Overview of ANL LOCA and Dry Cask Storage Programs

M.C. Billone
Energy Technology Division

Review of ANL LOCA and Dry-Cask-Storage Programs
Argonne National Laboratory
July 16-17, 2003

Argonne National Laboratory

Office of Science
U.S. Department of Energy

A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago

Summary of Programs

- **LOCA-Relevant**
  - Advanced alloy post-quench ductility testing (unirradiated)
  - Steam oxidation of high-burnup BWR and PWR cladding
  - LOCA Integral Tests with fueled BWR and PWR cladding
  - Post-quench ductility of high-burnup LOCA Integral Test specimens
  - Ramp-to-burst tests with fueled BWR and PWR cladding
- **RIA- and LOCA-Relevant**
  - High and low strain-rate tensile properties: axial and hoop
  - PSU biaxial "plane-strain" tests: limit and failure strains
- **Dry Cask Storage**
  - Burnup ≤ 45 GWd/MTU: PWR rod characterization after 15-y storage
  - High burnup: tensile properties, creep properties, fuel isotopic analysis, annealing, hydride reorientation/redistribution, etc.

Unirradiated Cladding and Fuel Rods at ANL

- **Unirradiated Cladding Alloys**
  - Zry-2: 9x9 (Limerick BWR “archive”); 10x10 (to be provided)
  - Zry-4: 15x15 (Robinson “archive”); 17x17 low-Sn (W and [F-ANP])
  - ZIRLO: 17x17
  - M5: 17x17 (two lots)
  - E110: tubing and cladding (etched/anodized or lightly oxidized)
- **Irradiated Fuel Rod Segments (see Table)**
  - Robinson 15×15 PWR rods (7 for LOCA/RIA + 3 for Dry Cask + 2)
  - Limerick 9×9 BWR rods (7 for LOCA/RIA)
  - TMI-1 15x15 PWR rods (2 for verification/validation tests)
  - Surry 15x15 PWR rods (3 rods dry-cask stored for 15 years)

Commercial LWR Fuel Rod Segments at ANL

Reactor (Design)	**Burnup GWd/MTU**	^{235}**U** wt.%	**Gd_2O_3** wt.%	**Clad.**	**React. EOL**	**Dry-Stored**
Robinson 15×15 PWR	64-67 63 47	2.90 3.85 1.95	0 0 10	Zry-4 Zry-4 Zry-4	1995 1995 1995	No No No
Limerick 9×9 BWR	54-57	3.95	0	Zry-2 Lined	1998	No
TMI-1 15×15 PWR	48-50	4.00	0	Zry-4 Low-Sn	1997	No
Surry 15×15 PWR	36	3.11	0	Zry-4	1881	15 y

Cladding Irradiation Parameters for Correlations

Reactor (Design)	**Burnup GWd/MTU**	**Clad.**	**Fast Fluence** 10^{25} n/m^2	**Oxide µm**	**H wppm**
Robinson 15×15 PWR	67	Zry-4	14	≥100	≥750
Limerick 9×9 BWR	57	Zry-2 Lined	11	≈10 + ≈10 crud	≈70
TMI-1 15×15 PWR	49	Zry-4 Low-Sn	9	≥30	≥170
Surry 15×15 PWR	36	Zry-4	7	≥40	≥300

General Approach

- **Post Quench Ductility of Unirradiated Advanced Alloys**
  - Compare advanced alloys to Zry-4 and Zry-2 using same test methods
- **High-Burnup Cladding Oxidation and LOCA Integral Tests**
  - Compare oxidation kinetics to archival cladding using same test methods
  - Compare LOCA/Post-LOCA performance to archival cladding
- **High-Burnup Tensile and Biaxial Tests**
  - Compare results to archival cladding performance
  - Compare irradiated Zry-4 to PSU results for pre-hydrided Zry-4
- **Special Dry Cask Storage Tests**
  - Compare Surry characterization and creep results to literature data/models
  - Robinson mechanical/creep results: pre-annealed vs. as-received
  - Compare hydride reorientation data to literature data/models

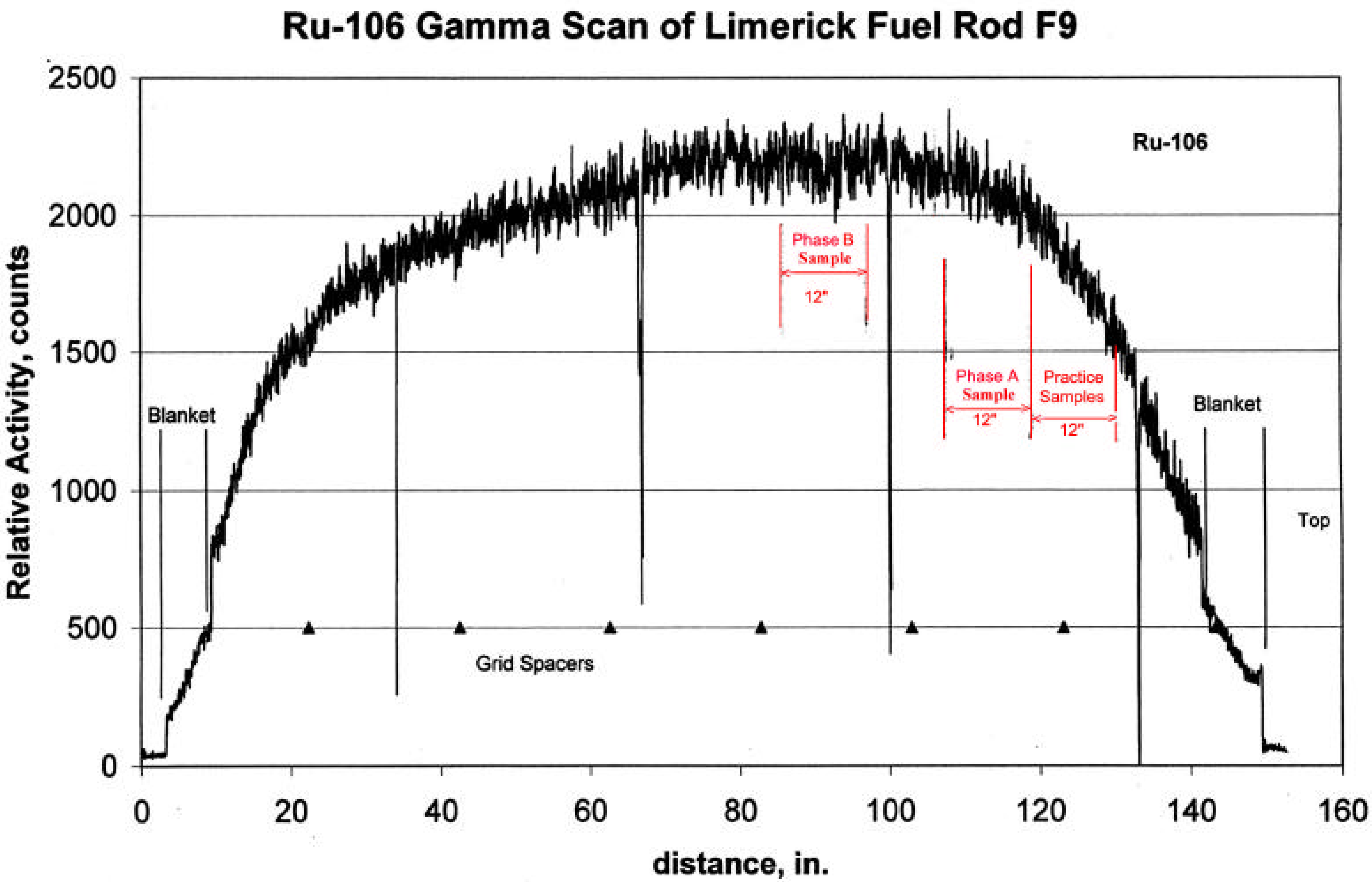
Advanced Alloy Post Quench Ductility

- **Receipt of Cladding and Tubing**
  - June 2002 – June 2003
  - GNF 10×10 Zry-2 and F-ANP Zry-4 to be provided
- **Verification and Validation Phase for Oxidation/Quench**
  - Initiated in Dec. 2002 with 1-sided oxidation of M5 and E110
  - Modification of test apparatus and methods for 2-sided oxidation
  - Extensive M5 and E110 testing; limited ZIRLO and Zry-4 testing
  - Thermal benchmark tests, metallography, O and H analyses
  - Ring compression validation tests completed in June 2003
- **Data for (1000-1260°C) Oxidized/Quenched Samples**
  - Completed for all alloys oxidized at 1100°C
  - Completed E110 study with emphasis on oxidation at 1000°C
  - Completion of as-received cladding testing scheduled for Dec. 2003

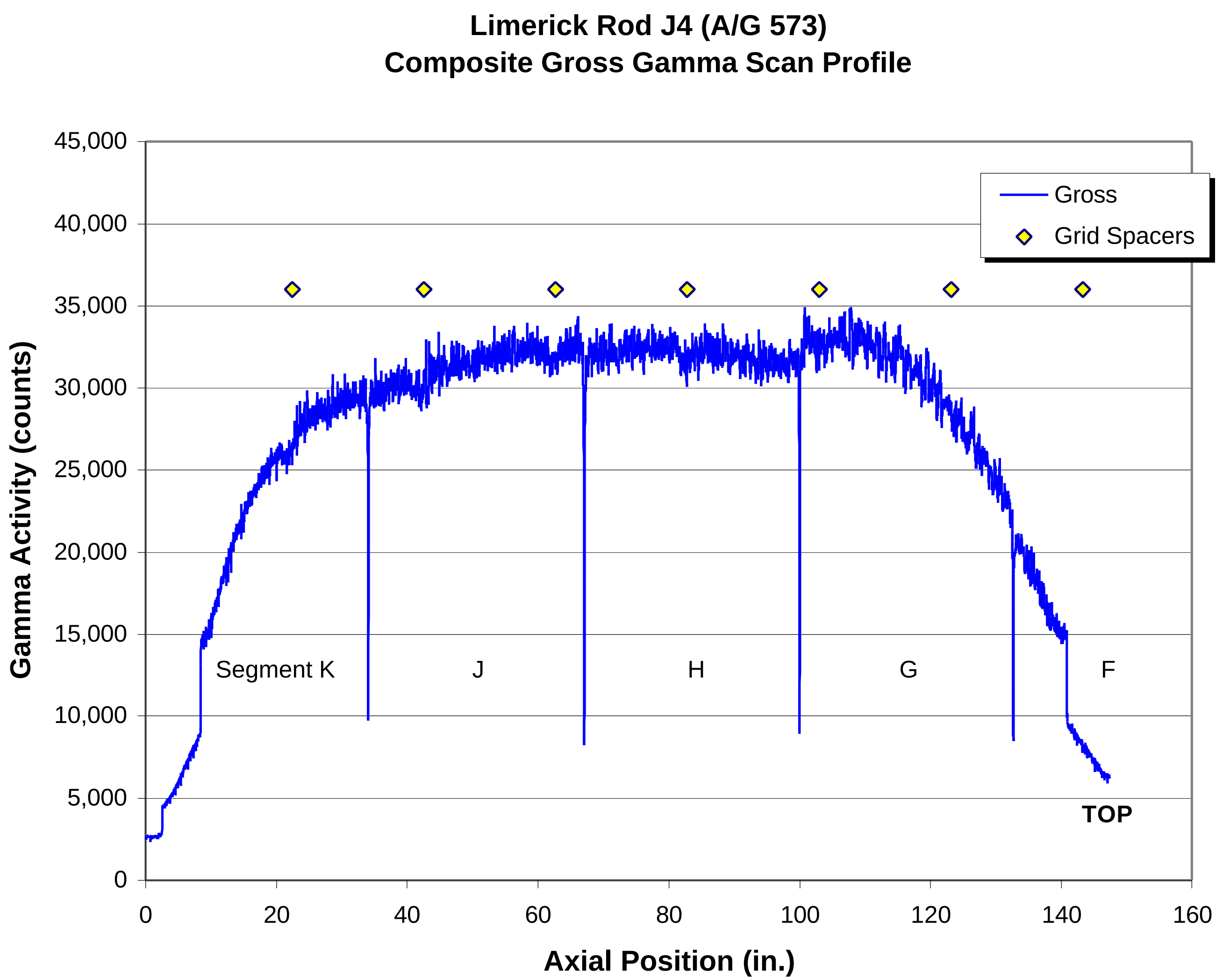
Characterization of Irradiated Fuel and Cladding

- **Gamma Scanning (see Limerick Rod F9 and J4)**
  - Determines integrity of fuel column, location of grid spacers, etc.
  - Results used to select uniform-burnup axial regions for specimen prep
- **Fuel Characterization (as-need basis to support tests)**
  - Metallography: microstructure, macro-micro cracks, fuel-clad. bond
  - Limited SEM and EMP to determine radial profile of U, Pu, etc.
  - Actinide and fission product isotopic analysis for dry cask storage
- **Cladding Characterization (as-need basis to support tests)**
  - Metallography: oxide thickness, hydride orientation/distribution
  - LECO: oxygen and hydrogen concentrations

Gamma Scan Results for Limerick BWR F9



Gamma Scan Results for Limerick BWR Rod J4



LOCA-Relevant Tests

- **Oxidation Kinetics Studies (1000°C, 1100°C, 1200°C)**
  - Limerick (10-µm oxide, 70-wppm H) completed (see NSRC papers)

    No significant difference observed for irradiated vs. unirradiated Zry-2
  - Robinson (100-µm oxide, 750-wppm H) to begin in October 2003
  - If oxide and hydrogen have significant effect on weight gain, repeat tests for lower elevation samples (50-µm oxide, ≈400-wppm H)
- **LOCA Integral Tests (1204°C for 5 minutes)**
  - Limerick ramp-to-burst and oxidation tests completed (Sept. 2002)

    Non-destructive results show more similarities than differences between unirradiated (with pellets) and irradiated (with fuel) Zry-2

    Determination of axial profiles for H and O are in progress
  - Run Limerick test with quench (August 2003)
  - Initiate Robinson (100-µm oxide, 750-wppm H) tests in Sept. 2003

LOCA-Relevant Tests (Cont'd)

- **Post-Quench Tests with High-Burnup LOCA Specimens**
  - Four-point-bend test: uniform moment along high O and H regions
    For 1204°C, expect O-embrittled burst region to fail for Limerick
    Robinson burst region may be more brittle due to O and H
  - Ring compression tests of H-embrittled regions away from burst
  - Decrease test time (<5 min.) and ECR if both tests indicate 0 ductility
- **Additional Robinson LOCA Integral Tests**
  - Repeat Robinson tests for lower elevation samples with 50-µm oxide layer and 400-wppm H if first Robinson sample has no ductility
  - Consider running tests at lower hold temperature (e.g., 1100°C)
- **Number of Tests in Test Matrix**
  - 3 for Limerick (ramp-to-burst, 5-min.-oxidation, quench)
  - 6 for Robinson (all with quench, vary ECR, H-content, hold T??)

Mechanical Properties Tests

- **Tensile Tests for Robinson Samples**
  - Recent progress made on characterizing unirradiated 15×15 Zry-4
  - TMI-1 (July 2002) ring test emitted significant contamination
  - Robinson axial tensile samples are 3R/h on contact (ALARA issue)
  - Elaborate glovebox built around Instron in Irradiated Materials Lab
  - Initiate axial tensile tests in August (RIA/LOCA & Dry Cask Storage)
  - Initiate hoop (RIA/LOCA) & PSU biaxial tests (RIA) in August
- **Defer Mechanical Properties of Limerick BWR Cladding**
  - Interesting: more radiation-induced embrittlement, << H-embrittlement
  - Should we be concerned about dry-cask-stored BWR Zry-2???

Dry-Cask Storage Program Overview

- **Dry-Cask-Stored Surry PWR Cladding (36 GWd/MTU)**
  - Phase 1 completed and documented in NUREG report
  - New creep test initiated at 400°C and 160 MPa; followed by 220 MPa
  - Hydride-reorientation/redistribution study (July 2003)
- **High-Burnup PWR Dry-Cask Storage**
  - Initiate axial tensile tests in August 2003
  - Thermal creep tests: 2 completed at 400°C, 2 more initiated at 380°C
  - Fuel isotopic/burnup analysis (actinides and fission products)

    1 Limerick BWR sample completed at meas./calc. 64 GWd/MTU

    2 Robinson samples will be completed in July-August

    7 more Robinson samples planned (depends on usefulness of data)
  - Need to define mechanical tests to address transportation concerns

Summary of Near-Term Efforts

- **In-Cell LOCA Integral Testing & Oxidation**
- **Mechanical Properties of High-Burnup PWR Cladding**
- **Effects of Annealing & H-Reorientation/Redistribution**
- **Thermal Creep of High-Burnup PWR Cladding**
- **Post-Quench Ductility of Advanced Alloys**
- **Isotopic Analysis of High-Burnup PWR Fuel**