From: Mike Billone <billone@anl.gov> RES
To: "Harold Scott (Harold Scott)" <hhs@nrc.gov>
Date: 2/13/06 4:54PM
Subject: SpellChecked Version

Dear Harold,

I corrected some obvious typos (see R2 files enclosed). I am shipping this off to my editor, who also processes the paperwork for WFO.

Mike

A-44

ADVANCED FUEL CLADDING RESPONSE TO LIMITING CONDITIONS

Detailed Work Scope, Milestones, Schedules and Budget Comments

1. BACKGROUND

Testing is being performed on high-burnup fuel rods with ZIRLO™, M5™, and Zircaloy cladding, along with archival tubing and prehydrided tubing for those rods, to characterize their behavior under conditions of interest. The fuel rod specimens must be remotely handled and tested in hot cells, so procedures are tedious and costs are high.

Two sets of conditions are of interest in relation to licensing criteria that need updating and evaluation models that need assessing. One corresponds to loss-of-coolant accidents (LOCAs) in operating reactors, and the other corresponds to dry cask conditions for transportation.

On August 21, 2003, the NRC-RES staff informed the Commissioners of an Updated Program Plan for High-Burnup LWR Fuel that addressed these two areas of interest. Because it was clear that high-burnup fuel rods with ZIRLO™ and M5™ cladding would not be available for testing for several years, the plan adopted a reasonable assumption that the burnup effects on LOCA behavior would be similar in all the zirconium alloys and that alloy effects would show up in tests with unirradiated material. Therefore, the test plan called initially for samples of high-burnup fuel rods with Zircaloy cladding along with samples of unirradiated Zircaloy, ZIRLO™, and M5™ cladding. Confirmatory tests with samples of high-burnup fuel rods with ZIRLO™ and M5™ cladding were to follow when that material was provided by the industry, which is cooperating in this research.

Under LOCA conditions, burnup-related effects can alter (a) cladding embrittlement, (b) oxidation kinetics, (c) ballooning and related flow blockage, and (d) axial fuel relocation into ballooned regions. A limit on cladding oxidation to prevent embrittlement is given in 10 CFR 50.46(b)(2), and this limit needs to be revised to account for burnup effects and differences in cladding alloys. A performance-based revision is planned to accommodate newer cladding alloys such as Framatome's M5™ alloy and Westinghouse's Optimized ZIRLO™ cladding, which are not covered by the present rule. The revision of 10 CFR 50.46(b)(2) only involves cladding embrittlement, although all of the above-mentioned phenomena are being investigated in this program. Therefore, only the embrittlement results are needed to initiate rulemaking, and investigation of the others can be completed after rulemaking starts.

LOCA embrittlement data at 1000°C and 1200°C, based on testing of short, defueled cladding samples, will be completed in FY 2006 and will provide the data needed to initiate rulemaking on 10 CFR 50.46(b)(2). Testing at 1100°C will be completed in FY2007. In parallel, unirradiated, prehydrided cladding samples will be tested to determine if prehydrided cladding is a good surrogate for high-burnup cladding. A discussion of the technical basis for this rulemaking was provided in a memorandum to the Commissioners on September 29, 2005. Integral tests, including a determination of ballooning size, axial fuel relocation, and fracture behavior, on high-burnup fuel rods with Zircaloy and advanced-alloy cladding will be completed in FY 2008.

Preparations are underway at EPRI and Framatome ANP to provide high-burnup fuel rods with M5™ cladding for testing at ANL. These fuel rods are expected to arrive at the laboratory in May-July 2006 time frame and be ready for testing in FY 2007 (1100°C) and FY2008 (fueled LOCA integral tests). Industry plans for providing ZIRLO™-clad fuel rods for fueled-cladding testing in FY 2008 have not been completed, but those rods have been requested. The LOCA-relevant testing of high-burnup fuel rods with Zry-4, M5™ and ZIRLO™ cladding is needed to confirm the assumption that burnup effects on LOCA behavior are similar in all alloys and to qualify pre-hydrided material as a substitute for irradiated material for the purpose of testing future cladding alloys at a much lower cost. Because we already know that one high-burnup effect (viz. hydrogen pickup during normal operation) differs from alloy to alloy, it is important to see if the overall alloy-to-alloy variations of LOCA behavior are bounded by the behavior of Zircaloy cladding.

10 CFR 71.55, 71.71, and 72.122 contain requirements for fuel rods in dry casks during transportation and storage. The phenomena that affect these requirements include hydride reorientation, crush resistance, and bending stiffness and resistance. Testing of these phenomena under dry cask conditions is also needed on high-burnup fuel with Zircaloy, ZIRLO™ and M5™ cladding. This testing uses the same hot cells, equipment, techniques, and source of test specimens as the LOCA-related testing. Consequently, these tests are proceeding in the same program as the LOCA-related tests and are included in this funding request. As with the LOCA-related tests, most of the testing on Zircaloy, M5™ and ZIRLO™ cladding will be completed in FY 2006-07. Impact and bend testing of fueled cladding segments will be completed in FY2008.

A final element of this program will provide mechanical properties for Zircaloy, ZIRLO™ and M5™ cladding that apply to LOCAs, dry casks, and other situations. Burnup affects these properties primarily as the result of hydrogen pickup from the normal corrosion process and radiation damage. Alloy and fabrication effects may also be significant. These properties are needed for almost all analyses that are made with computer codes used by applicants in preparing submittals and by the staff in reviewing submittals and making independent calculations related to fuel behavior. These properties will be measured during FY 2006-2008 as the cladding from high-burnup fuel rods become available.

2. OBJECTIVE

This program will provide the technical basis for (a) revising cladding limits in 10 CFR 50.46(b) for loss-of-coolant-accident (LOCA) analysis, (b) upgrading Interim Staff Guidance No. 11 for reviewing transportation and storage of spent fuel casks, and (c) determining the adequacy of related evaluation models.

3. REVIEW OF PREVIOUS WORK

No previous work has been performed under this contract. However, as this work is a continuation and completion of the previous work performed under Y6367 and related job code numbers, the previous work for Y6367 is reviewed in the following.

LOCA-related Tests with Zircaloy Cladding

In previous years, the only high-burnup fuel rods available for testing had the older Zircaloy cladding alloy. These rods were first used to develop appropriate testing techniques and basic oxidation data. In FY 2005, work focused on generating the data base that would be needed for rulemaking on 10 CFR 50.46(b), working on the assumption that burnup effects would be similar in all zirconium-based cladding alloys and that alloy effects will show up in tests with unirradiated material.

Oxidation kinetics data have been generated for as-fabricated, prehydrided and high-burnup Zircaloy cladding. Results to date confirm the best-estimate model (Cathcart-Pawel) recommended in Regulatory Guide 1.157 (1989) for calculating the metal-water reaction rate. The hydrogen content in high-burnup cladding has no effect on the oxidation kinetics, weight gain and oxidation pickup. For low predicted oxidation values (3-10%), the oxidation rate of high-burnup Zircaloy-4 is slightly slower than for as-fabricated cladding due to the presence of the corrosion layer formed during reactor operation. Thus, use of the Cathcart-Pawel model tends to give a slight over-prediction of transient oxidation for high-burnup cladding.

Following high-temperature steam oxidation and quench, unirradiated Zircaloy-4 cladding has been subjected to post-quench-ductility tests to determine ductility as a function of oxidation temperature, hydrogen content, and extent of oxidation. These tests were unique in that data were generated for samples with 200-800 wppm hydrogen at fixed oxidation values. The results are significant because high-burnup Zircaloy-4 with about 100 microns of corrosion layer has approximately 600-800 wppm hydrogen. The embrittlement oxidation levels are well below the 17% specified in 10 CFR 50.46(b), especially if the best-estimate model is used to calculate oxidation. The results for prehydrided cladding served as a baseline for planning and interpreting in-cell tests using high-burnup Zircaloy-4.

Samples from the high-burnup Zircaloy-clad fuel rods had corrosion layers of 50-100 microns and hydrogen contents of 400-800 wppm. Twelve ductility tests were completed: six with double-sided oxidation and six with single-sided oxidation. The results to date suggest the following: (a) the oxygen in both the corrosion layer and the fuel-cladding bond layer diffuses into the metal and contributes to cladding embrittlement, (b) corroded cladding embrittles at about the same rate as bare prehydrided cladding, even though transient weight gain and oxidation increase is slower, (c) prehydrided cladding may be a reasonable surrogate for high-burnup cladding, (d) slow-cooling enhances ductility compared to quenched cladding, and (e) the inclusion of the corrosion layer in the calculation of total oxidation, as recommended in NRC Information Notice 98-29, appears to account for the embrittling effects of hydrogen.

Four LOCA integral tests have been completed with fueled high-burnup BWR segments. These tests showed essentially no difference between as-fabricated and high-burnup ballooning-burst temperature and pressure, balloon size and axial extent of ballooning. The results also show excellent gas communication through the high-burnup fuel to the balloon region. However, high-burnup test segments showed much higher hydrogen pickup -- as much as 3000 wppm of secondary hydrogen -- in the balloon due steam oxidation inside the segments. These results indicate that the balloon region will embrittle at much less than 17% oxidation due to the high hydrogen pickup. This effect is not accounted for by the addition of the corrosion layer -- only 10 microns for the BWR Zry-2 cladding -- in the total oxidation.

LOCA-relevant tests with ZIRLO and M5 Cladding

The emphasis of this work has been on oxidation kinetics and post-quench ductility of unirradiated ZIRLO and M5, as compared to Zircaloy-4. For ZIRLO, very little work has been reported in the open literature. The limited testing done by Westinghouse in their comparison of ZIRLO to Zircaloy-4 is company-proprietary. Framatome, in cooperation with EdF and CEA, has sponsored an extensive comparison of M5 and Zircaloy-4 oxidation rate and post-quench ductility. Although some of this work is being published in the open literature, much of it remains company-proprietary. The ANL program is unique in that all three alloys are tested in the same apparatus for the same time-temperature oxidation and in the same ring-compression machine with data interpreted by a common methodology.

Oxidation kinetics tests for as-fabricated samples have demonstrated that all three alloys (Zircaloy-4, ZIRLO and M5) oxidize at the same rate at 1100°C and 1200°C, while at 1000°C ZIRLO oxidizes slower than Zircaloy-4 and M5 oxidizes slower than both Zircaloy-4 and ZIRLO. Following the oxidation-quench preparation of these samples, metallography, hydrogen analysis, and microhardness characterization have been performed. In parallel, ring-compression tests have been conducted. The results at 1000°C are particularly interesting: the alloys all embrittle after the same exposure time, independent of the measured weight gain and oxidation. Therefore, the ductility decrease and the embrittlement correlate much better with the oxidation calculated with the Cathcart-Pawel model, even though it is not a best-estimate for these advanced alloys. The results following 1200°C oxidation and quench are also important. When tested at room temperature, all three alloys embrittle at about 8-10% oxidation. However, retesting at 135°C -- the core temperature following quench -- enhances ductility such that the embrittlement oxidation is 18-20% when calculated with the Cathcart-Pawel model.

Cask-related Tests with Zircaloy Cladding

Characterization, creep and mechanical properties of low-burnup (36 GWd/t) PWR fuel following 15-years of dry-cask storage has been completed and documented in NUREG/CR-6831. Additional work for cladding creep, mechanical properties and axial diffusion of hydrogen has been documented in conference and open literature papers. The results were used in formulating NMSS ISG-11, Revisions 2 and 3. Creep tests have also been completed on high-burnup PWR Zircaloy-4 cladding. Both the low- and high-burnup creep results support the ISG position that creep during storage is not an issue for the temperature limit of 400°C specified in ISG-11 for normal drying, transfer, and storage operations.

Following the completion of the thermal-creep work and consistent with NMSS user needs, this effort was redirected towards generating data for the assessment of high-burnup cladding integrity during post-storage fuel retrieval and transport. Drying of high-burnup fuel produces high stress conditions, and high stress conditions can lead to unfavorable precipitation of hydrogen and low failure resistance during transfer and storage. Both prehydrided and high-burnup cladding have been exposed to cooling from 400°C at hoop stresses in the range of 0-150 MPa. The unfavorable precipitation of hydrogen appears to occur at drying stress > 90 MPa. However, more data are needed in this area to correlate decrease of failure energy with drying stress. In order to complete the test matrix in this area, crush impact tests, in addition to the high-strain-rate ring-compression tests are needed. Equipment has been constructed and tested out-of-cell to simulate the decrease of gas pressure and hoop stress during the slow cooling following the drying operation.

Mechanical Property Tests

Hoop tensile properties have been determined for as-fabricated Zircaloy-2 and Zircaloy-4 and for intermediate-burnup (50 GWd/MTU) PWR cladding. Measurement of hoop tensile properties, which was halted by NRC in FY2005 to expedite the LOCA work, will be re-initiated in FY2006 with cladding samples from high-burnup PWR rods.

Axial tensile properties have been measured at room temperature and 400°C for as-fabricated Zircaloy-2 and Zircaloy-4, for low-burnup PWR Zircaloy-4 (36 GWd/MTU) and for high-burnup PWR Zircaloy-4. Work is in progress to complete the test matrix by determining the properties for high-burnup PWR cladding at intermediate temperatures, at two different hydrogen levels, and at low- and high-strain rates. The test results give stress-strain properties needed for fuel-rod code analyses, as well as the failure limits needed for assessment of extent of cladding failure during in-reactor and cask-transport accidents.

4. WORK TO BE PERFORMED

The AGHCF was temporarily closed to programmatic work from July 26, 2005 through January 12, 2006. It was assumed that the facility would open early in 2006 following the independent readiness assessment requested by the ANL Director. However, on January 13, 2006, the Lab Director announced that the AGHCF would remain closed to programmatic work. In subsequent exchanges with NRC, the Lab Director indicated that no experimental work would be performed for NRC programs until full compliance with DOE orders for nuclear facilities was achieved. Although the future status of the AGHCF remains uncertain, for planning purposes it is assumed that the facility will be available for in-cell testing in FY2008.

The order to stop programmatic work in the AGHCF includes simple in-cell operations such as sectioning and defueling. During the period in which this order is in effect, sectioning and defueling will have to be outsourced to another nuclear facility. Negotiations are in progress to outsourcing the sectioning and defueling to BWXT.

The Lab Director's order applies not only to the in-cell facility but to all space within the wall boundaries of the AGHCF. It includes the out-of-cell LOCA apparatus, prehydriding system, laser welder, and impact tester; as well as the shielded glove boxes used for cladding cutting and cleaning and the shielded optical microscope and SEM for imaging irradiated samples. The out-of-cell LOCA apparatus, sample-preparation equipment, and impact tester have been moved and re-validated in a non-radiation-controlled lab spaces. Following completion of the testing of as-fabricated and prehydrided cladding, the out-of-cell LOCA apparatus will be moved to a beta-gamma hot cell in the Irradiated Materials Laboratory (IML) to allow testing of defueled cladding alloys to continue. Shielded glove boxes have been identified for re-establishing the capabilities of sample preparation and imaging of irradiated cladding alloys.

In general, the schedule has been revised to accommodate the change in experimental facilities available for this work: 1) conduct all tests with as-fabricated and prehydrided alloys first (FY2006); 2) conduct tests with defueled cladding samples second (FY2006-07); and 3) conduct tests with fueled cladding samples last (FY2008). The specific sequence of testing will depend on cladding materials available, as well as availability of sample-preparation equipment, experimental apparatus, and post-test characterization equipment.

Task 1: LOCA-relevant Testing for Zircaloy Cladding

<u>As-fabricated Zircaloys</u>

Included in the test plan is the determination of the post-quench ductility of 10×10 Zry-2 cladding. This cladding alloy will be oxidized at 1000°C and 1200°C to 10%, 13% and 17% CP-ECR, where CP refers to Cathcart-Pawel calculated, quenched, and ring compressed at RT (for 1000°C-oxidized samples) or 135°C (for 1000°C-oxidized samples). This work will be completed during the first quarter of CY2006.

One of the surprising results of the past research is that rough-surfaced 15×15 Zry-4 embrittles at a lower ECR (13% CP-ECR) as compared to smooth (belt-polished) 17×17 Zry-4 following oxidation at 1200°C. Belt-polished 15×15 Zry-4 will be oxidized at 1200°C to 13% and 17% CP-ECR, quenched, and ring-compressed at 135°C to determine if the lower ductility of the 15×15 Zry-4 is due to surface finish alone or to other factors.

With the emphasis on small-break vs. large-break LOCA, there is considerable interest in time for breakaway oxidation at lower oxidation temperatures for which the ECR is <17%. A review of the literature suggests that Zry-4 can exhibit breakaway oxidation at times as low as 31 minutes at 800°C, 53 minutes at 950°C, and 29 minutes at 1000°C. However, previous testing at ANL with belt-polished 17×17 Zry-4 oxidized at 1000°C shows no evidence of breakaway oxidation up to test times of 57 minutes. Both rough and belt-polished Zry-4 will be oxidized at 1000°C, 950°C and 800°C for one hour. The metric for this study will be hydrogen pickup rather than enhanced oxidation due to breakaway, as it is the hydrogen pickup that is embrittling. Test times corresponding to a hydrogen pickup of ≈100 wppm will be used to determine onset of breakaway oxidation for the purposes of determining an embrittlement threshold. Based on experience with E110, room-temperature embrittlement was observed at low ECR values following early breakaway oxidation at 200-300 wppm hydrogen pickup. This work is scheduled to be completed by the end of April 2006. Ample supplies of as-fabricated 15×15 Zry-4 (rough and smooth) are currently available at ANL to conduct these tests, but the current supply of 17×17 Zry-4 (belt-polished) is too limited for such tests.

Prehydrided Zry-4

The effects of hydrogen on post-quench ductility have been determined by ANL for 17×17 and 15×15 Zry-4 oxidized at 1200°C, quenched at 800°C, and ring-compressed at 135°C. Very limited CEA results suggest that slow cooling from 1200°C to RT, without quench, enhances ductility of 600-wppm-H Zry-4 at low ECR values. Prehydrided (300-600 wppm) 15×15 Zry-4 samples will be oxidized at 1200°C to 5% - 10% ECR, followed by slow-cooling to RT, for comparison with the existing database for samples quenched at 800°C. If no differences are found, then the study of cooling rate effects will have been completed. If there is a significant difference, samples will be quenched at 600°C to determine the effects of quench temperature. This work is scheduled to be completed in by the end of April 2006. It would be desirable to also determine the effects of quench temperature on 17×17 Zry-4, but the supply of this material is too limited.

High-Burnup Zry-4

Post-quench ductility tests have been completed for high-burnup 15×15 Zry-4 oxidized at 1200°C. However, as four of the samples were slow cooled and only one was quenched, the adequacy of this dataset depends on the results of the tests with prehydrided cladding, slow-cooled and quenched. If additional tests need to be conducted, BWXT or another nuclear facility will have to be used for the sectioning and defueling. The tests, if needed, would be completed by the end of FY2006.

Four or more tests are planned for high-burnup Zry-4 oxidized at 1000°C, with three of the samples slow-cooled and at least one sample quenched. The three slow-cooled samples will be sequential with the first test run to 10% ECR. Subsequent tests would be at higher or lower ECR values depending on the ductility of the slow-cooled 10% CP-ECR sample. These tests, which require defueled cladding, will be completed by the end of FY2006. Longer time tests will be conducted to determine breakaway oxidation time at 800°C, 950°C and 1000°C. These are scheduled for FY2007.

Task 2: LOCA-relevant Testing for ZIRLO Cladding

As-fabricated ZIRLO

In parallel with the Zry-4 breakaway oxidation study, belt-polished 17×17 ZIRLO will be oxidized at 1000°C, 950°C and 800°C for one hour. The metric for this study will be hydrogen pickup rather than enhanced oxidation due to breakaway, as it is the hydrogen pickup that is embrittling. Test times corresponding to a hydrogen pickup of ≈100 wppm will be used to determine onset of breakaway oxidation for the purposes of determining an embrittlement threshold. Previous experience with ZIRLO, the hydrogen pickup is about 100 wppm after 57 minutes at 1000°C. Based on experience with E110, room-temperature embrittlement was observed at low ECR values following early breakaway oxidation at 200-300 wppm hydrogen pickup. This work is scheduled to be completed by the end of April 2006. However, a new supply of belt-polished 17×17 ZIRLO is needed. The inventory of ZIRLO at ANL is very limited and the remaining tubing is scratched and abraded.

Prehydrided ZIRLO

The effects of hydrogen (200-500 wppm) on post-quench ductility will be determined for 17×17 ZIRLO oxidized at 1200°C to 5-13% CP-ECR, quenched at 800°C, and ring-compressed at 135°C. This work is scheduled for FY2007 because more as-fabricated ZIRLO is needed and because the testing of high-burnup ZIRLO has a higher priority during FY2006.

High-Burnup ZIRLO

The post-quench ductility will be determined for high-burnup ZIRLO oxidized at 1200°C and either slow-cooled (3 samples) or quenched (at least one sample). Defueled cladding (320 mm) irradiated in one of the North Anna reactors is available for this testing. The first test will be run to 10% CP-ECR and the ductility will be determined at 135°C. Subsequent tests would be at higher or lower ECR values depending on the ductility of the slow-cooled 10% CP-ECR sample. The probable range of ECR values for the slow-cooled tests is 7.5-13% CP-ECR. At least one of these test conditions with high (>10%) ductility will be repeated with quench. Additional tests with quench may be conducted if the thermocouples survive the first quench test. This work is scheduled for May 2006. LOCA integral tests at 1200°C are planned for FY2008.

Four or more tests are planned for high-burnup ZIRLO oxidized at 1000°C, with three of the samples slow-cooled and at least one sample quenched. The three slow-cooled samples will be sequential with the first test run to 10% ECR. Subsequent tests would be conducted at higher or lower ECR values depending on the ductility of the slow-cooled 10% CP-ECR sample. The probable range of ECR values for the slow-cooled tests is 10-17% CP-ECR. At least one of these test conditions with high (>10%) ductility will be repeated with quench. Additional tests with quench may be conducted if the thermocouples survive the first quench test. This work is scheduled for July 2006. LOCA integral tests at 1000°C are planned for FY2008.

Task 3: LOCA-relevant Testing for M5 Cladding

As-fabricated M5

In parallel with the Zry-4 breakaway oxidation study, belt-polished 17×17 M5 will be oxidized at 1000°C, 950°C and 800°C for one hour. The metric for this study will be hydrogen pickup rather than enhanced oxidation due to breakaway, as it is the hydrogen pickup that is embrittling. Test times corresponding to a hydrogen pickup of ≈100 wppm will be used to determine onset of breakaway oxidation for the purposes of determining an embrittlement threshold. Based on experience with E110, room-temperature embrittlement was observed at low ECR values following early breakaway oxidation at 200-300 wppm hydrogen pickup. This work is scheduled to be completed by the end of April 2006.

Prehydrided M5

The effects of hydrogen (75-200 wppm) on post-quench ductility will be determined for 17×17 ZIRLO oxidized at 1200°C to 5-13% CP-ECR, quenched at 800°C, and ring-compressed at 135°C. This work is scheduled for FY2007 because the testing of high-burnup M5 has a higher priority during FY2006.

High-Burnup M5

The post-quench ductility will be determined for high-burnup M5 oxidized at 1200°C and either slow-cooled (3 samples) or quenched (at least one sample). Defueled cladding (320 mm) irradiated in the Ringhals European reactor is available for this testing. The first test will be run to 10% CP-ECR and the ductility will be determined at 135°C. Subsequent tests would be at higher or lower ECR values depending on the ductility of the slow-cooled 10% CP-ECR sample. The probable range of ECR values for the slow-cooled tests is 7.5-13% CP-ECR. At least one of these test conditions with high (>10%) ductility will be repeated with quench. Additional tests with quench may be conducted if the thermocouples survive the first quench test. This work is scheduled for June 2006. LOCA integral tests at 1200°C are planned for FY2008.

Four or more tests are planned for high-burnup M5 oxidized at 1000°C, with three of the samples slow-cooled and at least one sample quenched. The three slow-cooled samples will be sequential with the first test run to 10% ECR. Subsequent tests would be conducted at higher or lower ECR values depending on the ductility of the slow-cooled 10% CP-ECR sample. The probable range of ECR values for the slow-cooled tests is 10-17% CP-ECR. At least one of these test conditions with high (>10%) ductility will be repeated with quench. Additional tests with quench may be conducted if the thermocouples survive the first quench test. This work is scheduled for August 2006. LOCA integral tests at 1000°C are planned for FY2008.

Task 4: Mechanical Property Tests

Ring Stretch Tests

These tests are conducted to provide baseline data for validating codes developed to model cladding performance during RIA and LOCA events. Four uniaxial hoop tensile tests with high-burnup Zry-4 are planned for FY2006 for high-burnup Zry-4: RT at low and high strain rate; and 400°C at low and high strain rate. Additional tests are planned in FY2007-08 for high-burnup Zry-4, ZIRLO and M5.

Plane strain ductility tests will also be performed in the range of 280-400°C. Four are planned for FY2006 with high-burnup Zry-4 rings, with additional tests planned for FY2007-08 for high-burnup Zry-4, ZIRLO and M5.

Axial Tensile Tests

Axial tensile tests conducted between RT and 400°C are sponsored by the SNF part of this program. Testing at >400°C is LOCA-relevant and will be conducted in FY2007-08.

Task 5: High-Burnup SNF Cladding Behavior during Cask Transport

Axial Tensile Tests

Two RT tests and one 400°C test have been completed for high-burnup Zry-4. The second 400°C test will be completed in April 2006. About 640-mm of defueled ZIRLO irradiated in the North Anna plant will be shipped from Studsvik to ANL in March-April 2006. Four of these 80-mm-long samples are reserved for axial tensile tests at RT (high and low strain rate) and 400°C (high and low strain rate). These tests will be completed in FY2006.

Effects of Drying Operations on Cladding Integrity

High-strain-rate ring compression and crush impact tests will be performed prehydrided (300-600 wppm H) and preconditioned Zry-4 (drying from 400°C at 0-150 MPa to induce radial hydrides. The hydride morphology for the preconditioned Zry-4 will be determined and correlated with the failure ductility and energy. The high-strain-rate and crush-impact failure energies will be compared to determine if impact tests are really necessary. The high-strain-rate ring compression tests will be conducted at 10 mm/s, while the crush-impact tests will be conducted at ≤4 m/s. This work will be completed by July 2006.

The preconditioning and ring-compression testing will be repeated for the soon-to-be available high-burnup ZIRLO cladding (four 80-mm-long) samples and defueled Zry-4 samples once they become available. The ZIRLO testing will be completed in FY2006.

6. PROPOSED PERSONNEL

The ANL Principal Investigator is Dr. M. C. Billone. The project staff includes: T. Burtseva, R.S. Daum, S. Majumdar, W. K. Soppet, H.C. Tsai and Y. Yan. Resumes for these staff members have been provided with the previous Y6367 High Burnup Cladding Performance program and are available upon request.

7. MEETINGS/TRAVEL

Travel for this program generally consists of domestic and foreign information exchange meetings, presentations at program review meetings, formal paper presentations at technical society and NRC-sponsored meetings, and special training courses. Travel by Argonne staff to such meetings will be pre-approved by the NRC with formality appropriate for the meeting. The FY2006 budget allows for ≈8 domestic trips and 2 foreign trip.

8. NRC-FURNISHED MATERIALS

Through its partnership with EPRI, high-burnup PWR Zry-4-clad rod segments and BWR Zry-2-clad rod segments have been supplied to ANL. The DOE shall retain ownership of the fuel from these rod segments and will be responsible for removal of the fuel from ANL to a repository or an intermediate site at a later date. Costs to NRC will include only an appropriate packaging of the segments and remnants for shipping to the repository site or an interim site. As the requirements for the packaging have not been determined, the precise cost cannot be determined at this time. NRC is also responsible for some of the AGHCF cleanup following the completion of this project. The costs for these activities (estimated to be $100K) will be provided to NRC during the final year of the program.

High-burnup segments of ZIRLO (4 segments, each 8-mm long) and of M5 (4 segments, each 8-mm long) were defueled and shipped from Studsvik to ANL in May 2005. These materials were provided at NRC expense. An additional shipment of defueled high-burnup ZIRLO (8 segments, each 8-mm long), also at NRC's expense, is expected in the March-April 2006 time frame. Also, NRC is working with EPRI to supply ANL with segments from high-burnup, fueled M5 rod and high-burnup fueled ZIRLO rod. The high-burnup M5 rod segments will arrive at ANL in the May-July 2006 time frame. High-burnup ZIRLO rod segments have been requested of EPRI by NRC, but no definite plans have been made for shipment to ANL. The LOCA integral tests planned for FY2008 are conditional upon the receipt of the high-burnup M5 and ZIRLO rod segments.

9. RELATIONSHIP TO OTHER PROJECTS

Cognizance of other research sponsored by the NRC (domestic and foreign), Department of Energy, reactor vendors, electrical utilities and other organizations will be maintained, and available results will be evaluated for use in this project. ANL results will also be made available to NRC partners. Particular attention will be given to NRC projects at PNNL, Halden, Studsvik, and IRSN (France). Collaboration will be maintained with other NRC partners (e.g., JAEA) who are doing LOCA-relevant and SNF-relevant research. Close coordination will be maintained with the DOE-RW-sponsored programs for transport of dry-cask-stored fuels to a permanent repository.

10. REPORTING REQUIREMENTS AND SCHEDULE

Monthly Letter Status Report

Monthly letter status reports (MLSRs) will be submitted to the NRC Project Manager (H. H. Scott) by the end of the month following the reporting period and will cover technical progress, financial status, meetings and travel, publications and presentations, and any problems encountered. Copies will be provided to the Division Director, ATTN: Management Analyst; and the Division of Contracts and Property Management (DCPM), Office of Administration. Copies without the budget and cost pages will also be provided to EPRI, EPRI consultants, DOE, and other NRC offices. The reports will identify the title of the project, JOB CODE, Principal Investigator, period of performance, and reporting period and will contain information requested by NRC.

Other Technical (Letter, Topical and NUREG/CR) Reports

ANL will prepare periodic letter or more formal reports (e.g., NUREG/CR) or outside publications at the completion of specific milestones. ANL will follow provisions of Management Directive 3.9 with regard to all publications.

11. SUBCONTRACTOR/CONSULTANT INFORMATION

Because the AGHCF is unavailable for sample preparation, particularly sectioning and defueling, these activities will have to be outsourced to another nuclear facility capable of doing this work. BWXT has been identified as a potential subcontractor for this work. Discussions and visits (BWXT to ANL and ANL to BWXT) have taken place and the paperwork for such a subcontract is in progress. The work will include sectioning and defueling of the high-burnup Zry-4 rod segments currently in the AGHCF, as well as for the high-burnup M5 rod segments expected in May-June 2006.

12. SPECIAL FACILITIES, IF REQUIRED

Fuel-rod segment shipping, receiving and storage for this project will utilize the hot cells in Building 212 AGHCF at ANL. Experiments during FY2006-08 will be conducted primarily in the Irradiated Materials Laboratory (IML) hot cells and glove boxes, also in Building 212. Other radiation-controlled and non-controlled lab space and facilities will also be used.

13. CONFLICT-OF-INTEREST INFORMATION

No apparent or actual conflicts of interest are anticipated to arise among DOE, ANL, its employees, and industries regulated by the NRC and suppliers thereof as a result of this work. NRC has established Memoranda of Understanding (MOUs) with EPRI, DOE-NE Framatome ANP, and Westinghouse for conduct of this research.

14. CLASSIFICATION OR SENSITIVITY, IF APPLICABLE

Not applicable.

15. ADDENDUM: COST AND SCHEDULE INFORMATION

Significant program milestones remaining for FY2006 and beyond are listed below. Because of the parallel milestones for LOCA-relevant work with Zircaloy, ZIRLO and M5, these are included together

Tasks 1-3: LOCA-relevant Testing for Zircaloy, ZIRLO and M5 Cladding

Draft NUREG report on previous results	0306
Completion of testing of as-fabricated Zry-2 and Zry-4	0406
Quench temperature effects on PQD of pre-H Zry-4	0406
Breakaway oxidation time for as-fabricated cladding alloys	0406
High-burnup ZIRLO oxidized at 1200°C	0506
High-burnup M5 oxidized at 1200°C	0606
High-burnup ZIRLO oxidized at 1000°C	0706
High-burnup M5 oxidized at 1000°C	0806
High-burnup Zry-4 oxidized at 1000°C	0906
Update NUREG report	0906
Prehydrided ZIRLO and M5 PQD testing	FY2007
Breakaway oxidation of high-burnup cladding alloys	FY2007
Update NUREG report	0907
LOCA integral tests with Zry-4, ZIRLO and M5	FY2008
Final report	1108

Task 4: Mechanical Properties

Ring stretch tests at RT and 400°C	0906
Letter report documenting results	1106
Completion of ring stretch tests	FY2007
Axial tensile tests at >400°C	FY2007

Task 5: High-Burnup SNF Cladding Behavior during Cask Transport

Zry-4 axial tensile test at 400°C	0406
ZIRLO axial tensile tests at RT and 400°C	0906
Pre-H/preconditioned ring-compression and impact tests	0706
Preconditioned high-burnup ZIRLO ring-compression tests	0906
Preconditioned high-burnup Zry-4 ring-compression tests	0906
Letter report documenting results	1006
Preconditioned high-burnup M5 ring-compression tests	FY2007
Integral impact and bend tests	FY2008

16. SPENDING PLAN

Page 1 of the budget pages lists the projected costs for FY2006-08. All costs are given on a "best-estimate basis" and are based on the ET effort-overhead rates and laboratory indirect rates for FY2006 and projected for FY2007-08. The ET Division and/or the Laboratory can change these rates anytime during a fiscal and make them retroactive to the beginning of the fiscal year. The NRC project manager will be informed of any rate changes as they occur.

The overall spending plan is given on page 3 of the budget pages.