operate 60 Years Unless Announced Shutdown Date, 5 New Builds Operate 40 Years, Current ISFSI Practices

Source: Derived from Data in “Commercial Spent Nuclear Fuel and High-Level Radioactive Waste Inventory Report”, FCRD-NFST-2013-263, Rev. 4, June 30, 2016

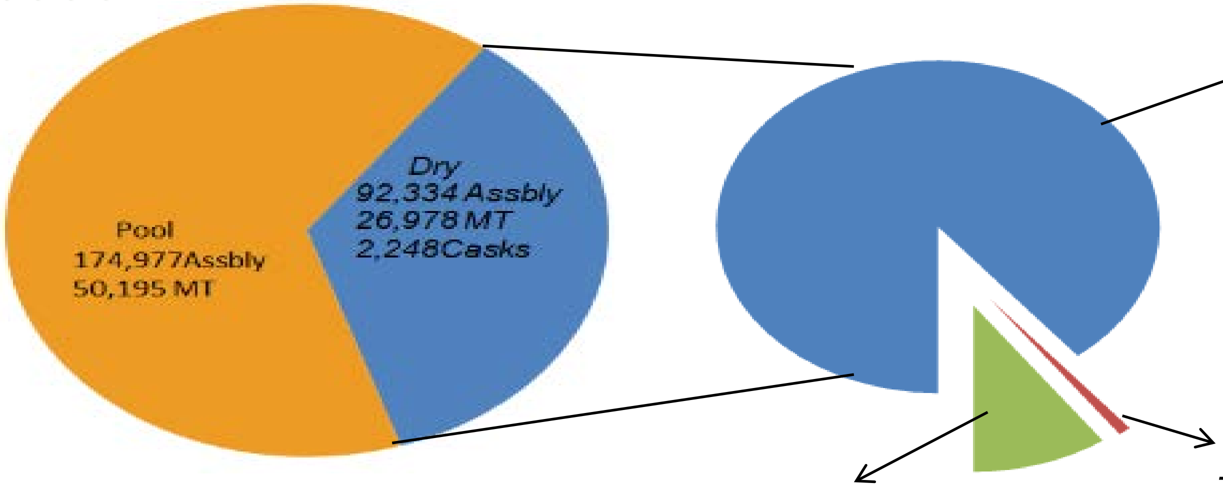
SNF is currently stored in both spent fuel pools and dry storage systems

Spent fuel pool at the San Onofre Nuclear Generating Station. Photo courtesy of the Nuclear Regulatory Commission.

A dry cask loaded with spent fuel being lifted from a horizontal transporter to be placed vertically on a storage pad. Photo courtesy of Sandia National Laboratories.

The existing commercial dry storage system inventory is diverse

Projected Reactor Discharges at Dec 2016, Dry Inventory as of May, 2016



2,032 Welded Metal Canisters In Vented Concrete Overpacks
82,318 Assemblies,
89.2% of Dry

Transnuclear (35.2%)
Holtec (49.7%)
NAC (12.9%)

204 Bolted-Lid Fuel Casks
9,150 Assemblies, 9.9% of Dry

12 Welded Metal Canisters in Transport Overpacks
866 Assemblies, 0.9% of Dry

- *Majority is in Large Welded Canisters*
- *Current dry storage inventory is diverse*
- *Trend toward higher capacities*

Transnuclear TN-32

Holtec Hi-Star 100

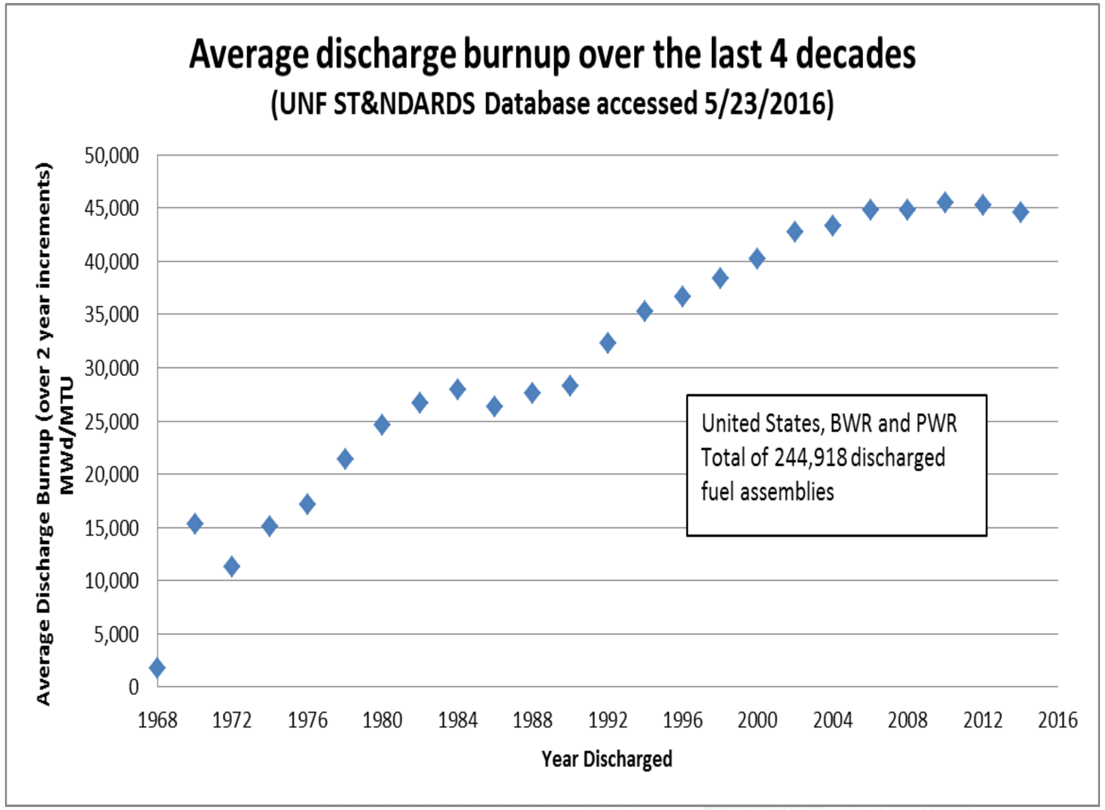
Source: Derived from Data in “Commercial Spent Nuclear Fuel and High-Level Radioactive Waste Inventory Report”, FCRD-NFST-2013-263, Rev. 4, June 30, 2016 and Data contained in ““Dry Storage Cask Inventory Assessment”, FCRD-NFST-2014-000602, Rev 2, August 30, 2016

R&D objectives reflect efforts to close knowledge gaps concerning SNF during storage and transport

1. **Support the development of the technical bases to demonstrate used fuel integrity for extended storage periods (aging management)**
2. **Support the development of the technical bases for fuel retrievability after long term storage**
3. **Support the development of the technical bases for transportation of high burnup fuel**

One technical concern is that SNF assembly average discharge burnups have steadily increased since the first reactor came online

- However, there is a scarcity of publically available data on HBU SNF properties
- In the US, typical SNF average assembly burnup has plateaued just above 45 GWd/MTU, and typical peak rod burnups are near 58 GW/MTU
- Per NEI (2012), dry storage of HBU fuel (>45 GWd/MTU) began in the last decade
  - Maine Yankee, beginning 2003, up to 49.5 GWd/MTU
  - Robinson, beginning 2005, up to 56.9 GWd/MTU
  - Oconee, beginning 2006, up to 55 GWd/MTU
  - Surry and North Anna, beginning 2007, up to 56.1 GWd/MTU



Average SNF discharge burnup from US commercial power reactors over the last four decades (ORNL)

OAK RIDGE National Laboratory

Thus, the US High Burnup SNF Data Project will experimentally define the effects of long-term storage and transportation on high burnup (HBU) SNF to provide data where there are knowledge gaps

- TN-32 cask to be loaded with HBU SNF in 2017 and opened in 2027 or later
- 25 “Sister Rods sent to ORNL for baseline testing
- Information to be collected for the project includes:
  - Initial condition of as-irradiated HBU fuel rods prior to drying, transfer and storage
  - **Impacts of drying, transfer, and storage on HBU fuel rods**
  - **Mechanical properties of HBU and dry-stored fuel rods**
  - **Effects of expected handling and transportation loads on the composite fuel system**
  - **Respirable release fractions from HBU fuel**

	1 6T0 Zirlo, 54.2 GWd 4.25%, 3cy, 11yr	2 (TC Lance) 3K7 M5, 53.4 GWd 4.55%, 3cy, 8yr	3 3T6 Zirlo, 54.3 GWd 4.25%, 3cy, 11yr	4 6F2 Zirlo, 51.9 GWd 4.25%, 3cy, 13yr	DRAIN PORT
5 3F6 Zirlo, 52.1 GWd 4.25%, 3cy, 13yr	6 (TC Lance) 30A M5, 52.0 GWd 4.55%, 3cy, 6yr	7 22B M5, 51.2 GWd 4.55%, 3cy, 5 yr	8 20B M5, 50.5 GWd 4.55%, 3cy, 5 yr	9 5K6 M5, 53.3 GWd 4.55%, 3cy, 8yr	10 5D5 Zirlo, 55.5 GWd 4.2%, 3cy, 17yr
11 Vent Port 5D9 Zirlo, 54.6 GWd 4.2%, 3cy, 17yr	12 28B M5, 51.0 GWd 4.55%, 3cy, 5 yr	13 F40 Zirc-4, 50.6 GWd 3.59%, 3cy, 30yr	14 (TC Lance) 57A M5, 52.2 GWd 4.55%, 3cy, 6yr	15 30B M5, 50.6 GWd 4.55%, 3cy, 5 yr	16 3K4 M5, 51.8 GWd 4.55%, 3cy, 8 yr
17 5K7 M5, 53.3 GWd 4.55%, 3cy, 8yr	18 50B M5, 50.9 GWd 4.55%, 3cy, 5 yr	19 (TC Lance) 3U9 Zirlo, 53.1 GWd 4.45%, 3cy, 10yr	20 0A4 ow-Sn Zy-4, 50 GW 4.0%, 2cy, 22yr	21 15B M5, 51.0 GWd 4.55%, 3cy, 5 yr	22 6K4 M5, 51.9 GWd 4.55%, 3cy, 8 yr
23 3T2 Zirlo, 55.1 GWd 4.25%, 3cy, 11yr	24 (TC Lance) 3U4 Zirlo, 52.9 GWd 4.45%, 3cy, 10yr	25 56B M5, 51.0 GWd 4.55%, 3cy, 5 yr	26 54B M5, 51.3 GWd 4.55%, 3cy, 5 yr	27 6V0 M5, 53.5 GWd 4.4%, 3cy, 8yrs	28 (TC Lance) 3U6 Zirlo, 53.0 GWd 4.45%, 3cy, 10yr
	29 4V4 M5, 51.2 GWd 4.40%, 3cy, 8yr	30 5K1 M5, 53.0 GWd 4.55%, 3cy, 8yr	31 (TC Lance) 5T9 Zirlo, 54.9 GWd 4.25%, 3cy, 11yr	32 4F1 Zirlo, 52.3 GWd 4.25%, 3cy, 13yr	

TN-32B cask for the High Burnup Spent Fuel Data Project

Each square represents a cask basket cell, with the cell identifier in the upper left corner and the identifying characteristics of the fuel assembly:

- Cell ID / cask instrument (TC Lance)
- Assembly identifier
- Cladding material, assembly average burnup
- initial enrichment, cycles operated, cooling time.

Red outline = cask fuel assemblies with rods considered to be sisters to one or more of the 25 sister rods

Orange outline = sister rod direct donor assemblies

* Red indicates data to be collected from ORNL SNF experiments

OAK RIDGE National Laboratory

Baseline testing on SNF is being done at ORNL. Twenty-five *sister rods* are being examined to provide a comparison point for the post-storage condition of the project cask rods

- Sister rods were received at ORNL in January 2016
- A *sister* or *sister rod* has similar characteristics to rods loaded into the project cask because they were extracted from assemblies with the same design and similar operating histories (symmetric partners) or from specific assemblies to be stored in the project cask
- Twenty-five 17×17 HBU rods from 7 commercial SNF assemblies operated at Dominion's North Anna Reactor will be examined
  - 9 M5™ rods
  - 12 Zirlo® rods
  - 2 low tin Zr-4 rods
  - 2 Zircaloy-4 rods

Above: Technicians at Dominion Virginia Power's North Anna nuclear plant prepare a shipping cask containing fuel rods from HBU assemblies for shipment to ORNL.
http://eprijournal.com/spent-nuclear-fuel-storage-demo-heats-up/

Right: The shipping cask is moved into the IFEL hot cell loading bay at ORNL.

OAK RIDGE National Laboratory
OAK RIDGE National Laboratory

Destructive examinations (DEs) will follow the NDE and will include a variety of testing to benchmark the pre-storage condition of the HBU SNF

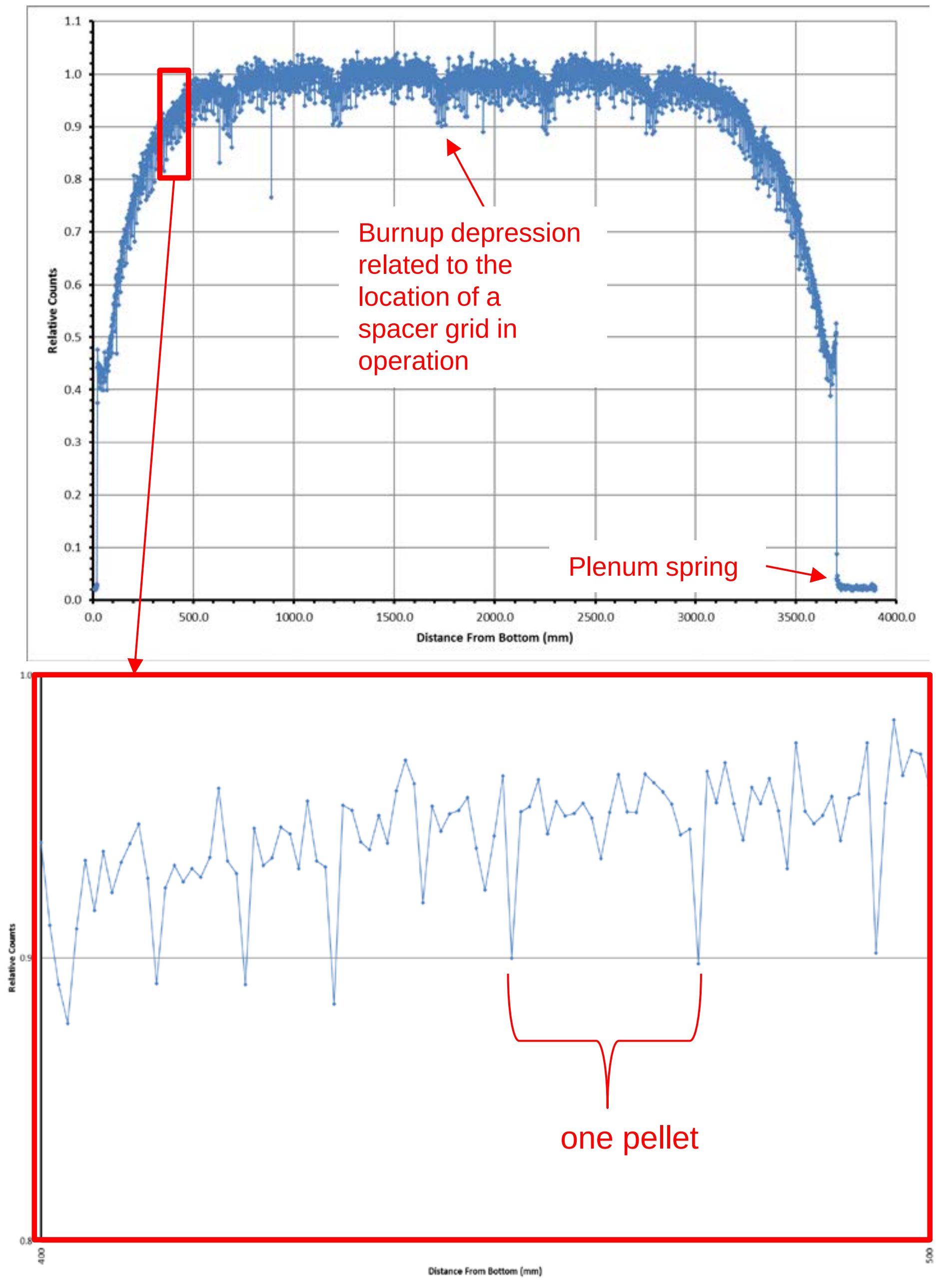
- Destructive examinations (DEs) will begin with rod puncture, gas sampling, and rod segmentation
- As each rod is punctured, rod internal pressure (RIP) will be measured
  - Pressure will be measured as a function of time as an indication of free communication through the pellet stack
  - Fission gas constituents, moles of each gas present, and rod free volume will be determined
  - The gas sample will be analyzed for the major fission gas isotopes
- Some of the 25 sister rods may be held in reserve for later use
- Some of the rods or rod segments will be heat treated to simulate cask drying conditions

Mechanical testing to be performed is still being specified, with several complimentary and overlapping tests being considered. Mechanical testing at various temperatures is also being planned.

- Proposed tests are being evaluated and prioritized and may include:
  - Fueled segments
    - Optical examinations, including metallography (MET) and scanning electron microscopy (SEM)
    - Spiral notch torsion toughness (SNTT)
    - Cyclic reversible bending fatigue (CIRFT)
    - Four-point bending
    - Ring compression testing
  - Defueled cladding
    - Clad hydrogen analysis (hot extraction method)
    - Tube tensile (axial) and burst testing
    - Ring compression testing
    - Expanded plug wedge testing
    - Hardness testing

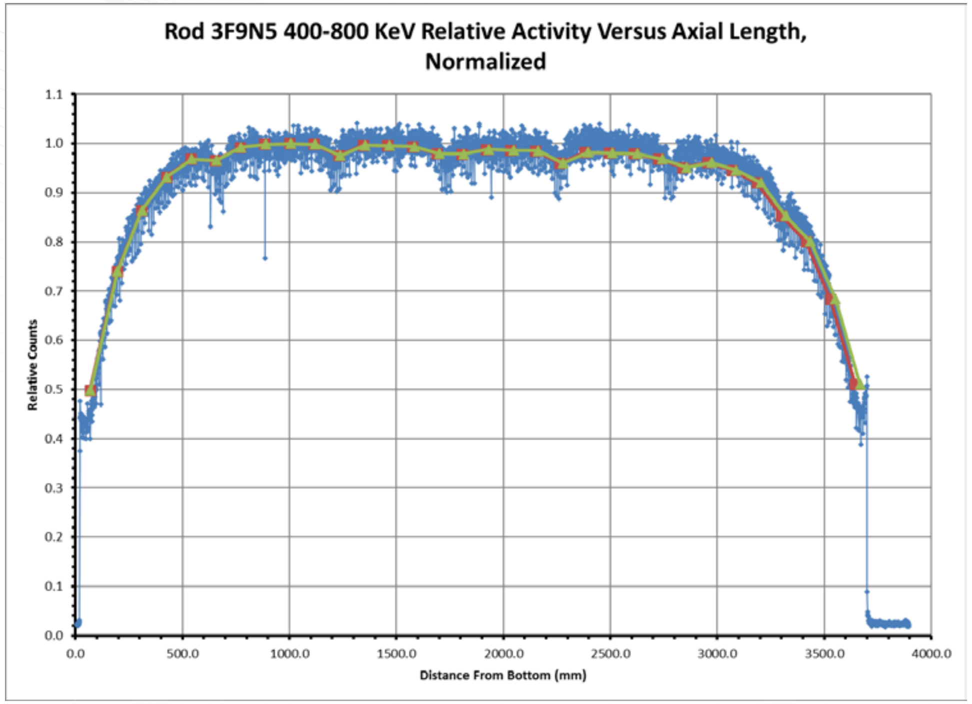
Gamma Scanning was completed on schedule; ORNL is now conducting profilometry

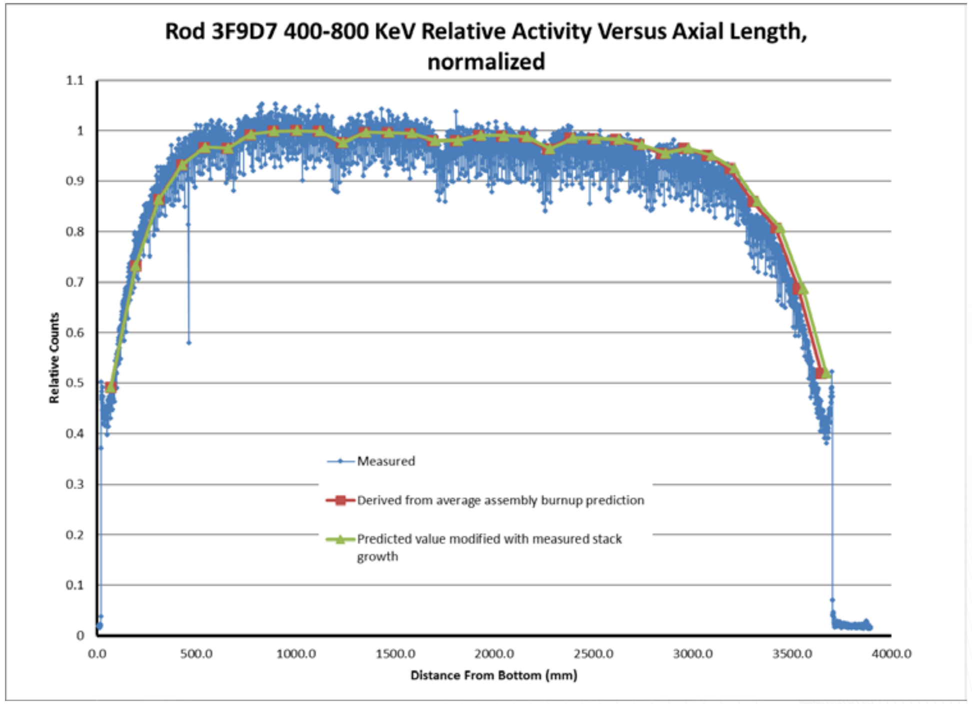
- One rod was measured at a time
- Goal is to define the overall axial burnup profile of the rod and look for any significant pellet gaps
- Measurements were taken at discrete points along the axis of the rod at ~1 mm intervals
- A NaI detector is used counting at 400 to 800 keV
- The detector isn't calibrated to a standard and all measurements are therefore relative
- The pellets are the source of the gammas and each pellet is observable
- Grid depressions are visible
- The plenum spring is visible but the rod end caps are not



National Laboratory

Preliminary Gamma Scanning results



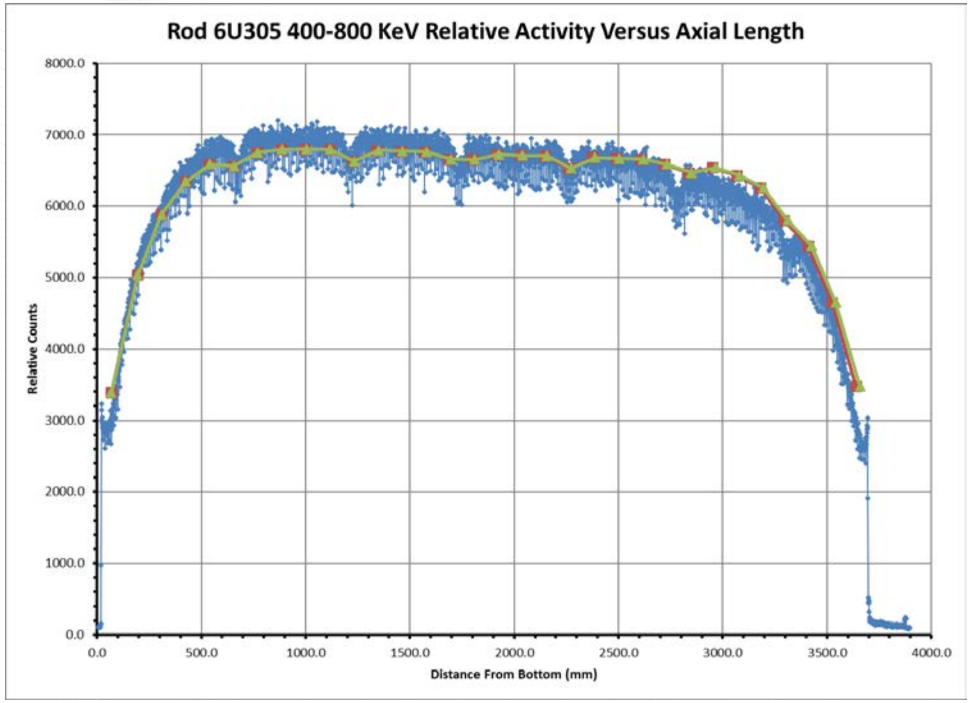


Assembly type: NAIF/P+Z
Cladding type: Zirlo
Avg. rod burnup/Avg. assembly burnup: 1.027
Stack growth: 0.640%
Rod growth: 0.402%
Anomalous indications: possible stack gap @800 mm

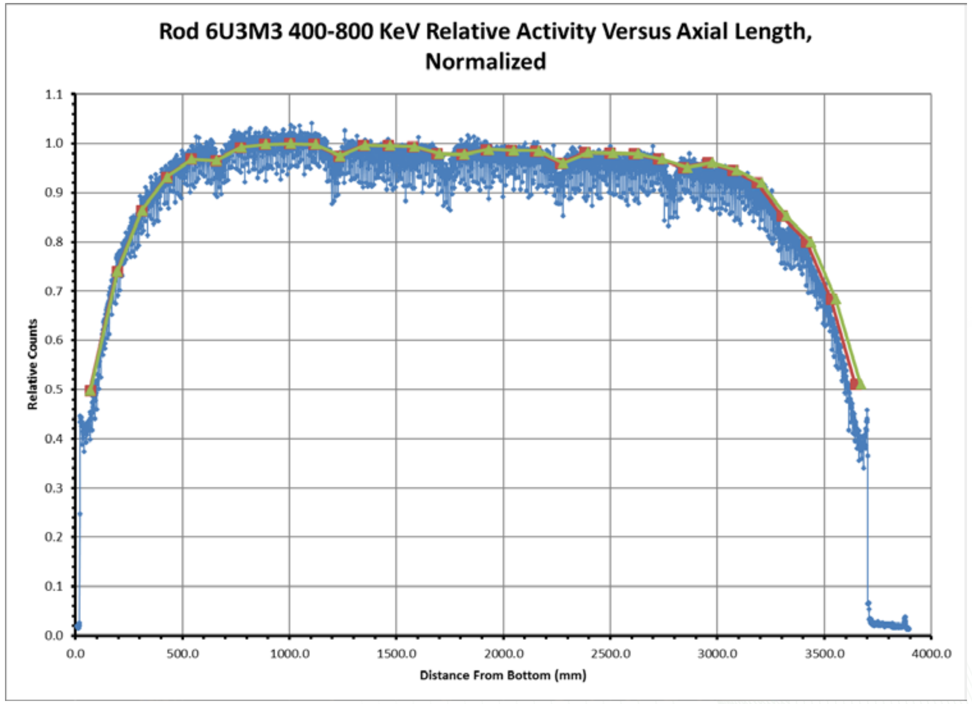
Assembly type: NAIF/P+Z
Cladding type: Zirlo
Avg. rod burnup/Avg. assembly burnup: 1.016
Stack growth: 0.722%
Rod growth: 0.351%
Anomalous indications: possible gap @462 mm

OAK RIDGE National Laboratory

Preliminary Gamma Scanning results



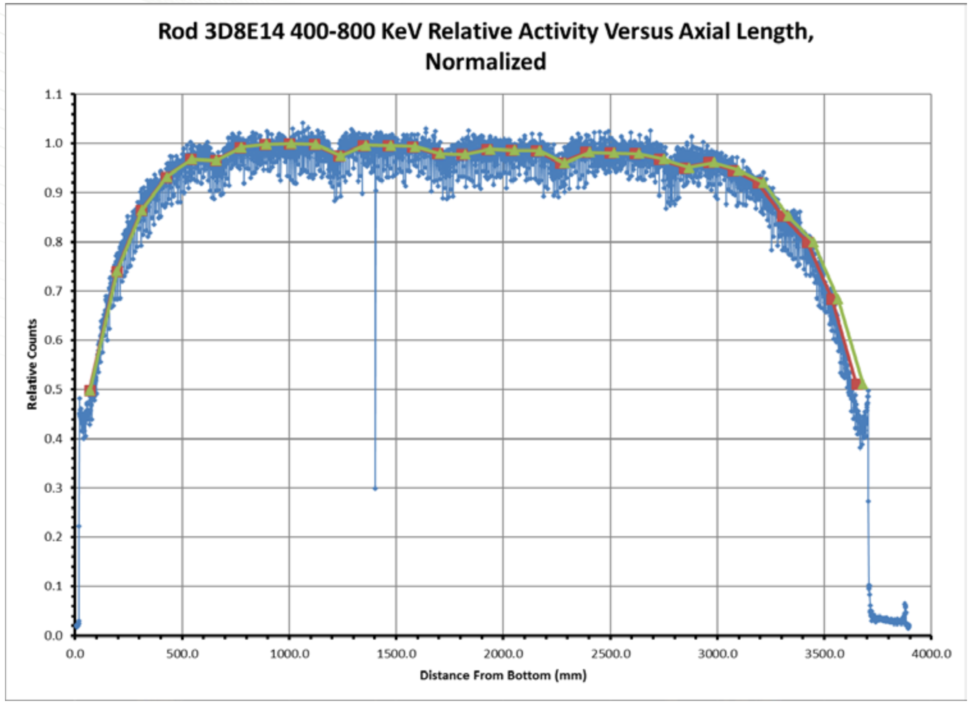
Assembly type: NAIF/P+Z
Cladding type: Zirlo
Avg. rod burnup/Avg. assembly burnup: 1.004
Stack growth: 0.503%
Rod growth: 0.362%
Anomalous indications: none



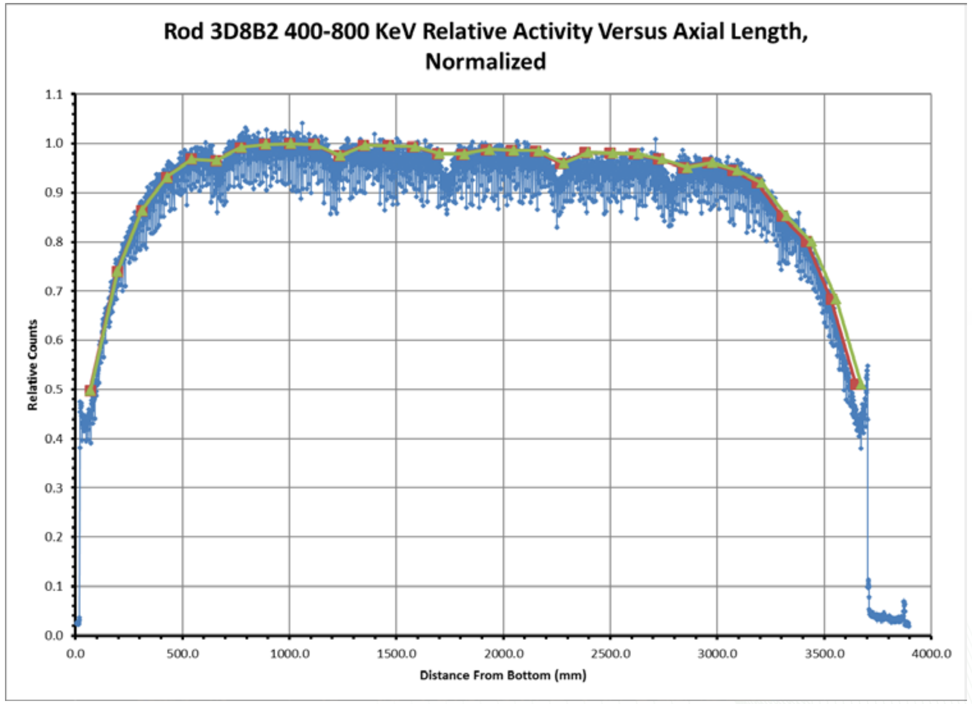
Assembly type: NAIF/P+Z
Cladding type: Zirlo
Avg. rod burnup/Avg. assembly burnup: 1.000
Stack growth: 0.667%
Rod growth: 0.405%
Anomalous indications: none

OAK RIDGE National Laboratory

Preliminary Gamma Scanning results



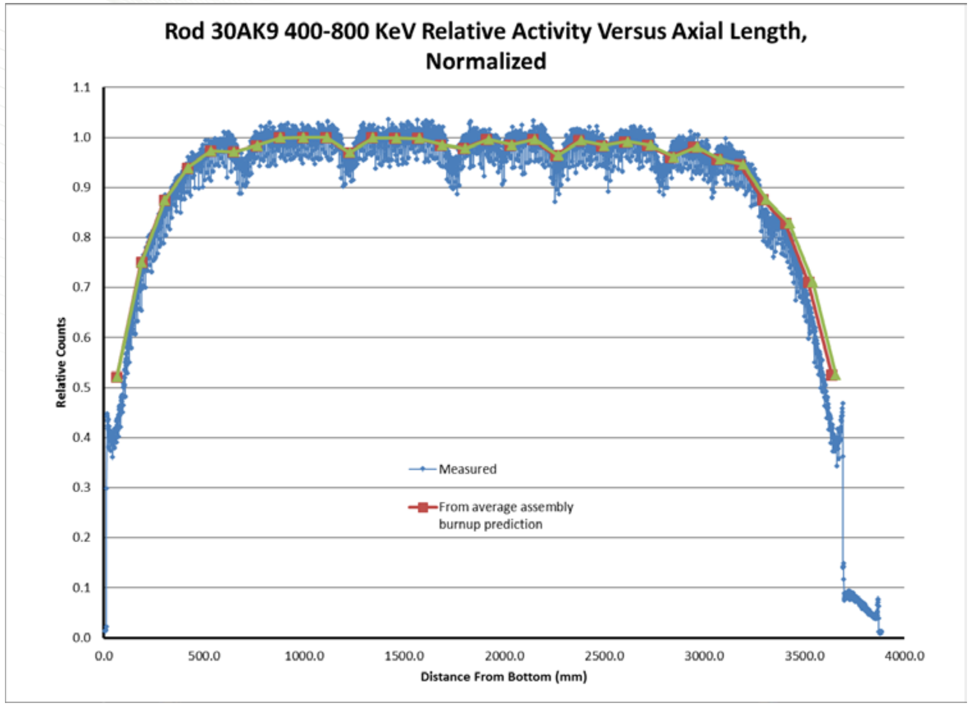
Assembly type: NAIF/P+Z
Cladding type: Zirlo
Avg. rod burnup/Avg. assembly burnup: 1.042
Stack growth: 0.804%
Rod growth: 0.448%
Anomalous indications: possible stack gap ~1400 mm



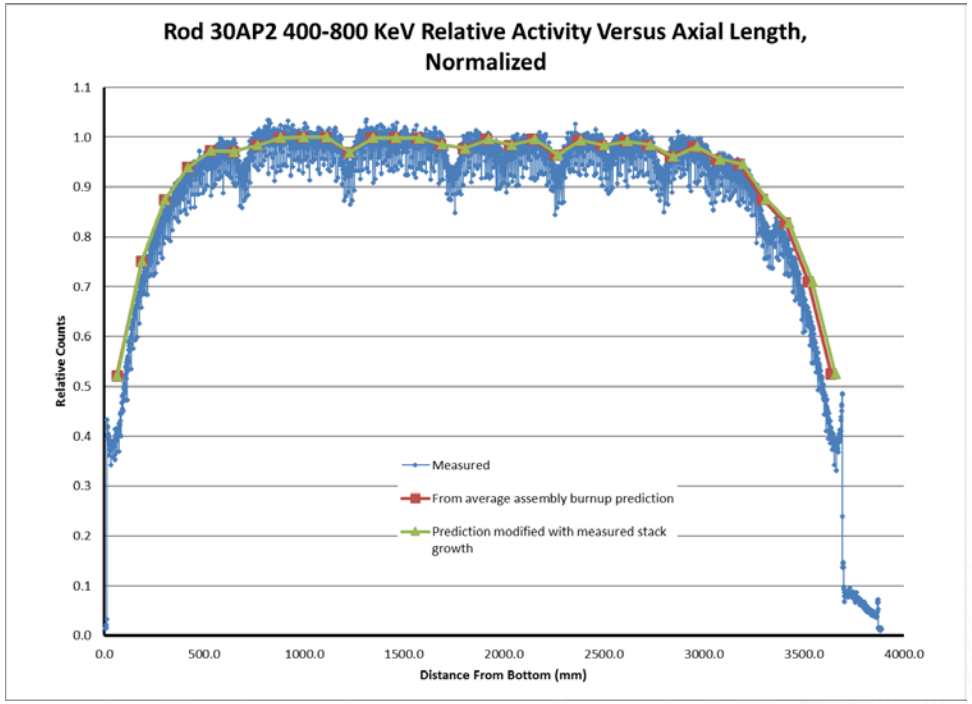
Assembly type: NAIF/P+Z
Cladding type: Zirlo
Avg. rod burnup/Avg. assembly burnup: 1.002
Stack growth: 0.694%
Rod growth: 0.340%
Anomalous indications: none

OAK RIDGE National Laboratory

Preliminary Gamma Scanning results



Assembly type: AMBW
Cladding type: M5
Avg. rod burnup/Avg. assembly burnup: 1.008
Stack growth: 0.585%
Rod growth: 0.415%
Anomalous indications: none



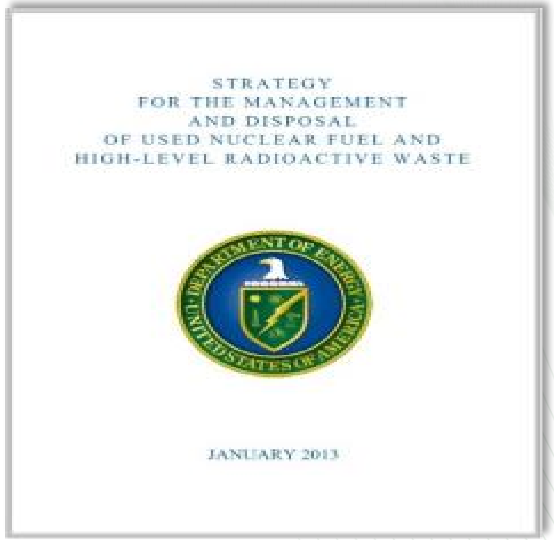
Assembly type: AMBW
Cladding type: M5
Avg. rod burnup/Avg. assembly burnup: 0.949
Stack growth: 0.585%
Rod growth: 0.422%
Anomalous indications: none

OAK RIDGE National Laboratory

Summary: The U.S. is planning for eventual consolidation of SNF and is conducting research to gather needed data. Long-Term program objectives include:

- Support the implementation of a full-scale NRC-licensed confirmatory storage demonstration facility, in collaboration with industry
- Develop the technical basis necessary to support eventual transportation of used nuclear fuel, including high-burnup fuel
  - Close technical gaps for extended dry storage
- Support the DOE's development of an Integrated Waste Management System that leads to implementation of integrated storage, transportation, and disposal concepts

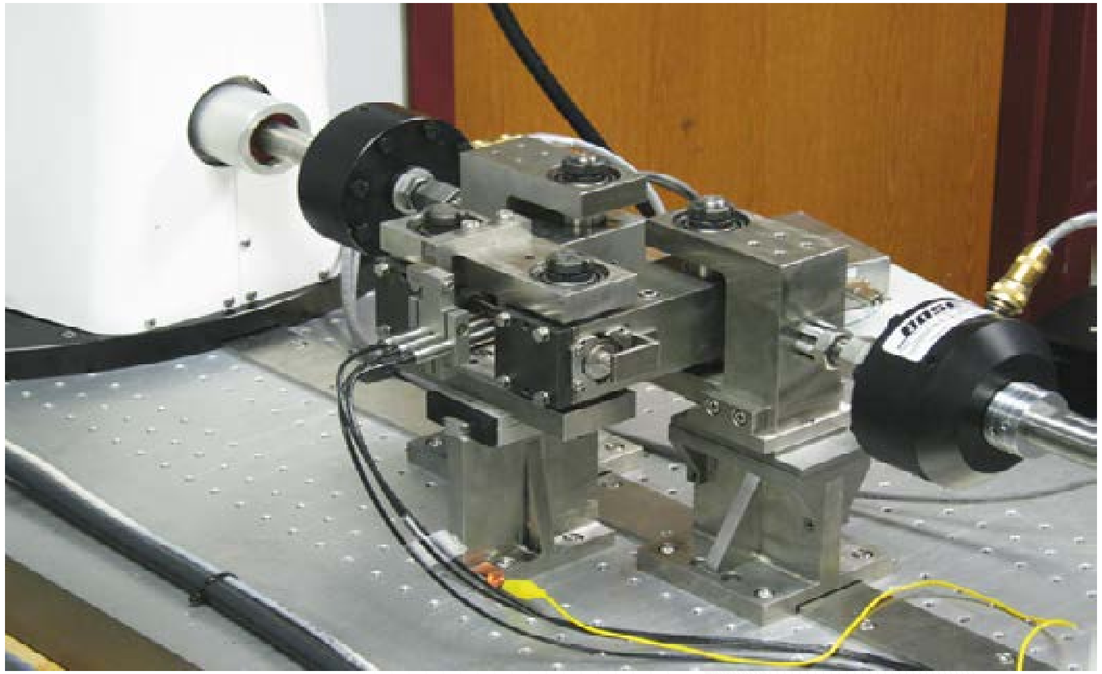
Support the Administration's 2013 *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste*



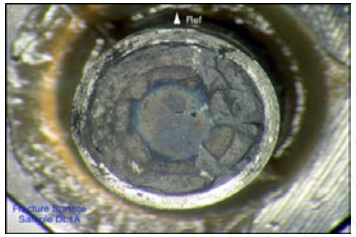
Backup Slides

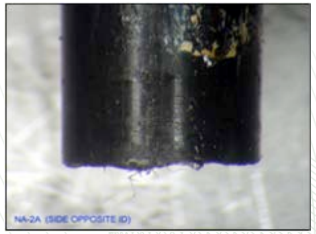
Cyclic integrated reversible-bending fatigue tester (CIRFT) will provide cumulative effects information on the fueled system during transport

- Minimum of 3 tests per rod:
  - Fatigue life (dynamic)
  - Mechanical properties (static)
  - Shock / impact effect on fatigue life (dynamic)
- Provides:
  - Load/cycle curve (S-N curve)
  - Fatigue strength
  - Flexural strength
  - Young's modulus
  - Ultimate tensile strength
- Also, for this test, any fuel aerosols that are released on rupture will be collected and quantified



The cyclic integrated reversible-bending fatigue tester (CIRFT)

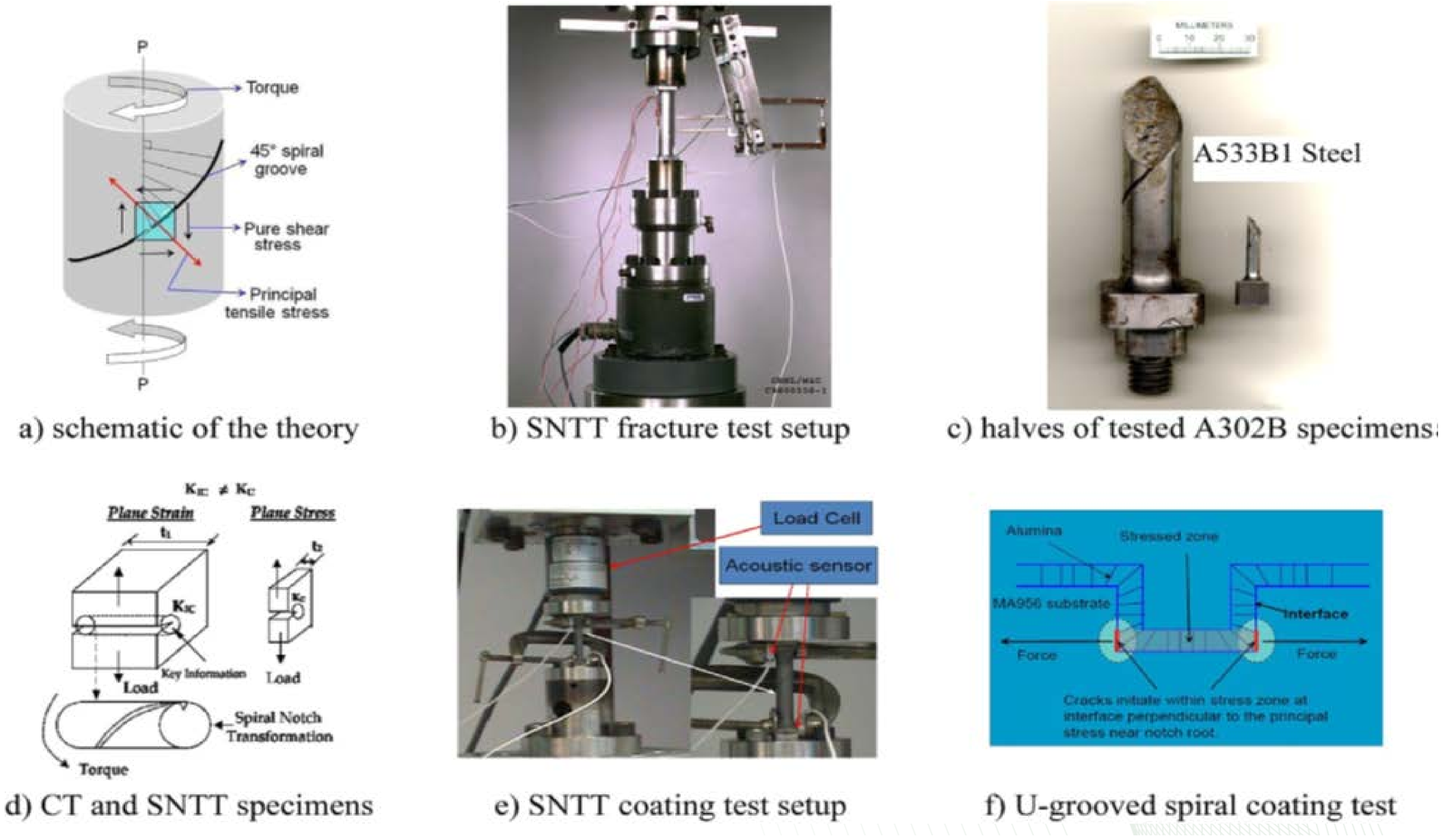




OAK RIDGE National Laboratory

Spiral Notch Torsion Testing (SNTT) will measure the fracture toughness of the composite pellet/clad system

- Predicts fuel performance during dynamic conditions
- Provides:
  - Fracture toughness,
  - Interface bonding efficiency
  - Torsional rigidity
  - Shear resistance/ modulus
  - Young's modulus
  - Ductile-to-brittle transition temperature (DBTT)



SNTT theory and test equipment

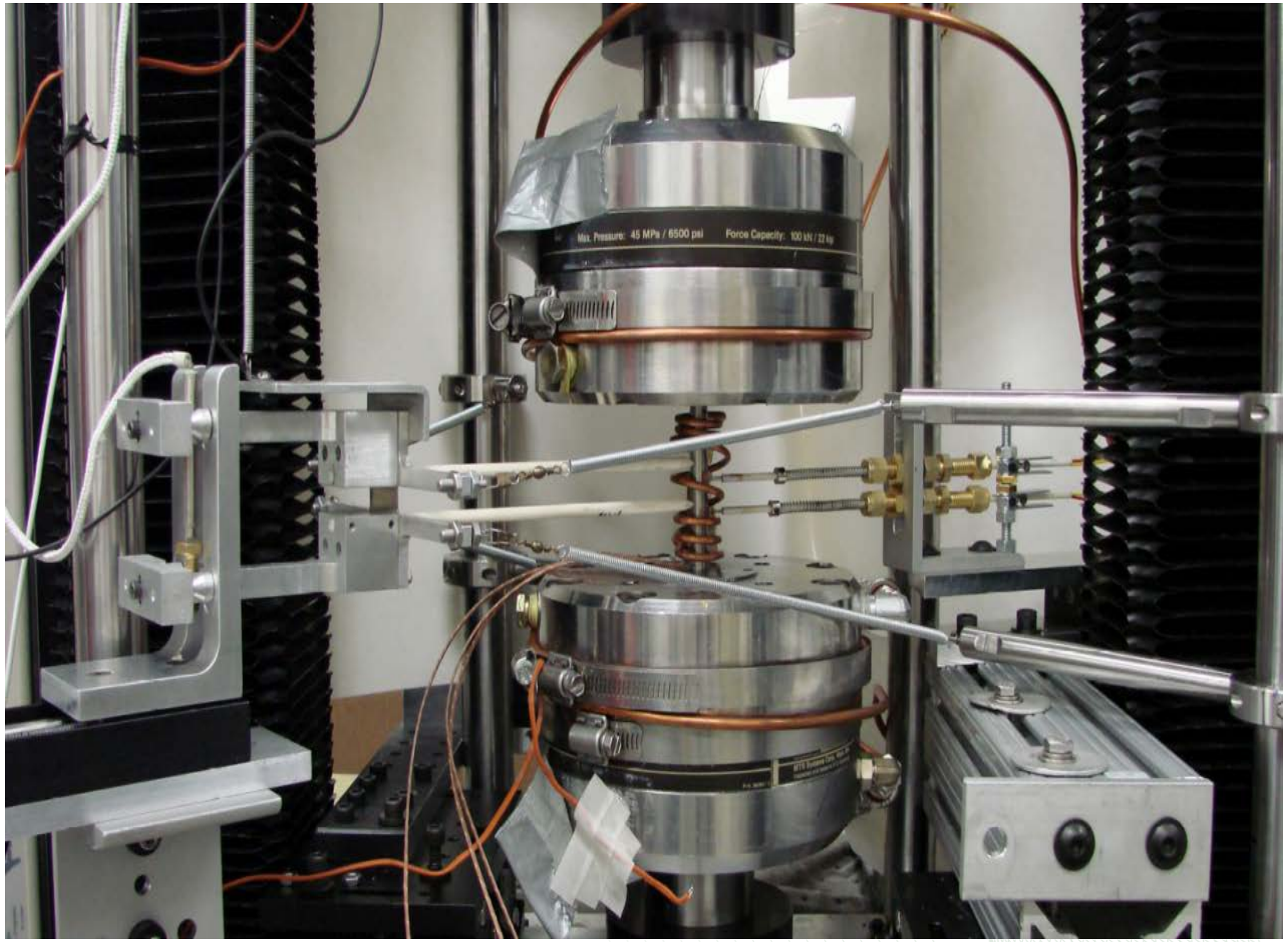
Ring Compression Testing (RCT) simulates a "pinch" type load at grid-spacer springs and potential rod contact on other fuel or the cask basket walls

- A database will be generated for fueled samples to compare to defueled tests being conducted at ANL, providing the following data:
  - Ductile/Brittle transition temperature (defueled testing)
  - Stress/strain in radial compression
  - Yield strength in radial compression
  - Young's modulus in radial compression
- Simulating drying conditions will allow evaluation of hydride reorientation affects

(b) Photograph of Instron 8511 with ring sample

Tube Tensile Testing (axial direction) provides the material properties of cladding (defueled)

- Information collected from these tests include:
  - Yield strength
  - Ultimate tensile strength
  - Uniform elongation
  - Total elongation
  - Young's Modulus
  - Poisson's ratio
  - Strain hardening
- Testing can be done at various temperatures

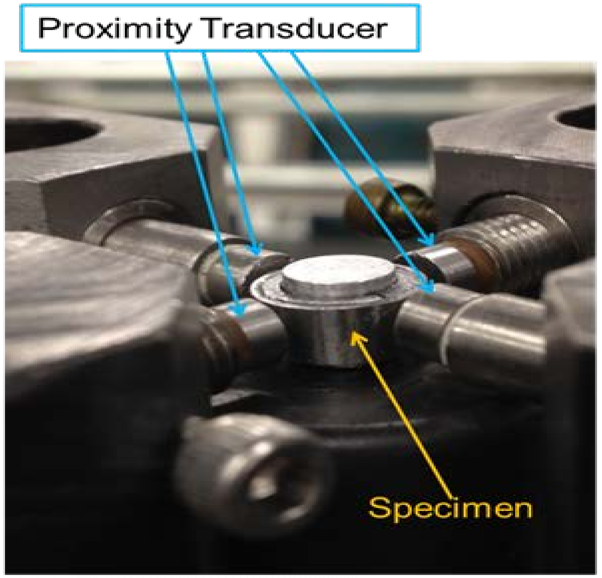


Tensile testing fixture (as configured for elevated temperature tests)

Expanded plug-wedge test provides transverse (hoop) tensile properties on clad materials

- Test methodology:
  - Utilizes four hardened steel wedges with an aluminum plug; when loaded, the plug will provide a radial expansion force to the clad ring.
  - Load-radial displacement data is converted into hoop stress-strain curves.
  - Test can be conducted at temperatures of interest
- Provides transverse (hoop) tensile properties:
  - Yield stress
  - Clad material hardening behavior
  - Ultimate tensile strength
  - Young's modulus
- Results also support DBTT analyses

MTS electro-magnetic load frame



Four Proximity Transducer

(Left) Side view, (Right) Top view of the tested specimen

Oak Ridge National Laboratory