Leaktightness of DOE Standardized SNF Canister

Presented to:

Nuclear Regulatory Commission

Brett Carlsen

Idaho National Laboratory

May 8 and 9, 2007

DOE SNF Transportation Safety

- Our safety strategy
  - To shift safety basis from reliance on fuel-specific performance characteristics to reliance on engineered barriers
- Our request
  - For NRC concurrence for the DOE standardized canister to be recognized and credited as a leaktight boundary during transportation

Meeting Objectives

- To demonstrate that canister analyses and testing is sufficient to confirm that canister integrity will preclude leakage under normal and hypothetical transportation accident scenarios
- To reach consensus on regulatory pathforward

Meeting Agenda
Tuesday, May 8

8:30 am	Canister Performance Objectives and Design
9:00 am	Canister Testing and Analyses
10:00 am	Break
10:15 am	Canister Testing and Analyses (continued)
11:15 am	Material Impact Testing
11:45 am	Public Comments
12:00 noon	Lunch
1:00 pm	Visit Test Facilities

Meeting Agenda
Wednesday, May 9

8:00 am	Recap yesterday and overview today
8:15 am	DOE SNF Characteristics
8:45 am	Aging/Degradation During Interim Storage
9:30 am	Reliability of Standardized Canister
10:00 am	Break
10:15 am	Pathforward
11:45 am	Public Comments
12:00 noon	Adjourn

Canister Performance Objectives and Design

Presented to:
Nuclear Regulatory Commission

Thomas Hill
Idaho National Laboratory

May 8, 2007

Outline

- Basis for Canister Design
- Design Performance Requirements
- Canister Modeling and Testing
- Prototype versus Detailed Design

Basis for Canister Design

- The purpose of the DOE canisters is to simplify the handling of DOE SNF during interim storage, transportation, and disposal at the repository
- Standardized DOE SNF canisters
  - Developed by DOE for DOE SNF sites
  - Used for interim storage, transportation, and disposal without reopening
  - Significantly minimizes fuel handling operations and worker exposure
  - Additional barrier for public safety
  - Provides a concept for interfacing with transportation package designs
  - Provides an interface for repository disposal

Evolution of the Standardized Canister Concept

- Each DOE SNF sites had unique cans for handling their SNF materials
- A joint DOE-EM/-RW meeting identified a vacant position in center of HLW disposal package (17-in. + diameter)
- Waste package adjusted to accommodate 18-in. pipe (24-in. pipe same as HLW can)
- Developed robust standardized canister for handling and loading into cask (up to 30-ft drop)
- Preclosure safety at repository surface facilities takes advantage of robust standardized canister and low probability of failure from 23-ft. drop

Planned Transportation Approach

- DOE-RW Transportation Cask studies in Summer 2004 identified the difficulties in shipping the multitude of DOE-EM SNF
  - Large rail cask, 7 to 9 canisters per cask
  - Cask vendors identified information required for transport of DOE-EM SNF prior to understanding the robust nature of the DOE standardized canister
  - Consolidating DOE-EM SNF in robust canisters would allow manageable approach to obtaining cask CofC.
- Independent review of DOE-EM approach to transportation resulted in recommendation to capitalize on robust nature of DOE standardized canister
- DOE-EM elected to prepare topical report on a standardized canister with a single basket for review and acceptance by NRC and subsequent use by cask vendors

Design Performance Requirements

- Interim Storage – 10CFR72
  - Deterministic
- Transportation – 10CFR71
  - Deterministic
- Disposal – 10CFR63
  - Risk informed
  - Performance allocation
- ASME B&PV Code Section III, Division 1

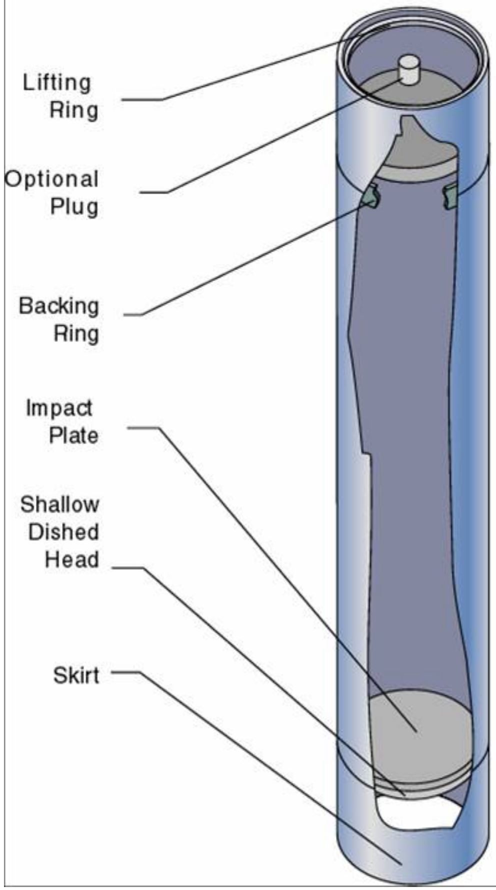
Standardized Canister Design Specification

- DOE-EM developed a preliminary design specification for the DOE Standardized Canister for DOE-EM site use
- DOE-ID contracted for the Idaho Spent Fuel Project invoking the preliminary design specification
- DOE-ID contractor prepared ASME Design Specification and design drawings for 18 and 24-in. diameter standardized canisters
- DOE-EM will make the Idaho Spent Fuel Project canister design documents available to other DOE sites for their use in packaging DOE-EM SNF

Design Specification Requirements

- Design Pressure – 50 psi
- Operating Pressure – 22 psi
- Design Temperature – 650/350 F
- Operating Temperature – 600/300 F
- Envelope Dimensions
- Weight Limits
- ASME B&PV Code stamped

Standardized DOE Spent Nuclear Fuel Canister



Nominal Outside Diameters:
18 in. and 24 in.

Wall Thickness:
3/8 in. for 18 in. canister
1/2 in. for 24 in. canister

Maximum Weight with Fuel:
5,000 to 10,000 lbs.

External Lengths:
Short Canister: 118.11 in.
Long Canister: 179.92 in.

Material:
Canister Body: SS316 L

GT00 0119

Canister Design Considerations

- Robust design
- Construct per American Society of Mechanical Engineers Boiler & Pressure Vessel Code Section III
- Material compatible with SNF contents and waste package
  - Corrosion resistant materials, austenitic stainless steel
  - >40 year design life
- Seal welded
  - Leak test to 1 x 10-4 std•cm3/s
- Four unique geometries
  - 18-inch and 24-inch nominal diameters
  - 10-foot and 15-foot nominal lengths

Transportation Accident Assumptions

- Canister subjected to 100g loading from cask
- Cask limits loads transmitted to canister
- Cask provides thermal barrier for hypothetical fire event
- Cask provides shielding function

Extensive Canister Modeling and Testing Program

- Canister modeled and analyzed using finite element analysis computer program ABAQUS/Explicit
  - Analyzed for 10CFR71.73 case drops
  - Analyzed for repository drop events
- Materials property testing program (dynamic and static)
  - Elevated and low temperature testing
  - Flaw propagation testing

Extensive Canister Modeling and Testing Program (cont'd)

- Full scale drop tests performed in 1999 and 2004 proved design concept
- Full-scale testing of 18-inch and 24-inch standardized canisters at Sandia drop test facility
  - Completed nine drop tests with prototype standardized canisters
    - Drop heights per 10 CFR 71.73(c)
    - 30-foot drop onto an essentially unyielding horizontal surface
    - 40-in drop onto a 6-in diameter bar
  - Completed two drop tests with Idaho Spent Fuel Project designed standardized canisters
  - Helium leak testing demonstrated leak-tight containment after drops on most damaged canisters
  - Computer analysis deformations matched actual results

DOE Prototype Canister vs Idaho Spent Fuel Project Canister

- Prototype Canister
  - Preliminary Design Specification
  - ASME B&PV Code Section III, Division 3
  - Uniform thickness head welded to pipe body
  - No shield plug, dependent on NSNFP remote closure weld and inspection development
  - Simplified vent plug
- Idaho Spent Fuel Project Canister
  - ASME Code certified design specification and drawings
  - ASME B&PV Code Section III, Division 1, and Code Case N-595
  - Thicker head material machined to match pipe body
  - Shield plug and shoring plug to permit semi-remote welding of top closure
  - Detailed design of vent plug

Standardized DOE SNF Canister Testing & Analysis

Presented to:
Nuclear Regulatory Commission

Spencer D. Snow
Idaho National Laboratory

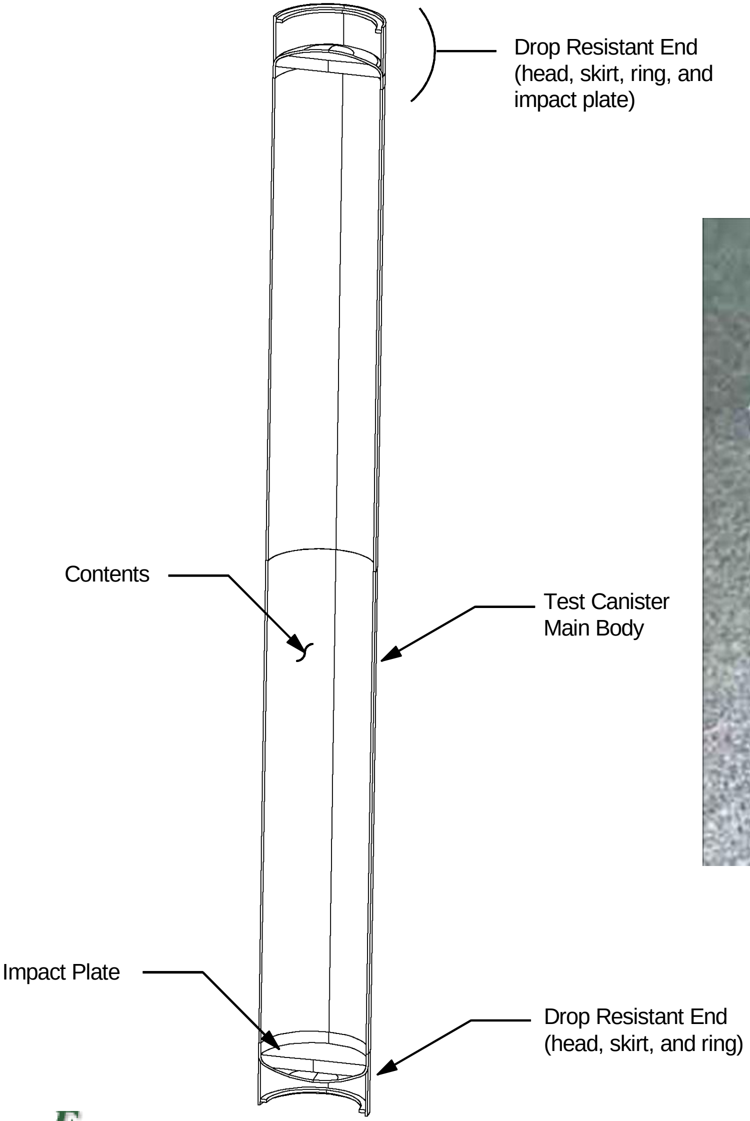
May 8, 2007

Outline

- Prototype canister
- FY1999 prototype canister drop testing
- Standardized DOE SNF canister design
- FY2004 standardized canister drop testing
- Analytical modeling of canister drop testing
- Canister transportation analyses
- Summary

Prototype Canister

Prototype Canister Section Views

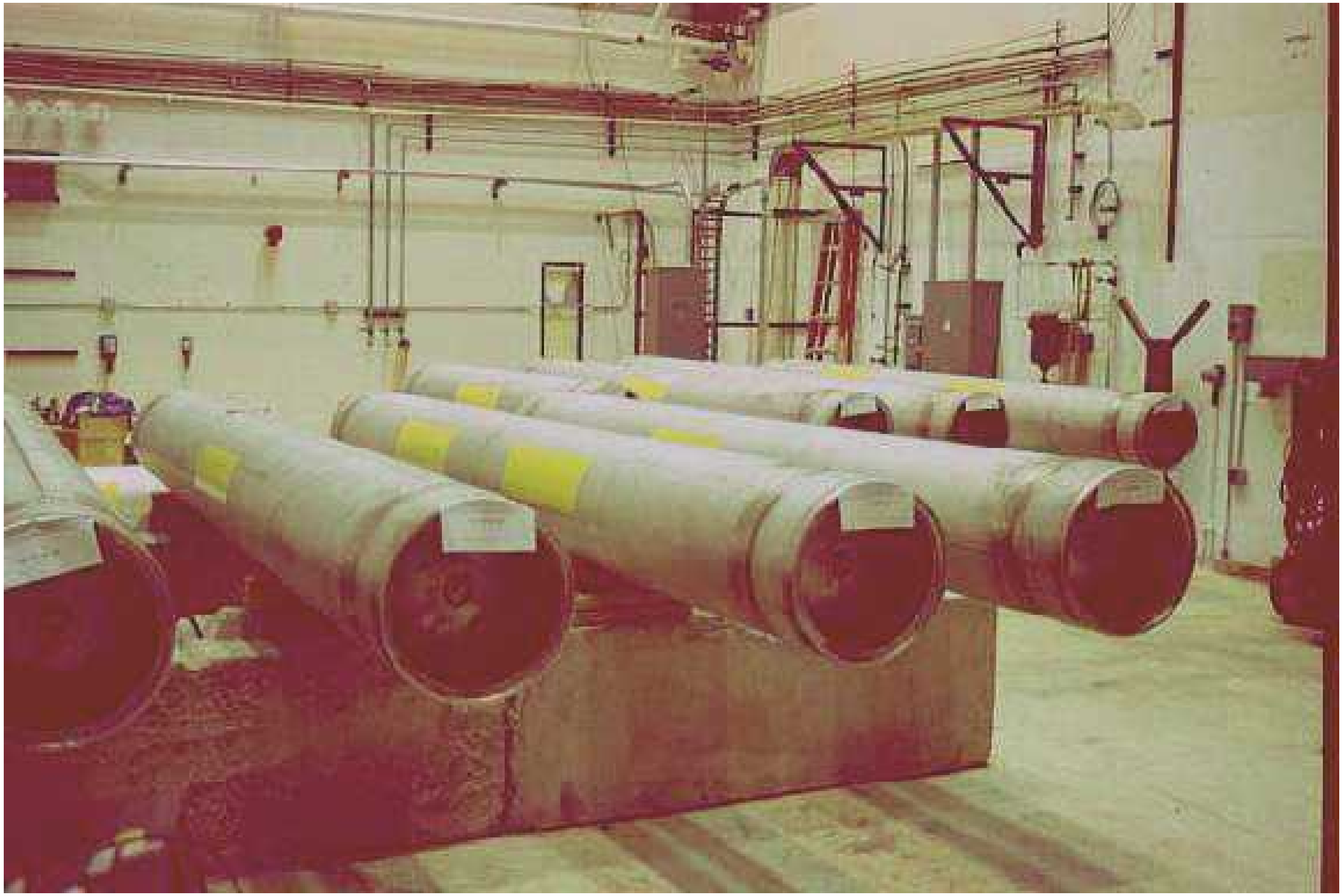


Prototype Canister Capacities

Canister Nominal Diameter (in.)	Nominal Wall Thickness (in.)	Nominal Overall Length (ft.)	Maximum Design Weight (lbs)
24	1/2	15	10000
		10	9000
18	3/8	15	6000
		10	5000

FY1999 Prototype Canister Drop Testing

Prototype Canisters Fabricated and Prepared at the INL



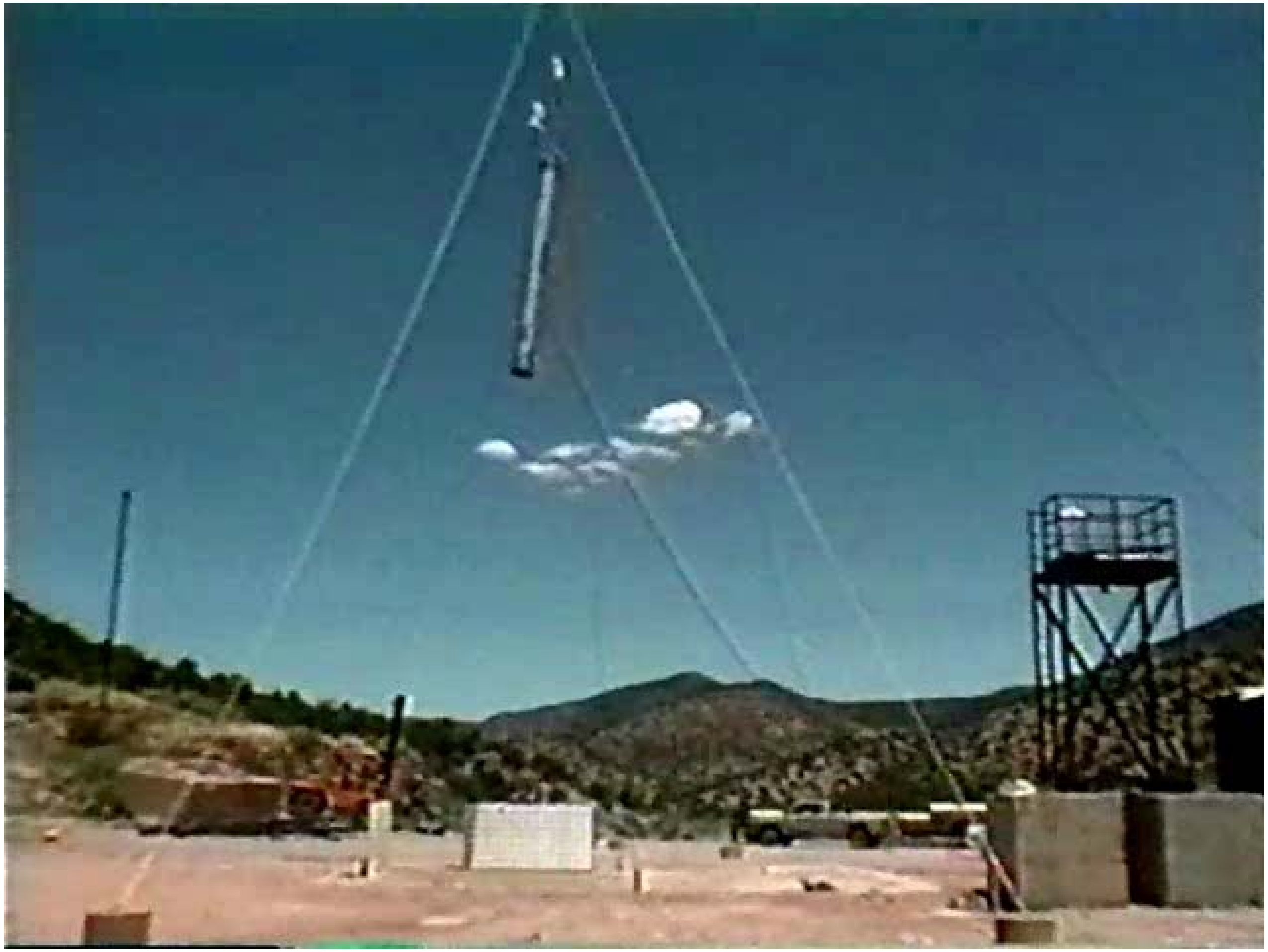
Nine 18" Diameter Prototype Canisters Drop Tested at SNL in FY1999

Canister Label No.[3]	Length (ft.)	Desired Impact Angle[1]	Total Weight (lbs)	Drop Height (ft.)	Contents[2]
18-15-00-01	15	0	6033	30	sleeve, spoked-wheel basket
18-15-06-02	15	6	5948	30	sleeve, spoked-wheel basket
18-15-90-03	15	90	5995	30	sleeve, spoked-wheel basket
18-15-45-04	15	45	5995	30	sleeve, spoked-wheel basket
18-15-80-05	15	80	5965	30	sleeve, spoked-wheel basket
18-10-90-06	10	90	3802	30	simulated High Integrity Cans
18-10-90-07	10	90	2997	30	simulated Shippingport fuel
18-15-PW-08	15	0	5972	2	spoked-wheel basket
18-15-PP-09	15	90	6085	40 inches	spoked-wheel basket

1. Impact angle in degrees is with respect to vertical.
2. Contents include rebar for all canisters.
3. Canister diameter – overall length – impact angle – canister number

Prototype Canister Internals

FY1999 Drop Testing
Selected Drops



Prototype Canister Resulting Deformations

Vertical Drop

6° Off-Vertical Drop

(Spoked Wheel Baskets)

45° Off-Vertical Drop

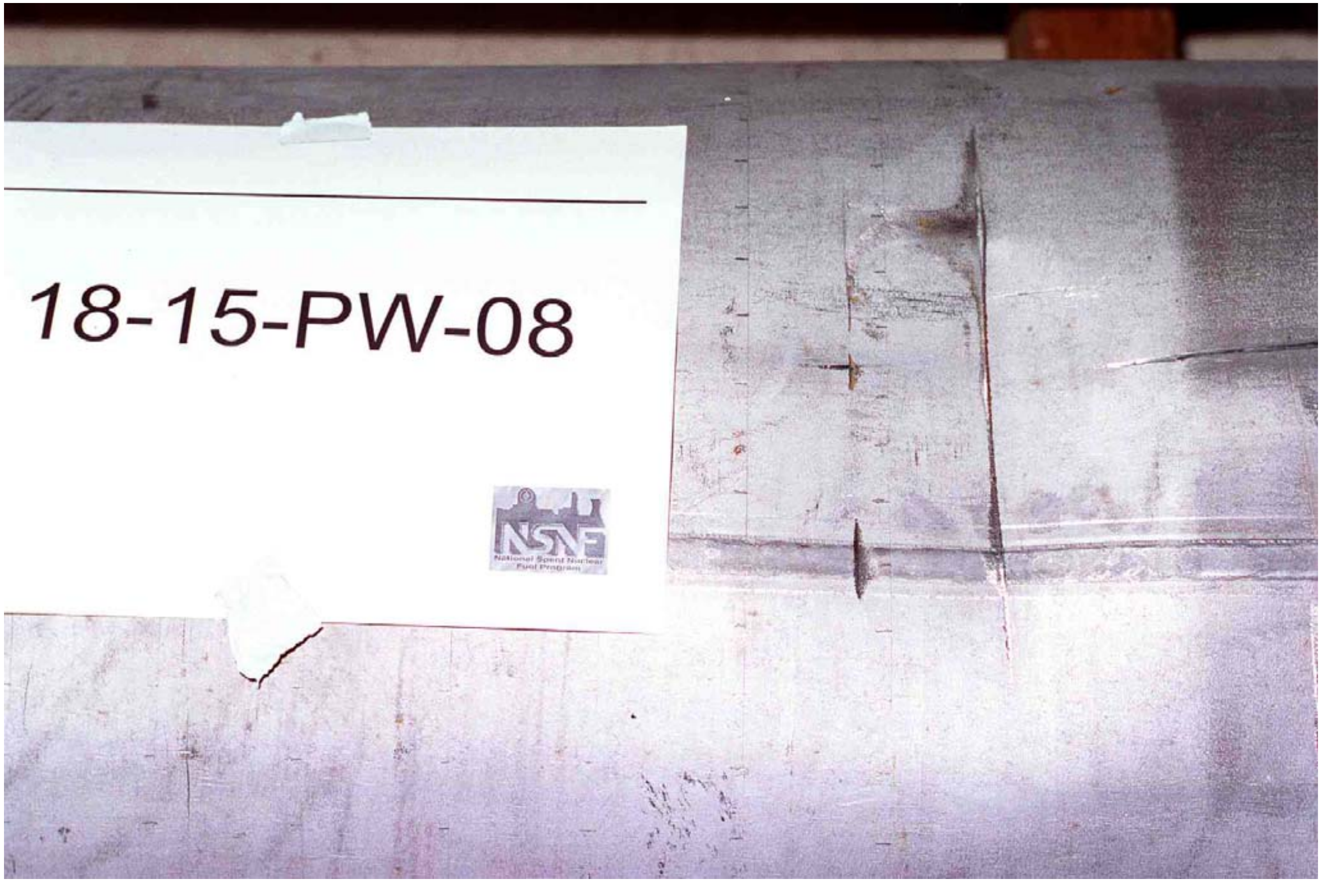
Resulting Deformations: Horizontal Drops

(10-ft. Prototype Canisters)

18-10-90-06
(High Integrity Cans)

18-10-90-07
(Shippingport Fuel Bundles

Resulting Deformations: Waste Package Edge Drop



Resulting Deformations: Puncture Drop

**(Spoked Wheel Basket,
Post Impacting Empty Sector)**

Post-Drop Evaluations

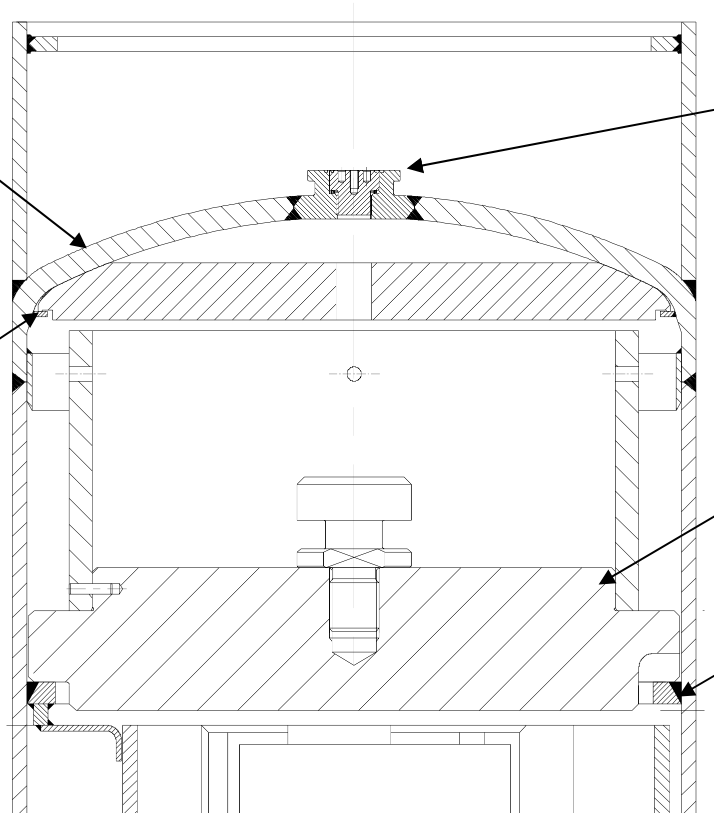
- No material rupture of any canister (no visual indication of impending material failure)
- All canisters held 50 psig for 1 hour
- Four worst damaged canisters were helium leak tested (per ANSI N14.5).
  - Results showed helium leak rates of less than 10^{-7} std cc/sec
- Liquid penetrant tests on the skirts where deformed the most showed no surface cracks

Standardized DOE SNF Canister Design

Standardized DOE SNF Canister Design

- Developed from the prototype canister for the Idaho Spent Fuel Project. Modifications include:
  - Thicker heads
  - Internal impact plate retaining rings welded to the inner surface containment boundary (heads)
  - Internal shield plugs
  - Shield plug support rings welded to the inner surface containment boundary (shell)
  - More substantial access port
  - No internal sleeve

Design Modifications



Thicker Heads

Access Port

Impact Plate Retaining Ring

Shield Plug

Shield Plug Support ring

FY2004 Standardized Canister Drop Testing

FY2004 Standardized Canister Drop Testing

- Two 24-inch diameter, 15-foot long, canisters were drop tested at Sandia National Laboratories in August 2004

Canister Label	Length (ft.)	Desired Impact Angle (deg.)	Total Weight (lbs)	Drop Height (ft.)	Contents
24MOD-45-1	15	45	10010	30	spoked-wheel basket, rebar, shield plug
24MOD-70-2	15	70	10027	30	spoked-wheel basket, rebar, shield plug

Test Canisters Fabricated and Prepared at the INL

FY2004 Test Canister Internals

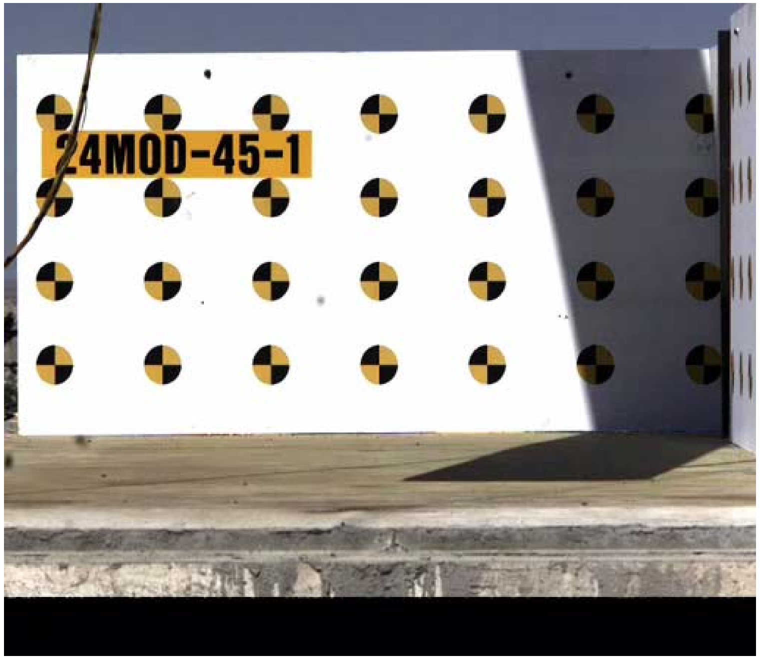
Bottom Spacer

Basket

Shield Plug

Rebar

FY2004 Drop Testing
45° Drop



Resulting Deformations: 45° Drop

Bottom End

Top End

Post Drop Evaluations

- No material rupture of any canister (no visual indication of impending material failure)
- Canisters held 50 psig for 1 hour
- Canisters were helium leak tested (per ANSI N14.5)
  - Results showed helium leak rates of less than 10^{-7} std cc/sec.

Analytical Modeling of Canister Drop Testing

Analytical Modeling

Purposes:

- Predict the deformed post-drop condition of each test canister
- Develop a validated analysis methodology for future use

Analysis Software:

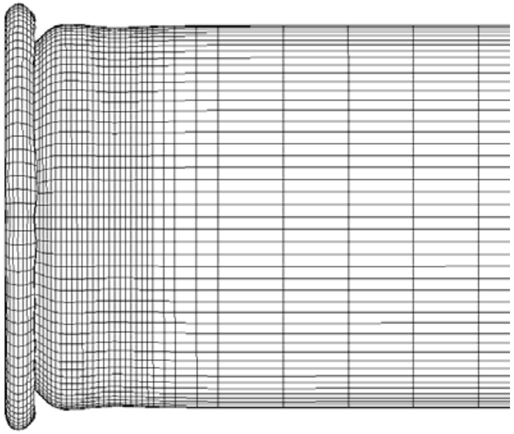
- ABAQUS/Explicit

316L Material Properties:

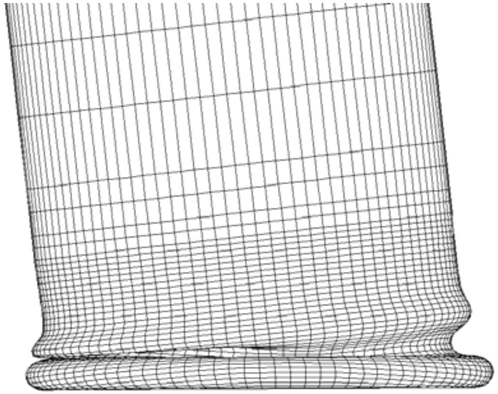
- Quasi-static stress-strain curves from INL testing
- Dynamically amplified stress-strain curves (1.2 factor on stress) to account for strain rate effects

Actual vs. Predicted Deformations

Vertical



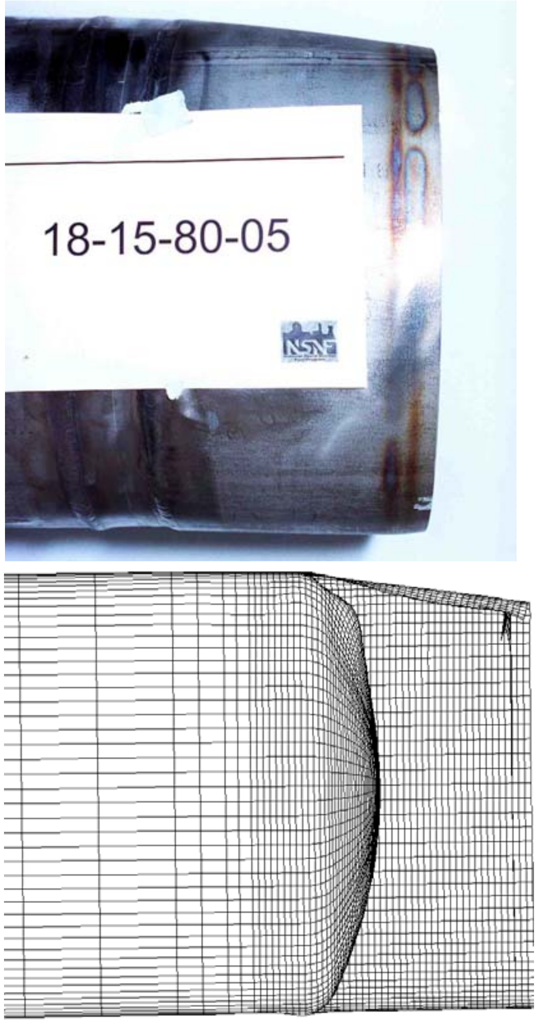
6° Off-Vertical



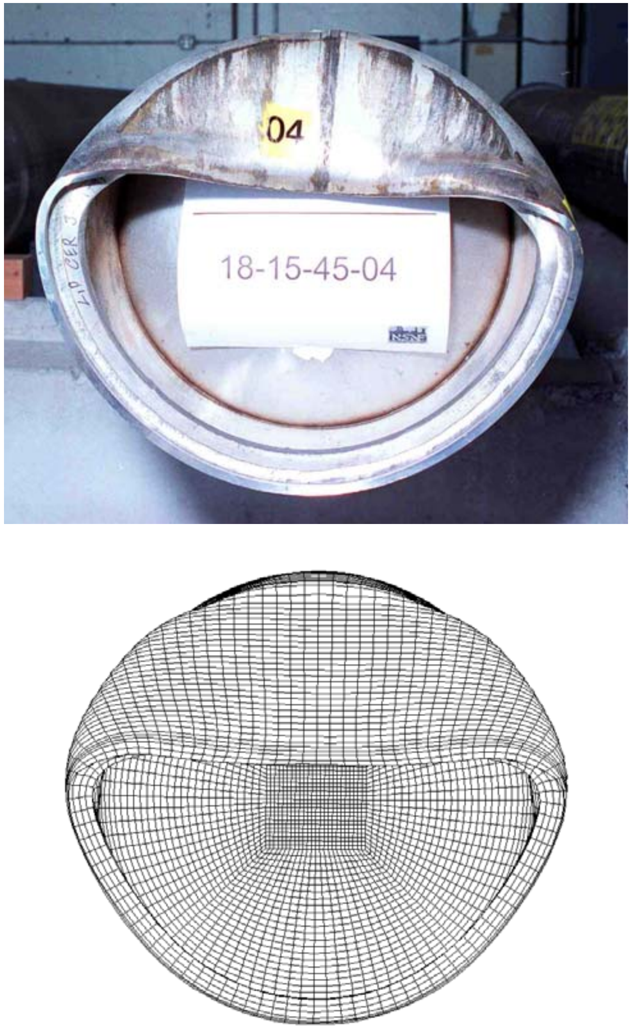
- Models conservatively predicted larger deformations for these drops
- Material under impact conditions was stronger than modeled

Actual vs. Predicted Deformations

80° Off-Vertical

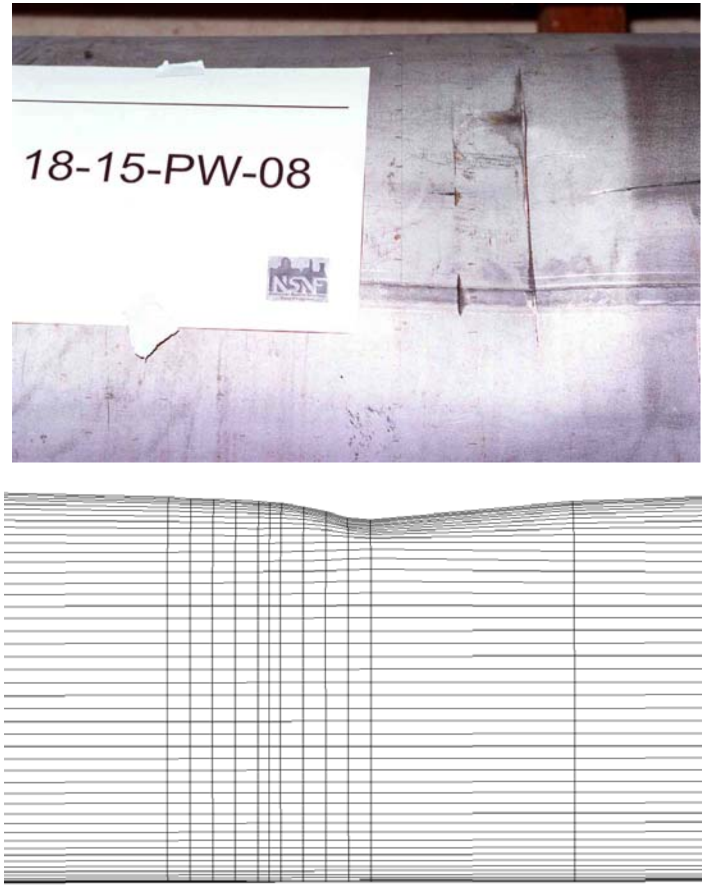


45° Off-Vertical

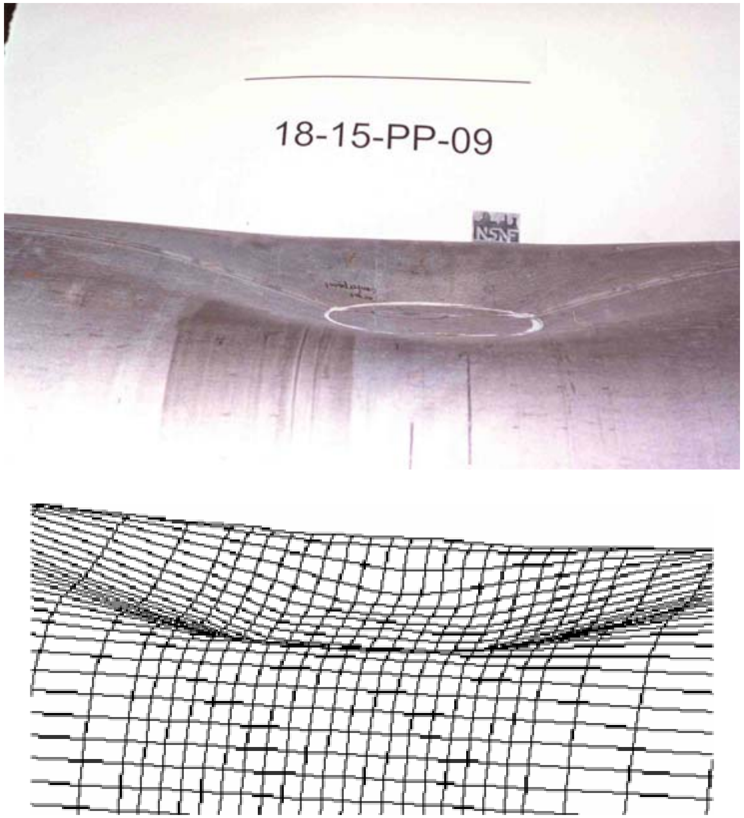


Actual vs. Predicted Deformations

Waste Package Drop



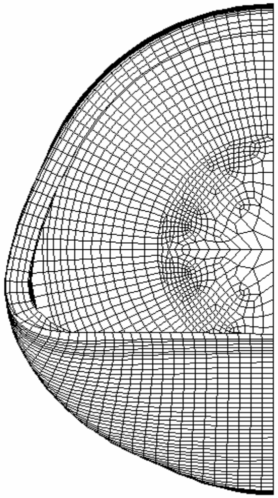
Puncture Post Drop



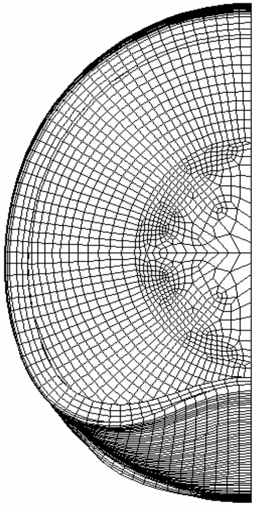
2004 Actual vs. Predicted Deformations

45° Off-Vertical

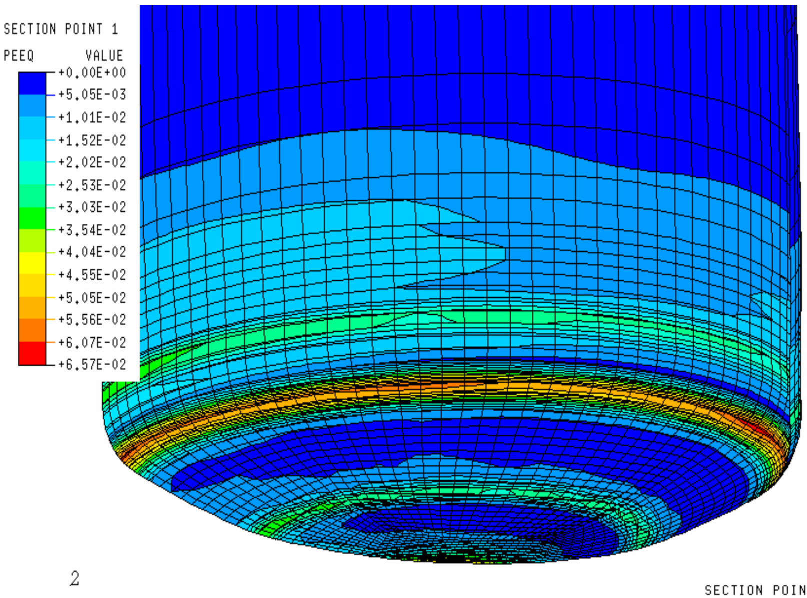
70° Off-Vertical



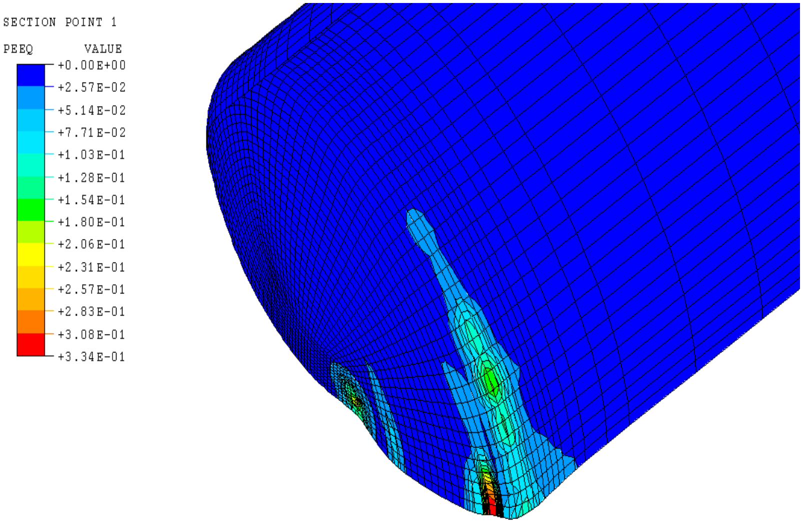
(half models)



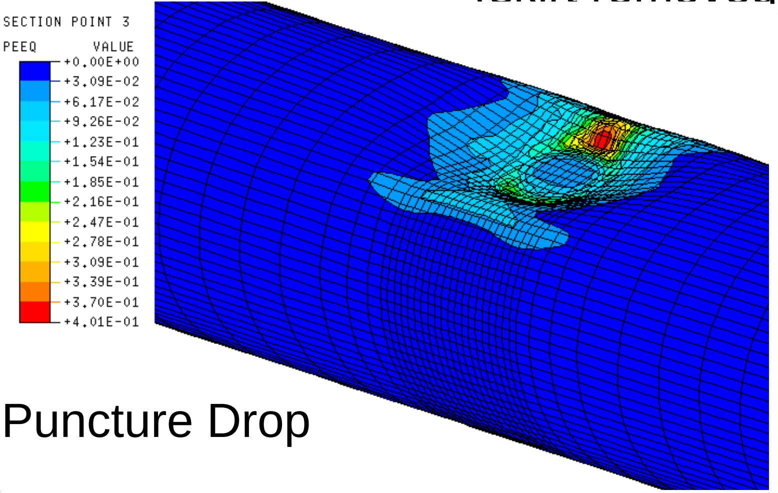
Resulting Strains – Examples



1999 Vertical Drop
(skirt removed)



1999 45° Drop
(skirt removed)



1999 Puncture Drop

1999 Prototype Canister Drop Testing Calculated Peak Strains – Summary Table

Canister	Peak Equivalent Plastic Strains (%)					
	Pressure Boundary Components			Skirts and Lifting Rings		
	Outside	Middle	Inside	Outside	Middle	Inside
18-15-00-01	7	3	6	91	17	75
18-15-06-02	9	3	10	107	21	94
18-15-90-03	40	15	26	10	10	10
18-15-45-04	33	9	36	52	33	84
18-15-80-05	**57**	**19**	**42**	24	20	19
18-10-90-06	44	17	31	21	10	18
18-10-90-07	62*	22*	42*	11	10	10
18-15-PW-08	20	7	18	38	38	38
18-15-PP-09	39	14	40			

*Strains are considerably overpredicted due to conservatively stiff modeling of internals (Shippingport fuel bundle).

2004 Design Canister Drop Testing Calculated Peak Strains – Summary Table

Canister	Peak Equivalent Plastic Strains (%)					
	Pressure Boundary Components			Skirts and Lifting Rings		
	Outside	Middle	Inside	Outside	Middle	Inside
24MOD-45-1	25	9	26	50	31	47
24MOD-70-2	**39**	**15**	**52**	41	24	46

Predicted Strain Results

- 1999 and 2004 analytical models did not predict canister containment boundary rupture (confirmed by helium leak testing on the actual canisters)
- Quasi-static material tensile testing showed elongations of 48% (1999 material) to 58% (2004 materials) for these 316L stainless steels. The actual ultimate tensile strain would exceed the elongation value significantly

Predicted Strain Results (cont'd)

- In comparison, the maximum containment material strains at the middle surfaces of 19% (1999) and 15% (2004) were well below the above elongation values
- The maximum surface strains of 57% (1999) and 52% (2004) were due to bending

Canister Transportation Analyses

Canister Transportation Analyses

Purposes:

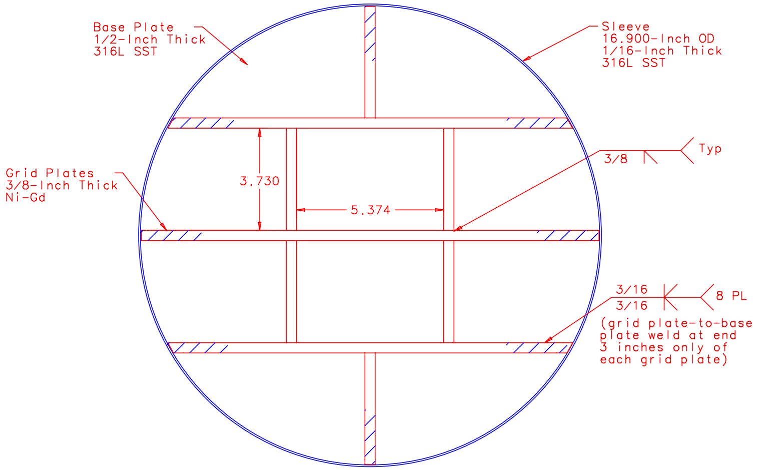
- Evaluate the standardized canister within a transportation cask for 10 CFR 71.73 conditions
- Evaluate the standardized canister for a water immersion scenario (290 psig external pressure per 10 CFR Part 71.61 and ISG-18)

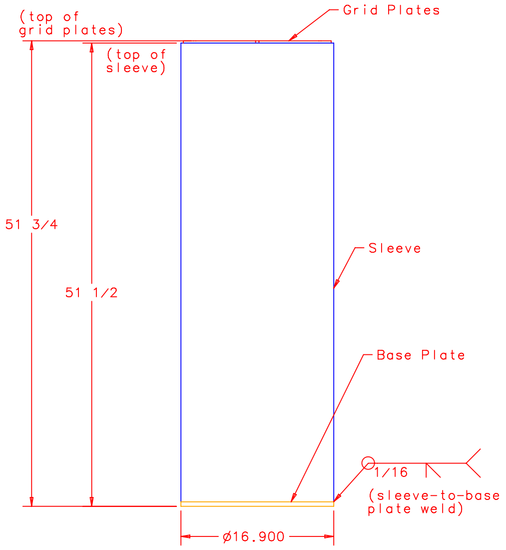
Transportation Cask Inputs

- 100-g deceleration magnitude
- Internal structures prevent canister interactions
- A flat surface at the canister ends with no significant gap
- A flat surface of support longitudinally for each canister (e.g., each canister positioned within a round or square tube)
- Cask assumed to protect canisters such that the 30-foot free drop is the enveloping design load for the structural response for the canisters, including the puncture drop event

Standardized Canister

- Canister prototype and standardized canister design evaluated for several accidental drop conditions
- Canister internals consisting of a shield plug, rectangular grid baskets (Type 1a), and fuels
- Fuel loadings at the canister design weight, an intermediate weight, and a 'minimum' canister weight





Canister Configurations Evaluated

Canister	Temperature (°F)	Material Properties	Number of Baskets	Total Canister Weight (lbs)	Impact Angles (degrees)
Prototype canister 18-inch diameter 15-foot long	-20 to 100 and 600	ASME Minimums and Dynamically Amplified	3	3700	0, 5, 45, 80, 90
Standardized canister 18-inch diameter 15-foot long	-20 to 100 and 600	ASME Minimums and Dynamically Amplified	1 & 3	3111 to 6000	0, 5, 45, 80, 90
Standardized canister 18-inch diameter 10-foot long	600	ASME Minimums	3	5005	45, 80, 90

Acceptance Criteria

Drop Evaluations (Containment Material):

- -20 to 100°F: material strains less than the maximum strains from 1999 drop testing evaluations (where post-drop helium leak-tightness was maintained) and below the ASME Code minimum specified elongation
- 600 °F: material strains less than the minimum elongation

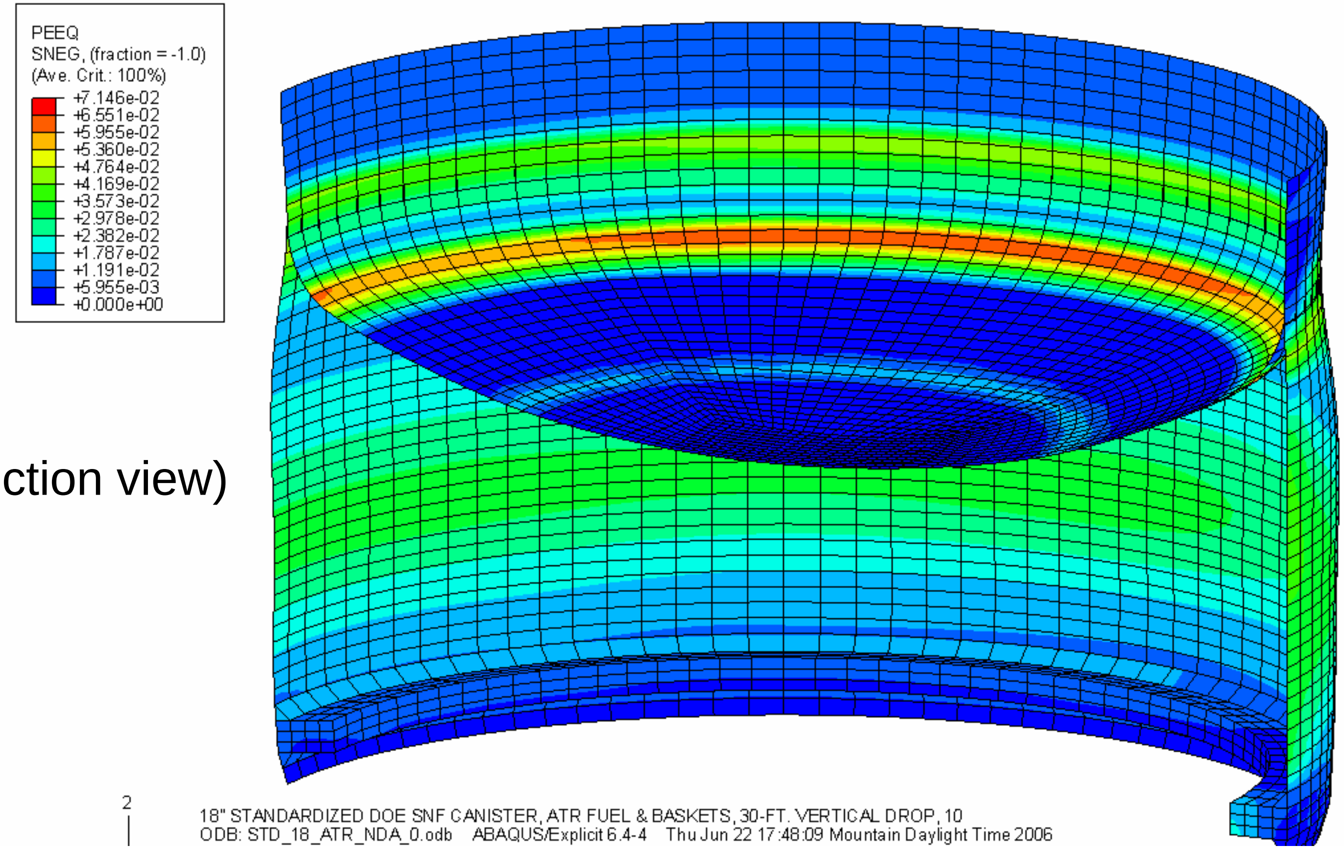
Water Immersion Evaluation:

- Per 10 CFR 71.61, the containment system must be “without collapse, buckling, or inleakage of water”

Typical Strain Results

100-g end (0°) impact

(section view)



Summary of Maximum Strains: -20 to 100 °F

Canister & Configuration	Temp. °F	Peak Equivalent Plastic Strains (PEEQ, %)								
		Bottom Head			Main Shell			Top Head		
		Out	Mid	In	Out	Mid	Ins	Out	Mid	In
Prototype 15-ft. 3 basket, 3700 lbs	-20 to 100	**7**	**5**	**9**	**2**	**0.3**	**2**	**7**	**4**	7
Design 15-ft. 3 basket, 3731 lbs	-20 to100	6	3	7	2	0.2	2	7	3	**8**
Allowable Strain Level (‘99 tests) (ASME elongation)		**57** **34**	**19** **34**	**42** **34**	**57** **30/22**	**19** **30/22**	**42** **30/22**	**57** **34**	**19** **34**	**42** **34**

Summary of Maximum Strains: 600 °F

Canister & Configuration	Temp. °F	Peak Equivalent Plastic Strains (PEEQ, %)								
		Bottom Head			Main Shell			Top Head		
		Out	Mid	In	Out	Mid	In	Out	Mid	In
Prototype 15-ft. 3 basket, 3700 lbs	600	13	6	10	3	0.7	4	10	6	9
Standardized 15-ft. 3 basket, 3731 lbs	600	7	5	8	3	0.4	3	8	4	8
Standardized 15-ft. 1 bsk, 6000 lbs	600	10	6	10	4	1	4	10	6	8
Standardized 15-ft. 3 bsk, 6000 lbs	600	9	5	5	4	2	3	10	6	7
Standardized 15-ft. 1 bsk, 3111 lbs	600	6	2	6	3	0.7	3	6	5	7
Standardized 10-ft. 3 bsk, 5005 lbs	600	12	7	6	5	1	4	10	6	7
Maximum PEEQ at 600 °F		**13**	**7**	**10**	**5**	**2**	**4**	**10**	**6**	**9**
Allowable Strain Level (elongation)		**23**	**23**	**23**	**17/13**	**17/13**	**17/13**	**23**	**23**	**23**

Water Immersion Results

- Standardized canister does not buckle under the 290 psig external pressure load
- Canister stresses under the 290 psig external pressure load are below the material yield strength (containment material remains elastic)

Summary

Summary

- Through full-scale testing, DOE has demonstrated that the standardized DOE SNF canisters maintain containment for 30-foot drops onto a rigid surface and a 40-inch puncture drop
- DOE has demonstrated that canister response to accidental drop events can be accurately predicted using analytical techniques
- DOE has demonstrated through analytical techniques that the canister within a transportation cask maintains containment for 10 CFR Part 71.73 accident conditions
- Canister does not buckle and remains elastic under the water immersion test of 10 CFR Part 71.61 and ISG-18

Material Impact Testing for the DOE SNF Canister Test Program

Presented to:
Nuclear Regulatory Commission

D. Keith Morton
Idaho National Laboratory

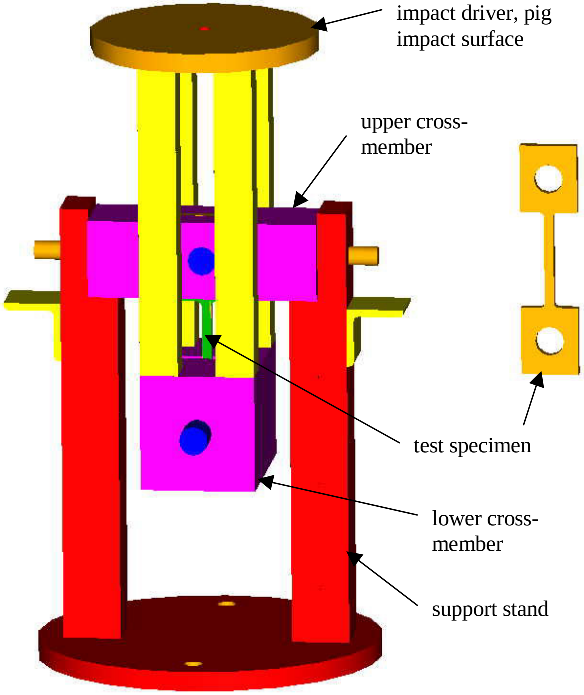
May 8, 2007

Test Program Approach

- Full-Scale Drop Tests (demonstrate structural performance with high strains)
- Computer Analysis Validation (investigate aspects not tested such as elevated temperatures with drop event)
- Material Impact Tests (refine material property input to computer analyses to account for strain rate effects, temperature, etc.)

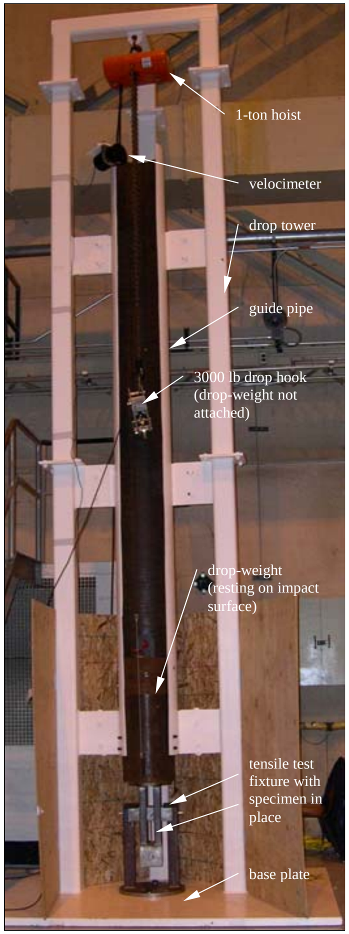
Material Impact Testing

- ASME Boiler and Pressure Vessel Code, Section III, Appendix F requires justification of stress-strain curves used when adjusted for strain rate effects
- Dynamic impact testing using dropped weights most closely matches accidental drops (energy-limited loading events)



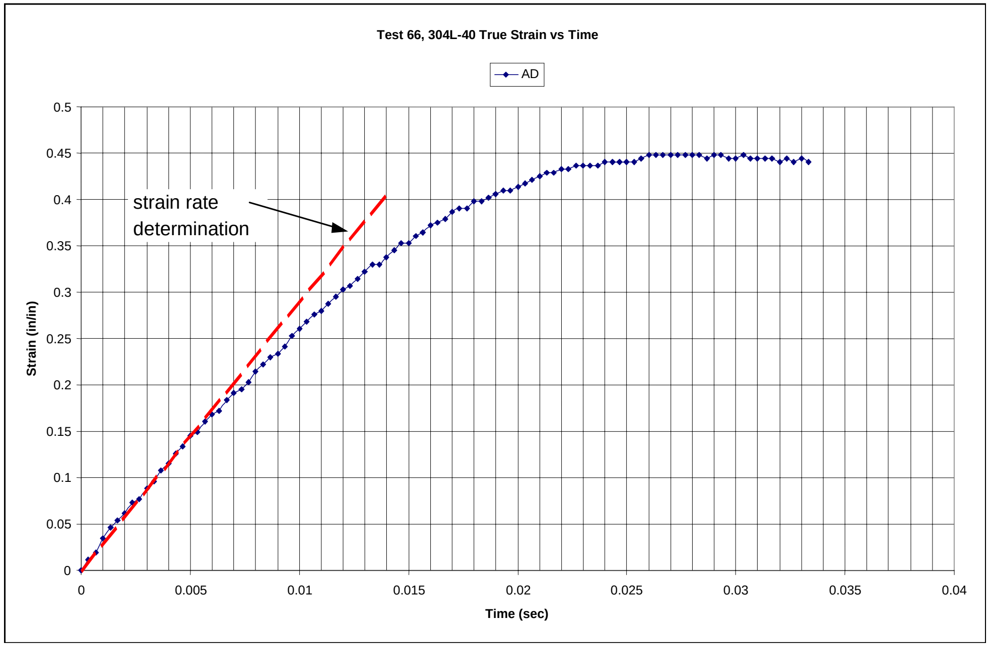
Material Impact Testing

- Impact Testing Machine developed at the INL
- Evaluating base and weld metal responses of 304L and 316L subjected to strain rates up to 35 per second at -20, room, 300 and 600^{o}F temperatures
- Testing results can also be used to support potential strain-based acceptance criteria



Strain Rate Determination

- Achieved using a digital high speed camera
- Strain rate is defined to be slope of initial strain history curve prior to energy dissipation



Methodology

- Area under a true stress-strain curve is equivalent to the amount of energy a volume of material can absorb up to a specific strain level achieved in the material
- An elevated (due to strain rate effects) true stress-strain curve is generated by multiplying each stress point on the quasi-static curve by a constant factor
- This factor is the ratio of the impact energy imparted to the test specimen divided by the area under the quasi-static true stress-strain curve up to the strain achieved in the impact test specimen

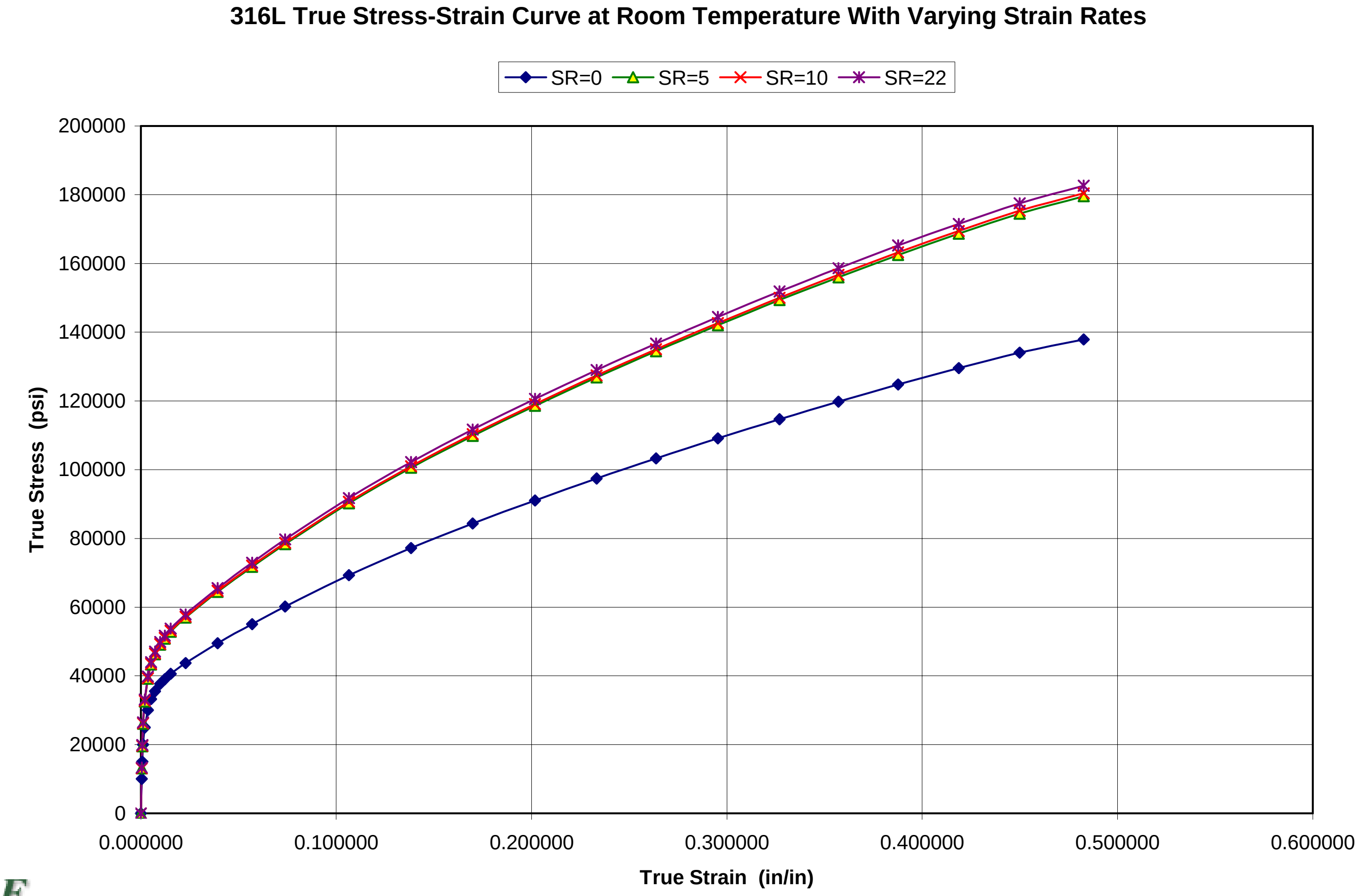
Results to Date

- The results to date reflect strain rates in the range of 5 to 35 per second
- A linear curve fit was applied to provide insights to data validity
- Results are preliminary since data evaluation is not complete

Calculated Factors

Strain Rate Per Second	-20F	Room Temperature	300F	600F
304L Stainless Steel				
5	1.40	1.26	1.18	1.04
10	1.41	1.30	1.22	1.09
22	1.42	1.38	1.33	1.21
35	1.44	1.46	1.44	1.34
316L Stainless Steel				
5	1.31	1.30	1.19	1.06
10	1.32	1.30	1.20	1.09
22	1.34	1.32	1.24	1.15
35	1.36	1.34	1.27	1.21

Elevated True Stress-Strain Curves Reflecting Varying Strain Rates



Enhancement of Analysis Predictions

- ABAQUS/Explicit analyses of material impact tests using quasi-static true stress-strain input (non-factored) and elevated true stress-strain curve input (factored)
- Considering axial deformation:
  - Non-factored: 10 to 55%
  - Factored: 0 to 19%

Pertinent Material Impact Insights

- Strain rate effects increase the amount of energy absorption per material volume
- Computer analyses using the factored test results better predict impact test specimen responses than using standard true stress-strain curve input based on quasi-static tensile testing
- The uniform strain limit (strain at the ultimate tensile strength) is a viable structural integrity limit for strain rates up to 35 per second for both base and weld material

Pertinent Material Impact Insights (cont'd)

- Welds appear to structurally behave similar to the base material
- Welds considered herein have lower uniform strain limits than the base metal
  - Design of standardized canister minimizes strains in weld regions
- Weld and base material straining below the uniform strain limit have not produced noticeable cracks or other structural concerns

Conclusions

- By bringing together full-scale testing, a validated analysis methodology, and justification for material properties considering strain rate effects, a high confidence level that the standardized DOE SNF canisters will remain leaktight under prescribed accident conditions
- DOE is continuing to provide the government and the nuclear industry with valuable analytical and material insights regarding canister and material performance under impact conditions

DOE SNF Characteristics

Presented to:

Nuclear Regulatory Commission

Bill Hurt

Idaho National Laboratory

May 9, 2007

Outline

- Scope of DOE SNF for discussions
- DOE SNF Origins
- Characteristics of DOE SNF

DOE SNF for Discussions

- DOE-managed SNF planned for direct disposal
  - Overview of all SNF
  - Fuel planned for Type 1a baskets
- Excludes:
  - Navy SNF
  - Sodium-bonded SNF

DOE SNF Origins

- Spent fuel generated from numerous reactors
  - Test, training and research reactors
    - DOE, NRC licensed, universities, foreign
  - DOE production reactors
    - N-reactor, Single Pass Reactors, etc.
  - Development
    - Fort St. Vrain, Shippingport, Fermi, etc.
  - Commercial power reactor SNF
    - TMI, Big Rock Point, Ginna, Dry Rod Consolidation, etc.

Characteristics of DOE SNF

- Fuel forms
  - All SNF - Rod array, plate array, rods, plates, tubes, blocks, pins, debris in cans
  - Type 1a SNF - Rod array, plate array, rods, plates, tubes
- Fissile species
  - All SNF - U-233, U-235, Pu-239, Pu-241
  - Type 1a SNF – U-233, U-235
- Fissile enrichments
  - All SNF - Depleted Uranium to 93%
  - Type 1a SNF – 5% to 93 %

Characteristics of DOE SNF (cont’d)

- Cladding types
  - All SNF – Aluminum, Stainless Steel, Zircalloy, Hastelloy, Inconel, Nichrome, and Coated Particles
  - Type 1a SNF – Aluminum, Stainless Steel, Zircalloy, Inconel, and Coated Particles
- Fuel compounds
  - All SNF – Alloy, oxide, carbide, nitride, hydride, metal, silicide
  - Type 1a SNF – Alloy, oxide, carbide, hydride, metal, silicide
- Matrices
  - All SNF – Aluminum, graphite, ceramic, and stainless steel
  - Type 1a SNF – Aluminum, graphite, and stainless steel

Characteristics of DOE SNF (cont'd)

- Condition
  - All SNF – Intact, cropped, corroded, disassembled, post irradiation examination residuals
  - Type 1a SNF – Intact, cropped, corroded, disassembled, post irradiation examination residuals
- Sizes
  - All SNF – 0.06 to 22 in wide; 4 to 177 in long
  - Type 1a SNF – 0.06 to 4 in wide; 12 to 144 in long
- Burnups
  - All SNF – From <1000 to >500,000 MWd/MTHM; 0.1% to >70% of original fissile
  - Type 1a SNF – From <1000 to >500,000 MWd/MTHM; 0.1% to >60% of original fissile

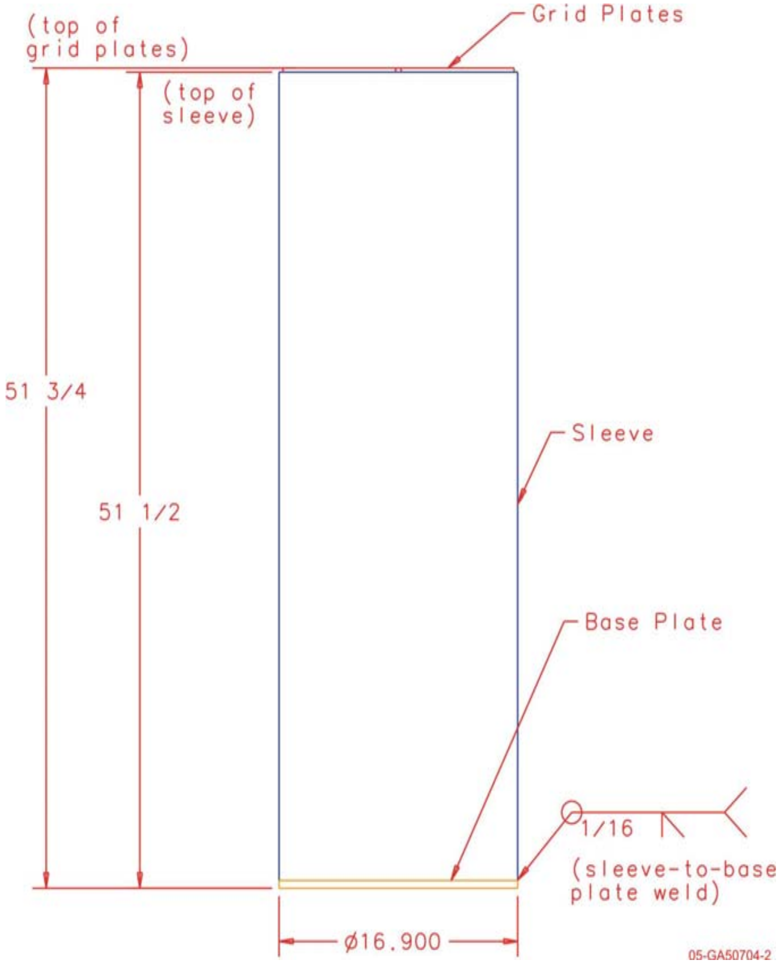
Comparison of all DOE SNF and Planned Type 1a Basket SNF

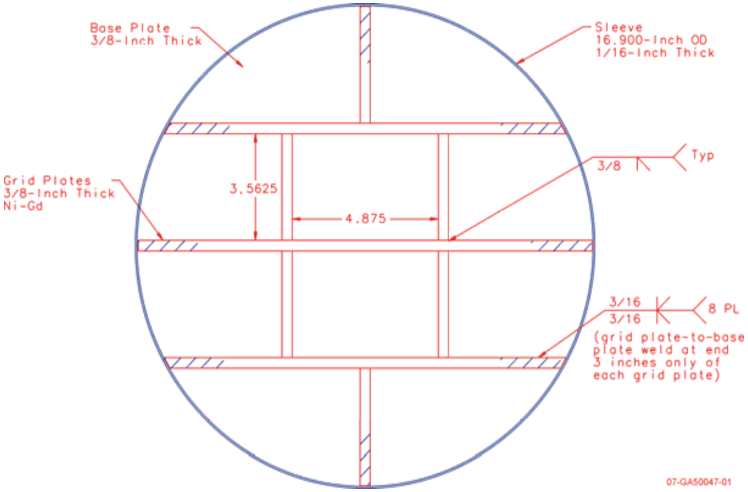
	MTHM	SNF Volume (M^3)	Canisters
All DOE SNF	2,470	1,870	3500
Planned Type 1a Basket	28	160	1035

Variety of Fuels in Type 1a Basket

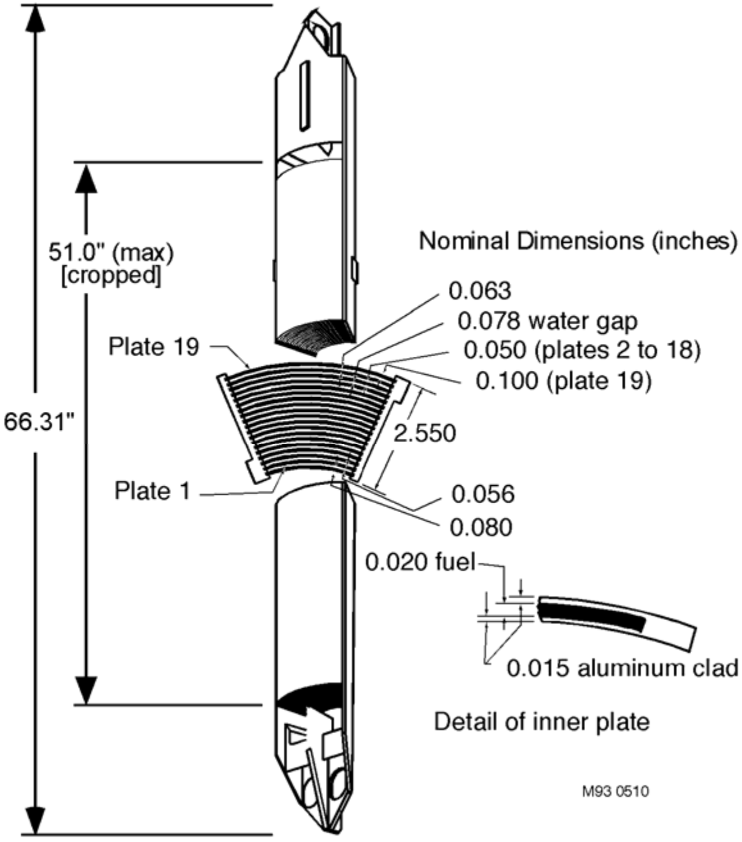
Fuel Compound	MTHM	SNF Volume (M^3)	Canisters
U-Metal Alloy	6.5	3.1	30
U Oxide (Zirc Clad)	0.3	0.1	4
U Oxide (Alum Clad)	0.4	4.3	46
U-Alx	9.3	103.3	637
U_3Si_2	3.6	13.2	136
Th/U Carbide & Oxide	8.0	35.2	182

Type 1a Basket

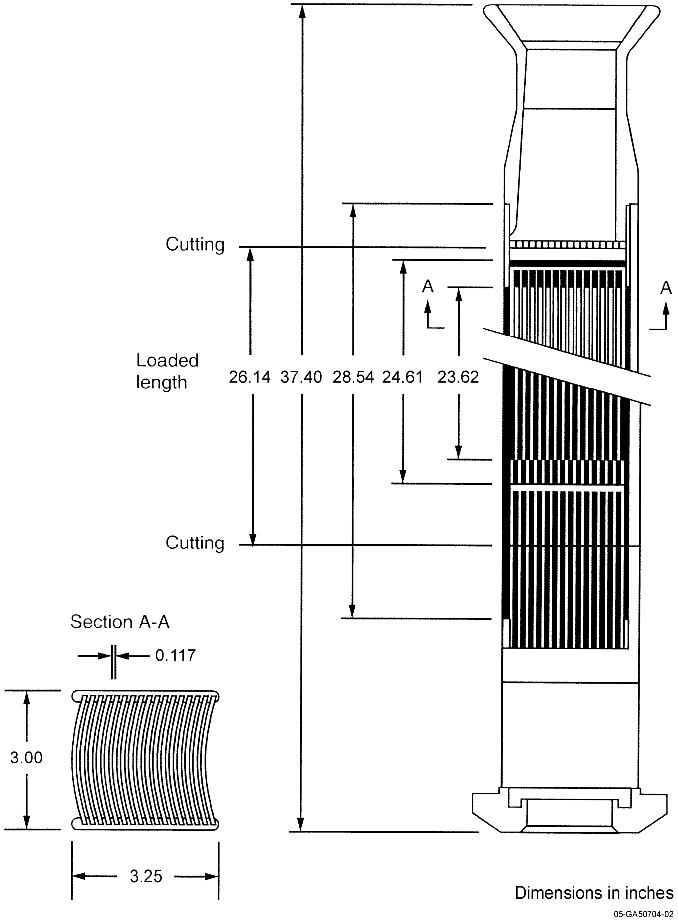




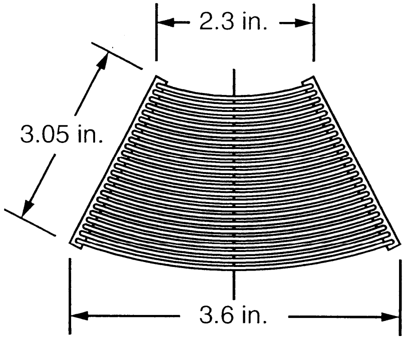
ATR and ORR Fuel Assemblies



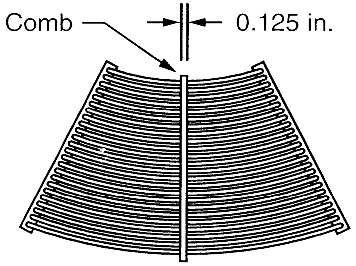
ATR Fuel



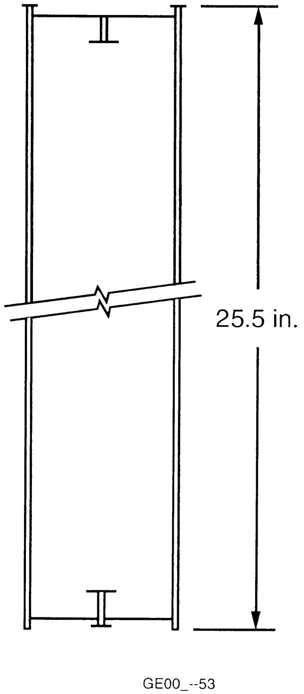
MURR and MIT Fuel Assemblies

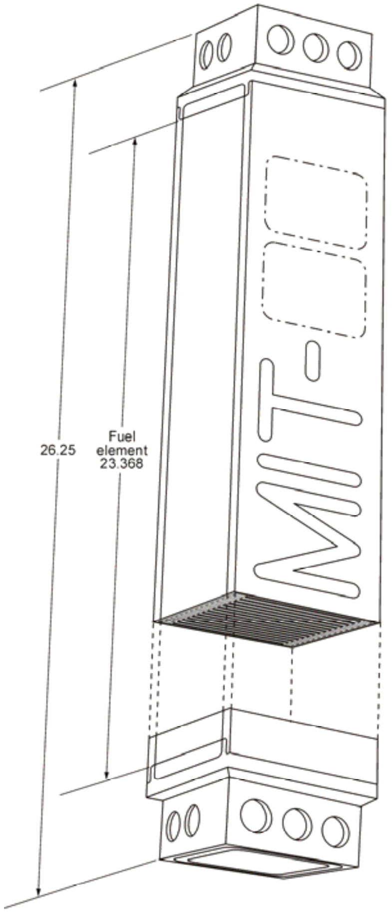


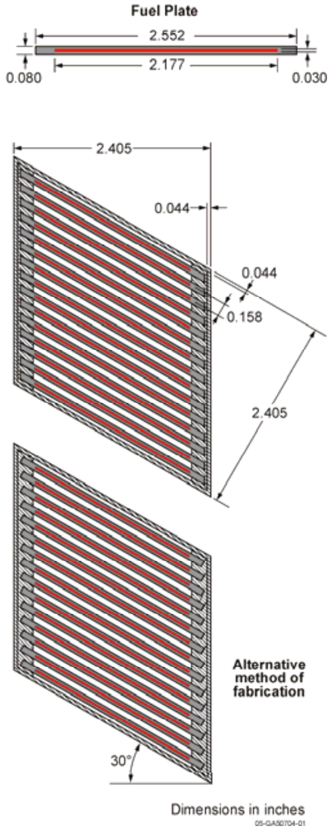
Typical x-section
without comb
24 fuel plates



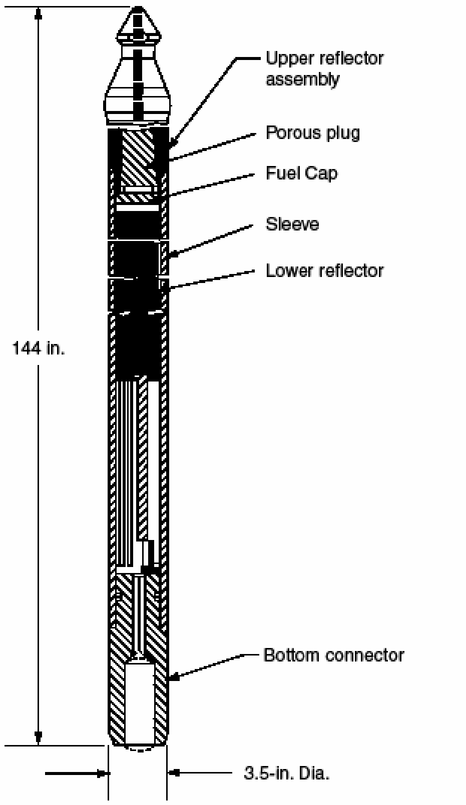
Typical x-section
with comb







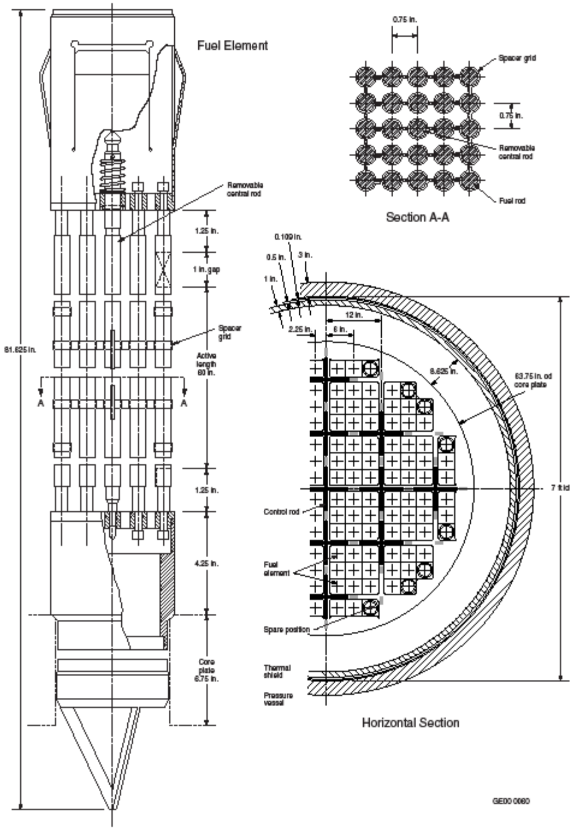
Peach Bottom Unit 1 Fuel



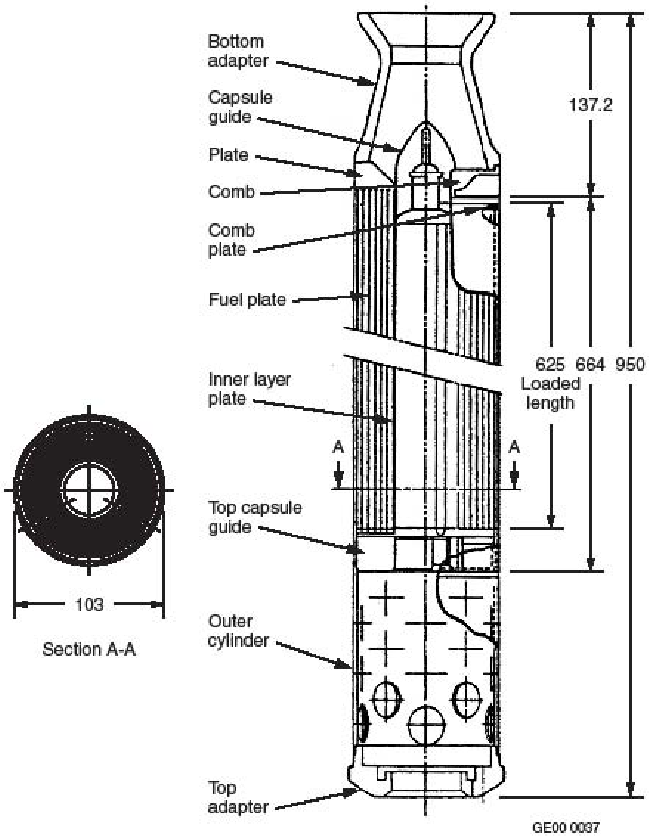
Peach bottom assembly

J96 0201

Elk River Reactor

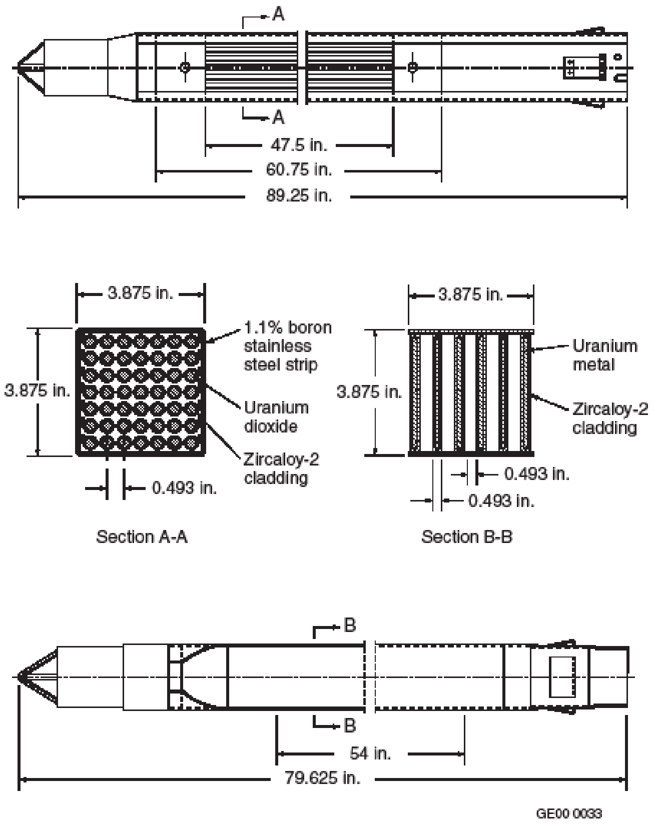


MTR Tube Type Fuel



Dimensions in millimeters

Experimental Boiling Water Reactor



Summary

- DOE SNF inventory includes diverse fuels from various experimental, research, and production reactors
- DOE SNF inventory includes fuels with a wide range of enrichments, mechanical, and chemical properties
- DOE SNF inventory planned for Type 1a basket includes a wide variety of DOE SNF

Aging of DOE Standardized Canisters During Interim Storage

Presented to:
Nuclear Regulatory Commission

Matt Ebner
Idaho National Laboratory

May 9, 2007

Focus of the Discussion

- Potential degradation of the DOE standardized canister
- Outline
  - Canister characteristics
  - Proposed drying protocol
  - Degradation mechanisms
    - Canister corrosion
    - Embrittlement
    - Radiation damage
  - Canister pressurization

Canister Characteristics

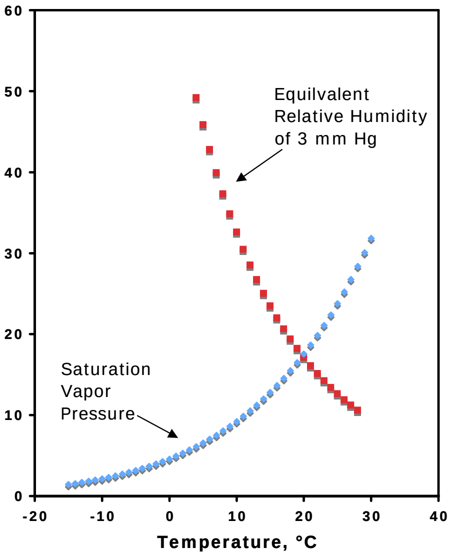
- 316L Stainless Steel
- Operational parameters
  - He backfill
  - Design pressure: 50 psig
  - Temperature range: -29 to 315 °C
- SNF contents
  - Al plate fuel
  - U metal, UZr, UMo
  - U-ZrH_x
  - UO_2, $(U, Th)O_2$
  - $(U, Th)C_x$

Proposed SNF Drying Protocol

- Vacuum drying to <3 mm Hg at 20 °C
- Endpoint: pressure rebound <3 mm Hg in 30 min at 20 °C
- Removes
  - Liquid water
  - Physisorbed water
  - Some chemisorbed water, e.g.

$Al(OH)_3 \text{ --> } AlO(OH) + H_2O$

$UO_2(OH)_2\text{-}H_2O \text{ --> } UO_2(OH)_2 + H_2O$

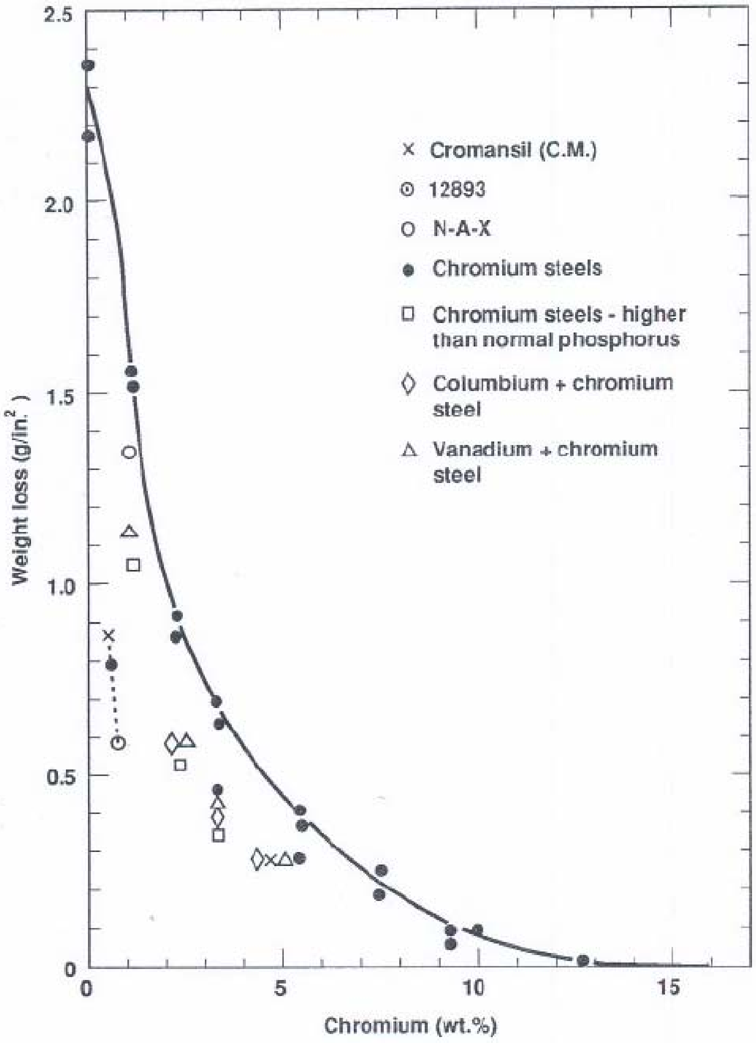


Potential Degradation Mechanisms

- Corrosion of Canister
  - General corrosion
    - Atmospheric
    - Aqueous
  - Localized corrosion
  - Heat sensitization
- Metal embrittlement
  - Hydrogen embrittlement
  - Liquid metal embrittlement
- Radiation damage
- Gas pressurization

General Corrosion of SS 316L

- 316L (S31603) is highly resistant to corrosion
  - Nominal composition is 16-18 wt% Cr, 10-14% Ni, 2-3% Mo, 2% Mn, <0.03% C
- Steel with >12 wt% Cr forms passive film (Cr_2O_3)
- Passive film is only 1-5 nm thick
- Mo maintains passive film in non-oxidizing media



General Corrosion of SS 316

- Atmospheric Corrosion
  - Corrosion by H_2O vapor, O_2
  - Electrochemical mechanism
    - Anode reaction
      $M \rightarrow M^{+n} + ne$
    - Cathode reactions
      $2H^+ + 2e \rightarrow H_2$
      $O_2 + 4H^+ + 4e \rightarrow 2H_2O$
      $O_2 + 2H_2O + 4e \rightarrow 4OH^-$
  - Requires >70% RH for condensation of H_2O films
    - Temp swings >10 °C
- Rates enhanced by some contaminants (halides, sulfides)

Condition	**Rate, µm/yr**	**Test Duration, yrs**
Rural	0.0	16.0
Urban	0.009 – 0.014	5.0
Industrial	0 – 0.030	2.0 – 5.0
Marine	0 – 0.033	5.0 – 16.0

General Corrosion of SS 316

- Aqueous corrosion
  - Very low for SS 316; comparable to atmospheric corrosion rates
  - Measurable rates in seawater, but localized corrosion prevalent

Water Type	Conditions	Corrosion Rate, µm/yr	Test Duration, yrs	Comments
Lake	Ambient, Immersion	0.0	16.0	
River	Ambient, 1000 mg Cl/L	0.0	0.5	No pitting or crevice corrosion
Seawater	Ambient, immersion	15.0 6.4 1.25	1 8 16	Pitting and perforations
	20 – 30 °C, pH 6.6	2.5 – 5.0		
	90 – 100 °C, pH 7	5		

Localized Corrosion of SS 316

- Types
  - Pitting (contaminants)
  - Crevice (shielded/occluded configuration)
  - Intergranular (e.g., sensitized steel)
  - Stress corrosion cracking
- All involve an electrochemical mechanism,
  - Liquid water
  - Condensed water films
- Mechanism is not possible in dry, non-condensing conditions (e.g., 3 mm Hg H_2O vapor)

Localized Corrosion of SS 316

- Initiation at local weak sites in passive film
  - Inclusions in surface (e.g., MnS)
  - Physical heterogeneities (grain boundaries, steps, flaws)
  - Local adsorption of accelerants (Cl ions)
  - Displacement or depletion of adsorbed O_2
  - Depletion of Cr, $Cr_{23}C_6$ precipitation by heat sensitization
- Weak sites become locally anodic, dissolve metal

Localized Corrosion of SS 316 (cont'd)

- Propagates by local acidification to low pH
  - Metal dissolution (anodic)

    $Cr \dashrightarrow Cr^{3+} + 3e^-$
  - Metal ion hydrolysis and acidification

    $Cr^{3+} + 3H_2O \dashrightarrow Cr(OH)_3 + 3H^+$

    $Cr^{3+} + 3Cl^- \dashrightarrow CrCl_3$

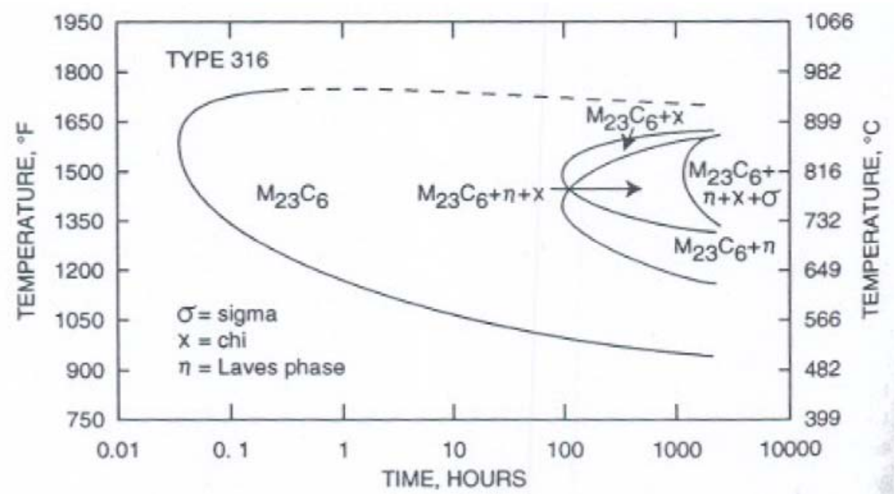
    $CrCl_3 + 3H_2O \dashrightarrow Cr(OH)_3 + 3H^+ + 3Cl^-$
  - Local acidification to pH=0-2; local [Cl^-] may reach 5-6M
- Electrochemical process requires
  - Aqueous medium
  - Anodic & cathodic reactions (reduction of H^+ or O_2)
  - Cl >300-1000 ppm (pitting, crevice corrosion, SCC in 316L)
- Inhibitors -- I^-, OH^-, NO_3^-, SiO_4^{2-}, SO_4^{2-}, CrO_4^{2-}, CO_3^{2-}

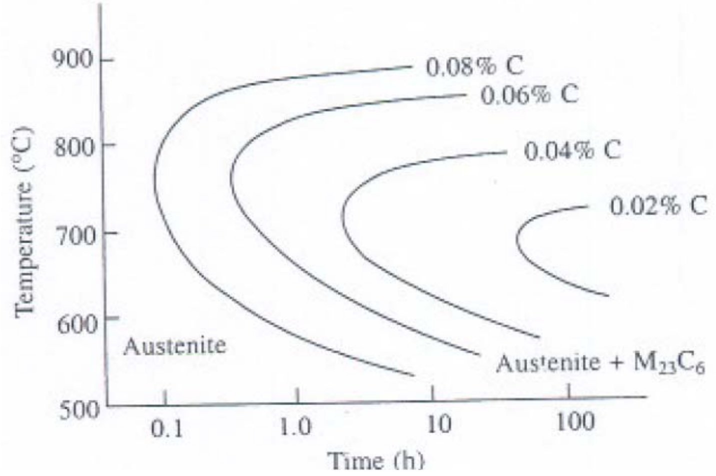
Corrosion Effects on Canister

- If canister is dried to 3 mm Hg (as H_2O), internal corrosion does not occur
- If canister equilibrates to 10 mm Hg H_2O,
  - Atmospheric or local corrosion possible
  - In 50 years, canister wall might thin by <0.7 µm (<0.03 mils), assuming urban corrosion rate
  - Localized corrosion impeded by low O_2, lack of O_2 cathodic reaction
  - Localized corrosion impeded by low Cl^-, S^{2-} initiators
- No measurable corrosion is expected

Heat Sensitization

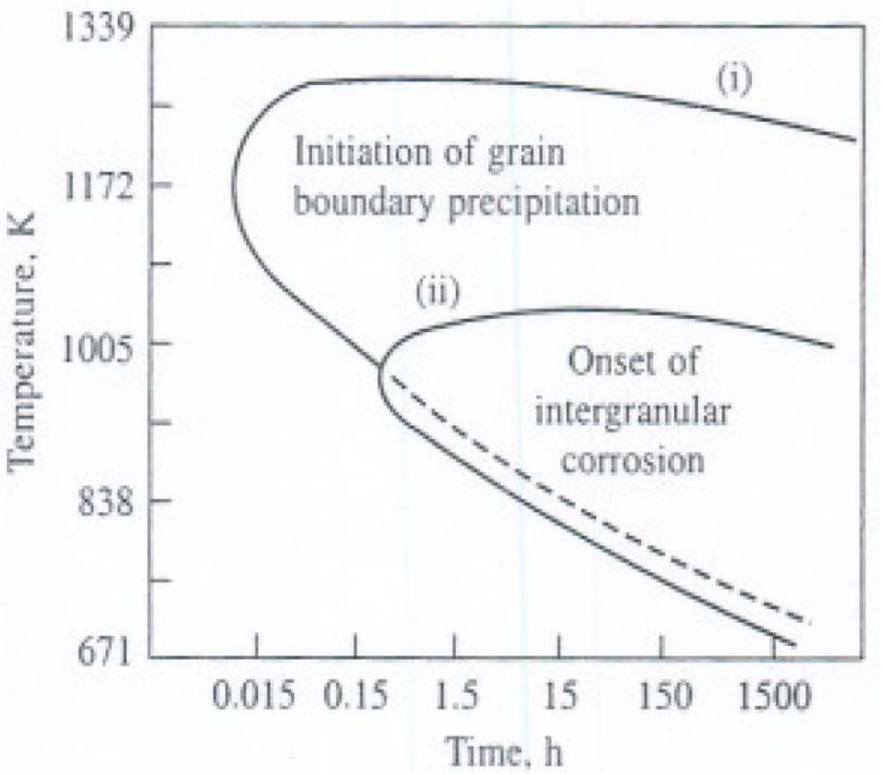
- May cause intergranular corrosion
- Heat affected zone of welds may be susceptible
- Sensitization caused by
  - Heating at 500-950°C for SS 316
  - Localized depletion of Cr to <12 wt%, loss of protective oxide film
  - Precipitation of $(Cr,Mo)_{23}C_6$ at grain boundaries
- Sensitization retarded by lower C content





Heat Sensitization (cont'd)

- Sensitization can cause
  - Intergranular corrosion, if grain boundaries sufficiently depleted
  - Cl stress corrosion cracking
- For 316L, safe at 500 °C, or ≈1 hr at 600 °C
- Avoid sensitization and IGC/SCC
  - Rapid cooling
  - Critical cooling rate is 6 to 14°C/min, depending on extent of cold work
  - Non-condensing conditions in canister
- Mock-up weld tests on DOE standardized canister show no sensitization



Canister Embrittlement

- Two mechanisms considered
  - – Hydrogen embrittlement
  - – Liquid metal embrittlement
- H_2 embrittlement is unlikely
  - – Usually associated with
    - IGC or SCC in electrochemical corrosion; liquid H_2O required
    - Sensitized steel, martensitic steel
    - Conditions (S^{2-}, CN^-) preventing recombination of H* to H_2
    - Steels of yield strengths >560 MPa; 316 strength is 205 MPa
  - – For SS 304, onset of loss of ductility at P_{H2} >200 atm at 200°C; SS 316 is more resistant

Canister Embrittlement (cont'd)

- Liquid metal embrittlement conditions:
  - Liquid-solid metal (alloy) couples, for wetting and diffusion into solid surface
  - Not a general phenomenon; unique to certain combinations of liquid and solid metals
  - Known embrittling agents for steel
    - As liquid metal: Cd, Cu, In, Li, Sb, Te, Zn
    - As liquid alloys: Pb-Sn solders, brass, Al bronze

Canister Embrittlement (cont’d)

- Cs-Te mixtures may embrittle SS 316
  - Pure Te, Cs, and Cs/Te>2 are ineffective
  - Cs/Te <2 can embrittle rapidly
    - Te is the embrittling agent
    - Cs is the flux, destroys protective Cr_2O_3 layer
    - Liquid Cs serves as Te transport medium
  - Fission product simulants of Cs, Cd, In, Sn, and I were ineffective
  - Requires temperature >450 °C for good wetting
- Embrittlement not relevant for DOE standardized canister service conditions

Radiation Damage

- High energy neutrons damage steel by impact displacement, can form physical defects in structure
- Alpha, beta, and gamma are relatively ineffective
- Damage threshold is 10^{18} to 10^{22} n/cm^2 for energies >1 MeV
- Spontaneous fission in SNF may emit 10^7 n/s per assembly
- Requires 7×10^6 years to reach threshold

Gas Pressurization

- H_2 generation from residual water vapor by
  - Corrosion
  - Radiolysis of residual water

Pressurization by Corrosion

- Corrosion production of H_2 is limited
  - At ambient temps, by kinetics of metal corrosion
  - At transient temperature peaks, by available residual water
- Kinetics limits
  - For 316L atmospheric corrosion, $P_{H2}<0.1$ atm
    - Assumes condensing conditions, 50 year reaction time
  - Further Al fuel corrosion limited by
    - Al + H_2O vapor reaction kinetics
    - AlOOH decomposition kinetics
- Decomposition thermodynamics and kinetics for AlOOH corrosion product are not known

Pressurization by Radiolysis

- Radiolysis issues: radiolytic H_2 yield (G_{H2})
  - Physical state of the water
    - Physisorbed water
    - Chemisorbed water
    - Water vapor
  - Energy transfer by U, Fe, Al, others
- Science of H_2O radiolysis is still evolving
  - Experimental data are limited, particularly for non-liquid systems
  - Significant work published since 2000

Pressurization by Radiolysis (cont'd)

- Calculated radiolytic H_2 pressure is 1.9 atm, assuming
  - 1.7 L residual H_2O, as physisorbed and chemisorbed AlOOH
  - G_{H2} = 0.2 molecules/100 eV for Al_2O_3
  - Rad field = 10^5 R/hr
  - Total dose = 4.4×10^{10} R
  - Radiolysis time = 50 years
  - Back-reactions were ignored

Pressurization by Radiolysis (cont'd)

- Recent test data suggest low H_2 yield, $G_{H2} = 0.01$
- Test conditions
  - UO_2, U_3O_8, UO_3 with added H_2O as physisorbed,chemisorbed, and liquid water
  - Sealed capsules
  - 2-year irradiation in gamma (HFIR SNF, Co-60) and alpha fields
  - Dose rates 10^7-10^8 R/hr; Total dose 3-8 x 10^{10} R
- Test results
  - Immediate pressure spike of 5 psi; fast decay to fill pressure
  - H_2 less than 1 vol%; one test, H_2 = 10 vol%
  - Final H_2 <0.06 mol% of initial H_2O added
  - O_2 consumption; UO_2, U_3O_8, UO_3 oxidation

Conclusions

- The evaluation of potential canister degradation mechanisms concluded that
  - Corrosion, embrittlement, and radiation damage are of no consequence
  - Radiolysis and other canister pressurization mechanisms, with the exception of corrosion product decomposition, are of no consequence
- Potential canister pressurization by decomposition of hydrated SNF corrosion products is being evaluated

Reliability of Standardized Canister

Presented to:

Nuclear Regulatory Commission

Brett Carlsen

Idaho National Laboratory

May 9, 2007

Deterministic Case

- Canisters are designed, fabricated, and inspected per applicable ASME codes
- ISG-18

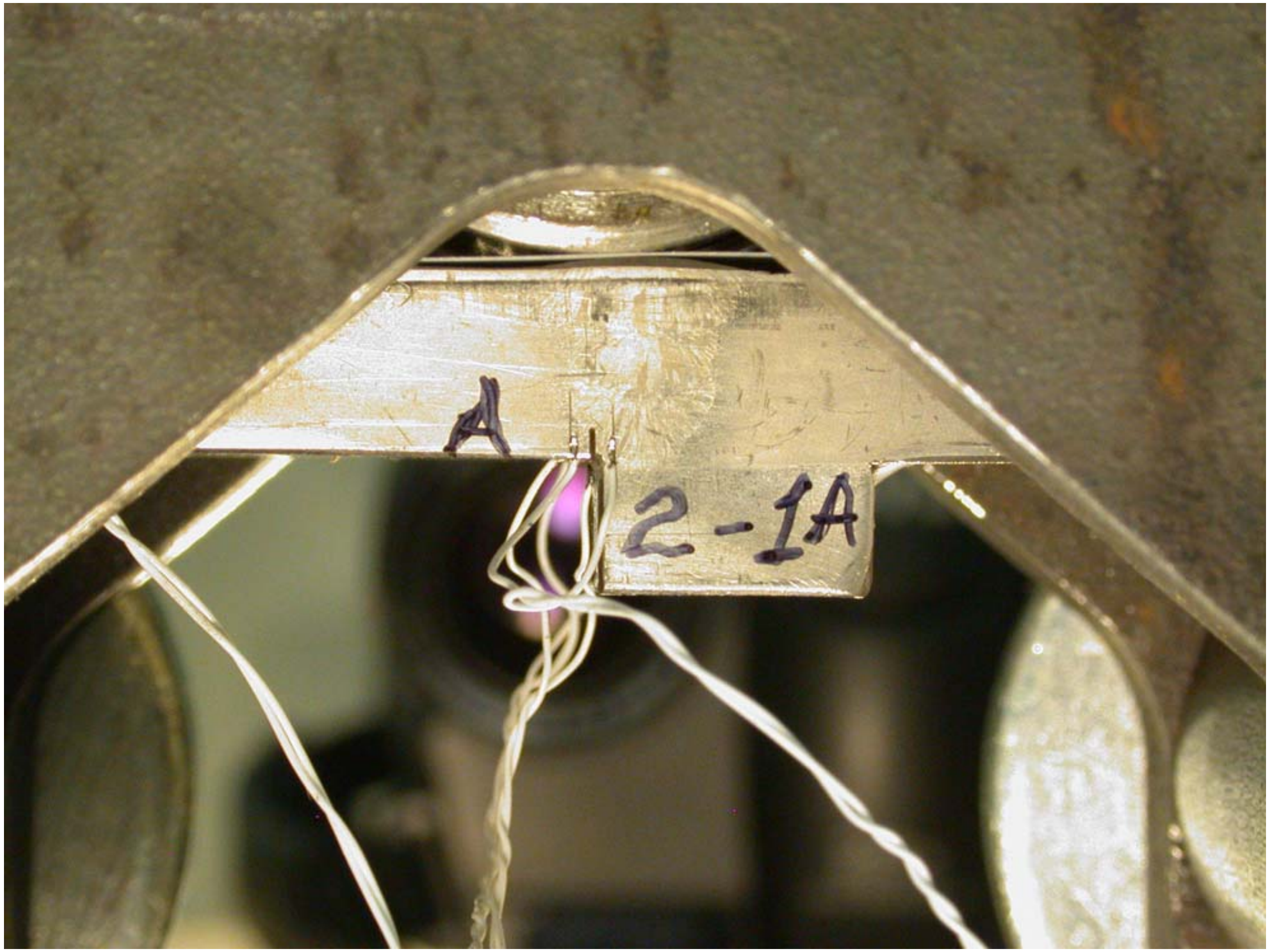
> “The purposes of this ISG are to address the qualification of the final closure welds of austenitic stainless steel canisters……. as an adequate containment boundary under 10CFR Part 71 for purposes of demonstrating no credible leakage during transportation.
>
> When the final closure welds of austenitic stainless steel canisters are executed in accordance with ISG-15, the staff concludes that no undetected flaws of significant size will exist.”

Deterministic Case (cont'd)

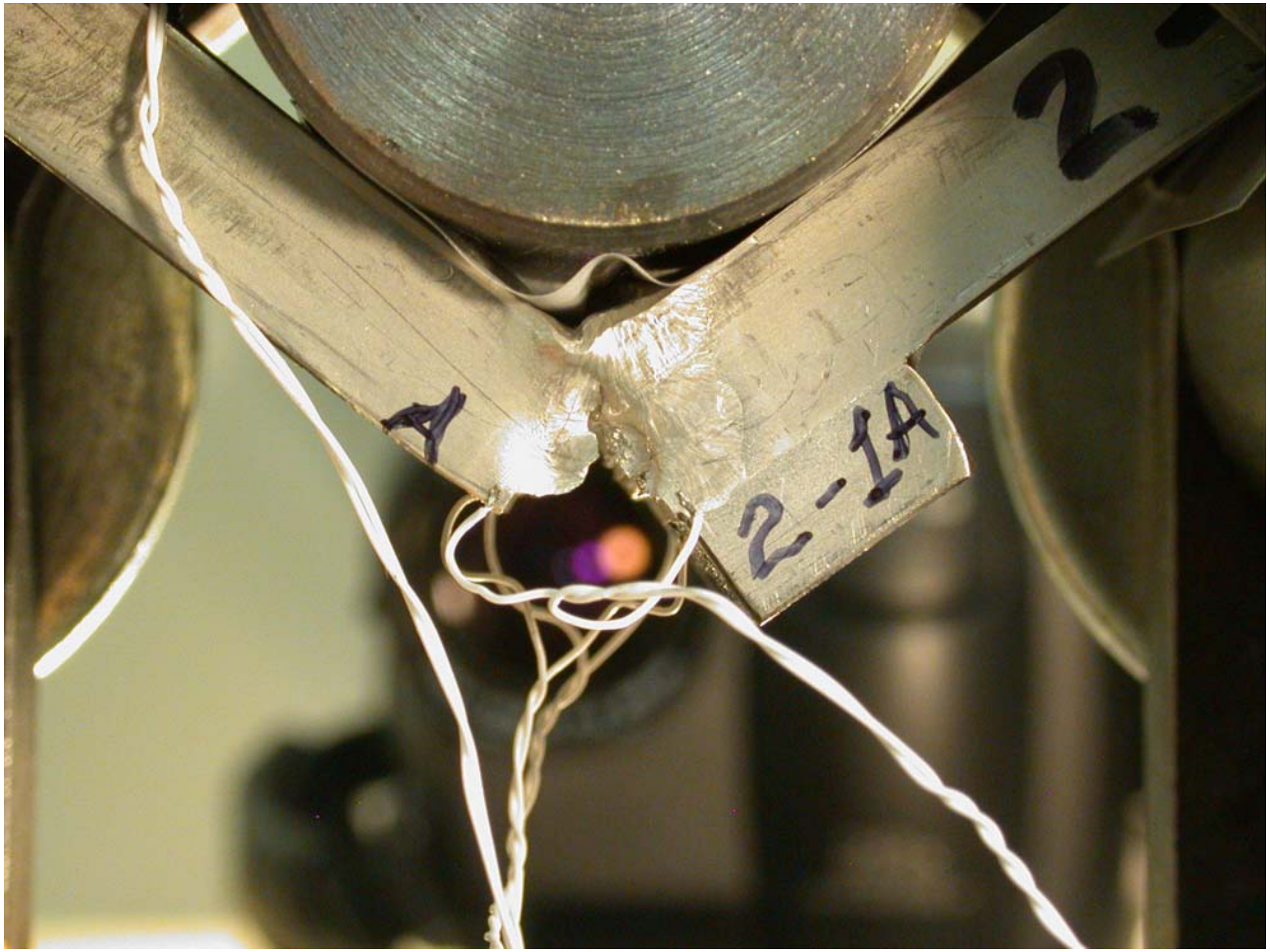
- Per ISG-15, for designs employing austenitic stainless steels, the minimum detectable flaw size must be demonstrated to be less than the critical flaw size

- Flaw propagation testing conducted in 2004 demonstrated that flaws well in excess of detectable limits would not propagate through the canister wall under strains well beyond those encountered under 10CFR71.73 test conditions

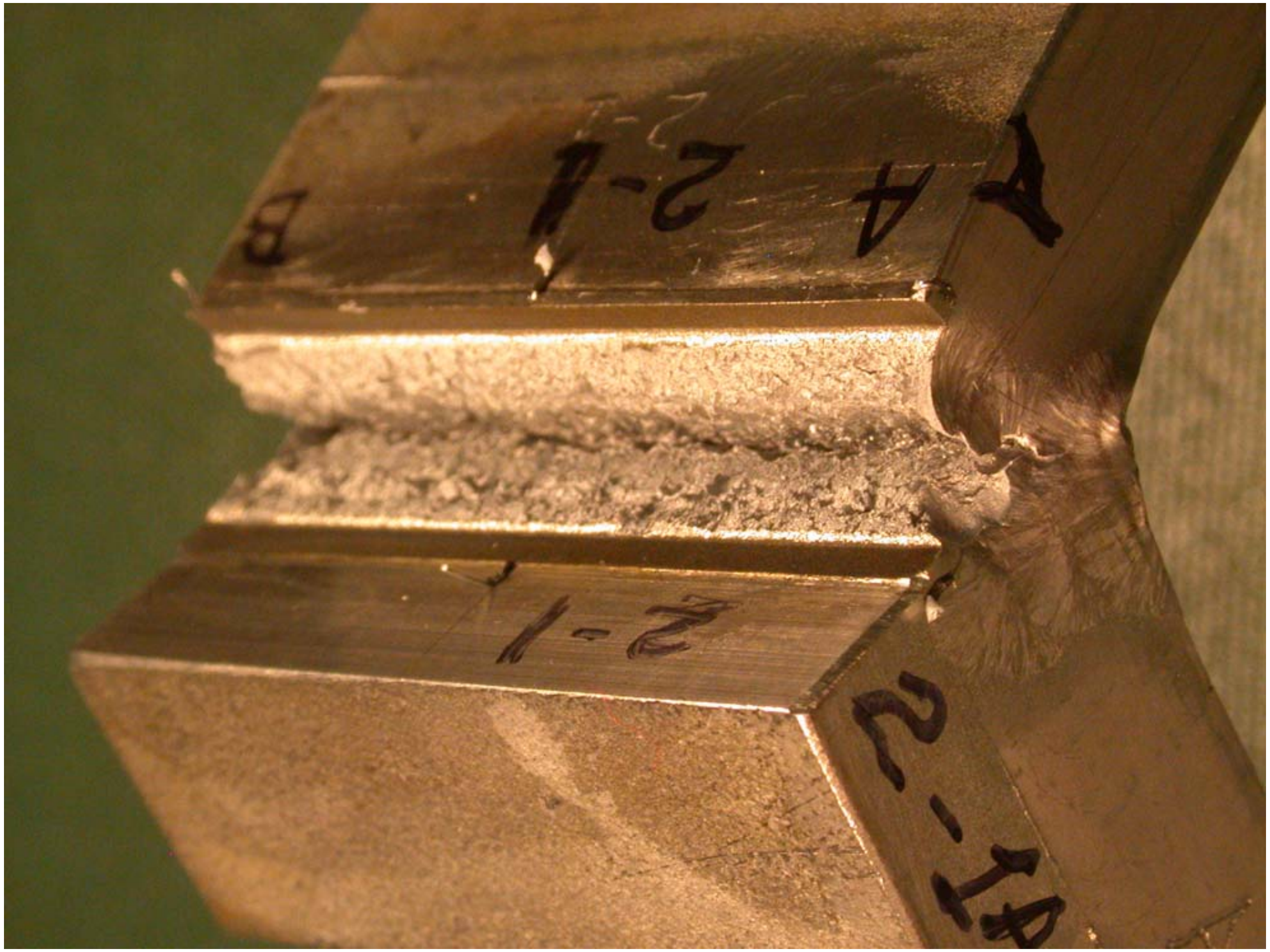
Flaw Propagation Tests



Flaw Propagation Tests



Flaw Propagation Tests



Deterministic Case (continued)

- Canister closure weld design, materials, fabrication, and inspection procedures meet the criteria prescribed by ISG-15

- Consistent with ISG-18, the canister closure welds may be qualified as an adequate containment boundary under 10CFR Part 71 for purposes of demonstrating no credible leakage during transportation

Probabilistic Case

- ISG-2 recently issued by NRC Division of HLW and Repository Safety

> The application of codes and standards to the design and operation of an ITS SSC is an accepted engineering practice recognized by the Commission in ensuring safety in the nuclear industry. The staff should recognize the high confidence in SSC reliability that is afforded by codes and standards. However, use of an applicable code or standard …. does not by itself … ensure a level of reliability sufficient to screen out failure-related event sequences from further consideration ….(e.g. 1E-6 failures/yr)

- Fragility analyses will be performed to develop an estimate of canister reliability

Probabilistic Case (continued)

- U.S. DOE SNF Canister Survivability, 000-PSA-WHS0-00100-000-000, Rev. 0
  - Estimates conditional probability of canister failure, given any drop, to be 2.3E-4
  - Conservatively assumed that any human error or undetected equipment failure in the drying process will result in conditions that will cause degradation such that a canister will fail under any drop scenario
  - Also assumed that all other failure modes (using code and ISG-based arguments) are negligible relative to this conservatively derived failure rate

Probabilistic Case (cont'd)

Transportation Criticality Risk

Event	Likelihood	Source
Train accidents per mile	4.3E-06	Federal Railroad Administration , Office of safety Analysis (all railroads, all causes, all track types)
Estimated number of miles per shipment	1500	Average miles per shipment
Probability of water entering cask given an accident	7.8E-09	NUREG/CR-4829, page 9-25 (>2% strain and becoming submerged)
Probability of canister breach given an accident	2.3E-04	U.S. DOE SNF Canister Survivability, 000-O-PSA-WHS0-0100-000, Rev. 0, July 2004
Probability of criticality given water in fuel cavity	1.00	Fuel-specific characterization data is not available for many DOE SNFs. Hence, a bounding assumption is used (i.e. fully degraded and optimally reconfigured and critically unsafe under these conditions)
Probability of criticality accident per shipment	1.2E-14	Calculated
Estimated # of shipments	450	Assumes 4 MCOs or 9 canisters per rail cask
Probability of a criticality accident over all anticipated shipments of DOE SNF	5.2E-12	Calculated

Compatibility with 10CFR 71.55(b)

- Package must be subcritical with leakage into the containment system in most reactive credible configuration and with moderation by water to the most reactive credible extent
  - Nonmechanistic leakage into containment system (cask cavity) is assumed
  - DOE SNF canisters provide a leaktight boundary assuring further leakage is not credible
  - Subcriticality is demonstrated with the cask cavity fully flooded and with canister internals fully degraded and optimally reconfigured

Compatibility with 10CFR 71.55(e)

- Following tests prescribed by 10CFR71.73 and consistent with its damaged condition, package must be subcritical with leakage into the containment system in most reactive credible configuration and with moderation by water to the most reactive credible extent
  - See compliance basis for 71.55(b)
  - Transportation cask will remain leaktight following tests prescribed by 10CFR 71.73
  - Standardized DOE SNF canisters have been demonstrated to remain leaktight following drop testing prescribed by 10CFR71.73

Pathforward

Presented to:

Nuclear Regulatory Commission

Brett Carlsen

Idaho National Laboratory

May 9, 2007

Our Request

DOE-EM is requesting NRC concurrence for the DOE standardized canister to be recognized and credited as a leaktight boundary during transportation

Questions

- Is NRC concurrence with our packaging strategy, prior to loading canisters, a reasonable expectation?
- Is our proposed interpretation and method of demonstrating compliance with the regulation reasonable in light of our canister performance and the ACNW recommendations?
- Is a topical report the right vehicle to proceed?
  - If so,
    - does the proposed scope of the topical report meet NRC needs?
    - what are staff expectations regarding the level of detail?
  - If not, what is suggested?