ORNL/MD/LTR-195
Revision 0

Post-Irradiation Examination Plan For ATR MOX Capsules Withdrawn at 30 GWd/MT and Higher

R. N. Morris

September 2000

Fissile Materials Disposition Program

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Distribution

Post-Irradiation Examination Plan For ATR MOX Capsules Withdrawn at 30 GWd/MT and Higher

The enclosed document details the PIE plans for the next series of MOX Average Power Test capsules, which will be withdrawn with burnups of 30 GWd/MT and higher. These differ from previous withdrawals in that residual pellet-clad contact is expected. This document updates the PIE planning in accordance with the current program interests. This work will be carried out at the Irradiated Fuels Examination Laboratory by the staff of the Metals and Ceramics Division of the Oak Ridge National Laboratory.

This is a Level-2 document as defined in the Fissile Materials Disposition Program Light-Water Reactor Mixed-Oxide Fuel Irradiation Test Project Plan, ORNL/MD/LTR-78

Sincerely,

Robert N. Morris
Fissile Materials Disposition Program

Enclosure

Distribution: See enclosure

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LIST OF ACRONYMS

ATR	Advanced Test Reactor
ES&H	Environment, Safety, & Health
FMDP	Fissile Materials Disposition Program
GWd/MT	Giga Watt days per Metric Ton
ID	Identification
INEEL	Idaho National Engineering and Environmental Laboratory
IFEL	Irradiated Fuels Examination Laboratory
LANL	Los Alamos National Laboratory
LWR	Light Water Reactor
MOX	Mixed Oxide
ORNL	Oak Ridge National Laboratory
PIE	Post Irradiation Examination
PPM	Parts Per Million
SEM	Scanning Electron Microscope
TIGR	Thermally Induced Gallium Removal

ABSTRACT

Post-irradiation examination (PIE) is to be performed on the ATR Average Power Test MOX fuel capsules that have received burnups (generally in sets of two) of approximately 30, 40, and 50 GWd/MT. This task will have an emphasis in two areas. The first is monitoring of capsule behavior to determine if the fuel is performing as predicted with special attention to pellet swelling. The second is the monitoring of fuel pin material behavior, particularly any transport of trace gallium and its effects on the fuel pin. This PIE will include visual and dimensional inspection, gamma scanning, metallography, fuel and clad gallium analysis, and burnup estimation. Clad ductility testing is also planned pending the completion of a test description and the fabrication of the necessary apparatus.

As soon as the necessary information (as described in Sections 3.1 through 3.5 of this report) is available for the 30 and 40 GWd/MT withdrawals to support decision making with respect to the safety of the continued irradiation of the remaining capsules, ORNL will provide these results to INEEL. The Quick Look PIE reports will follow shortly thereafter.

1. INTRODUCTION

1.1 Background

The Fissile Materials Disposition Program (FMDP) Fuel Irradiation Test Project Plan details a series of test irradiations designed to investigate the use of weapons grade plutonium in mixed oxide (MOX) fuel for light-water reactors (LWR) [Ref. 1]. These irradiations are being performed in the Advanced Test Reactor (ATR) at the Idaho National Engineering and Environmental Laboratory (INEEL). This irradiation series was originally designed to end at a burnup of 30 GWd/MT, but program interest shifted toward higher burnup levels during the years the capsules have been in the reactor. The new burnup goal is 50 GWd/MT with an additional capsule withdrawal and post irradiation examination (PIE) at 40 GWd/MT to provide assurance that the irradiation is proceeding as predicted.

The focus of the PIE work for this MOX irradiation is to track the behavior of gallium present in the fuel [Ref. 2]. During the course of the fabrication and testing, it was discovered that fuel fabrication left about 1-5 ppm gallium in the fuel. Recent analysis has revealed that trace gallium has been present in LWR fuel systems for years. This test involves fuel gallium levels that exceed that expected to be present in the mission fuel.

The first two PIE results at 10 and 20 GWd/MT burnup have indicated that the gallium is not migrating and its presence is therefore insignificant [Refs. 3 and 4]. While gallium behavior at the few ppm level is still of interest, the major concern for the 40 GWd/MT PIE is fuel performance, specifically fuel swelling and clad strain.

The test capsules were originally designed to accommodate burnups of 30 GWd/MT, but later calculations have shown that the capsules will not exceed operational limits at the 50 GWd/MT burnup if the fuel continues to behave in the manner predicted. The major purpose of this plan is to detail the PIE steps necessary to provide data to allow the designers to measure the performance of the test fuel.

1.2 Goals and Objectives

The primary goal of this task is to provide information that will allow the capsule designers to determine if the fuel is performing as predicted. A second goal is to experimentally verify the presence or absence of material interactions in the MOX fuel pin and to track any migration of the gallium.

The early objectives of this PIE task are to:

1. Visually inspect (low magnification) the capsules for defects including cracks, broken welds, and corrosion. Dimensionally inspect the capsule diameter as a function of

length to provide indications of any capsule deformation;

2. Gamma scan the capsules before opening to obtain nondestructive information on the fuel stack length and the integrity of the internal components;

3. Measure the capsule pressure to indicate fuel pin integrity and measure fuel pin pressure and ^{85}Kr inventory;

4. Remove the fuel pin from the capsule and visually inspect (low magnification) the fuel pin for defects including cracks, broken welds, and corrosion. Dimensionally inspect the fuel pin diameter as a function of length to provide indications of fuel clad strain including any evidence of excessive fuel swelling or clad bambooing.

Once these early objectives have been completed and reported, the PIE will continue:

5. Segment the fuel pin and prepare samples for metallography and radiochemistry analysis. Examine the samples for pellet-clad gap, fuel restructuring, fuel matrix performance, burnup, and gallium migration;

6. Prepare clad specimens for ductility testing and perform the tests when the apparatus and the approved irradiated clad integrity test plan are available.

A final report will be prepared for each PIE once the examination has been completed. These goals may be modified during the course of the PIE to incorporate new information or changes in program goals. The test engineers are to check with the project office before proceeding with any destructive analysis to insure that the latest plan is in place.

1.3 Scope and Conduct

This document describes the generic sequence of tasks for the PIE examination of the capsule and its inner fuel pin assembly at the planned burnups of 30, 40, and 50 GWd/MT. The major PIE work will be done in the Irradiated Fuels Examination Laboratory (IFEL), Building 3525. Radiochemistry and ductility testing work will be done in other ORNL facilities as necessary. The ORNL FMDP project office will be consulted before work is begun to assure that the most recent plans are being followed.

Detailed procedures for the PIE work will be written prior to the performance of the subtask and will be approved before use. Work will be conducted under the *Fissile Materials Disposition Program Quality Assurance Plan*, QAP-X-FMDP-01, Rev 0 and the *Quality Management Plan for Metals and Ceramics Division Non-Reactor Nuclear Facilities*, QAP-X-MC-HC-01, Rev 0. All work will be done under the appropriate facility ES&H guidelines and will fall under the *Metals and Ceramics Division Conduct of Operations*, MET-ESH-SOP-2.

2. TEST DESCRIPTION

2.1 Fuel Types

Two fuel types, which differ in their treatment of a common PuO_2 source, are included in this average-power test. Fuel type B was fabricated with plutonium dioxide that was subjected to a thermal treatment, Thermally Induced Gallium Removal ("TIGR"), for gallium removal prior to pellet fabrication. Fuel type A was fabricated with plutonium dioxide that was not treated. Ten pellets of each batch were analyzed at ORNL for gallium content [Ref 5]. Batch A had an average gallium content of 2.97 ppm (mass) and Batch B had a average gallium content of 1.33 ppm (mass). The 95% confidence interval for Batch B was 0.79 to 1.88 ppm and 1.00 to 4.95 for Batch A. Los Alamos, based on the analysis of two pellets just after fabrication, had previously reported average values of 2.0 ppm for Batch A and 0.7 ppm for Batch B. See Reference 5 for additional detail with respect to initial pellet gallium content.

Both batches of fuel achieved high density in part due to the extended sintering schedule. Average immersion densities of 94.5 % TD and 95.3 % TD were measured on fuel types A and B respectively. Essentially no density change was achieved during a subsequent 24 hour thermal densification test. The porosity distribution includes a uniform distribution of fine pores and the average grain size (reported by LANL) is 10 µm (fuel type A) and 11 µm (fuel type B). A typical pellet is shown in Fig. 1.

2.2 Irradiation Geometry

The fuel pellets and stainless steel springs were loaded into Zircaloy fuel pins and the pins sealed by welding at Los Alamos. The pins were then transferred to Idaho National Engineering and Environmental Laboratory (INEEL), where they were loaded and seal welded into closely fitting stainless steel capsules (to meet the ATR pressure vessel operational requirements for this type of experiment as loaded into the reflector I-holes). Finally, the capsules were loaded into a basket assembly that was subsequently inserted into the ATR reflector for irradiation. Figs. 2 through 4 show the geometry of the configuration.

2.3 Preirradiation Dimensional Data

Table 1 lists the dimensional data and part identification of the fuel capsule test series components prior to assembly. Capsules 1, 2, 8, and 9 have already been subjected to PIE. Capsules 7 and 11 are archives. The remainder will be irradiated to burnups of 30 GWd/MT or higher.

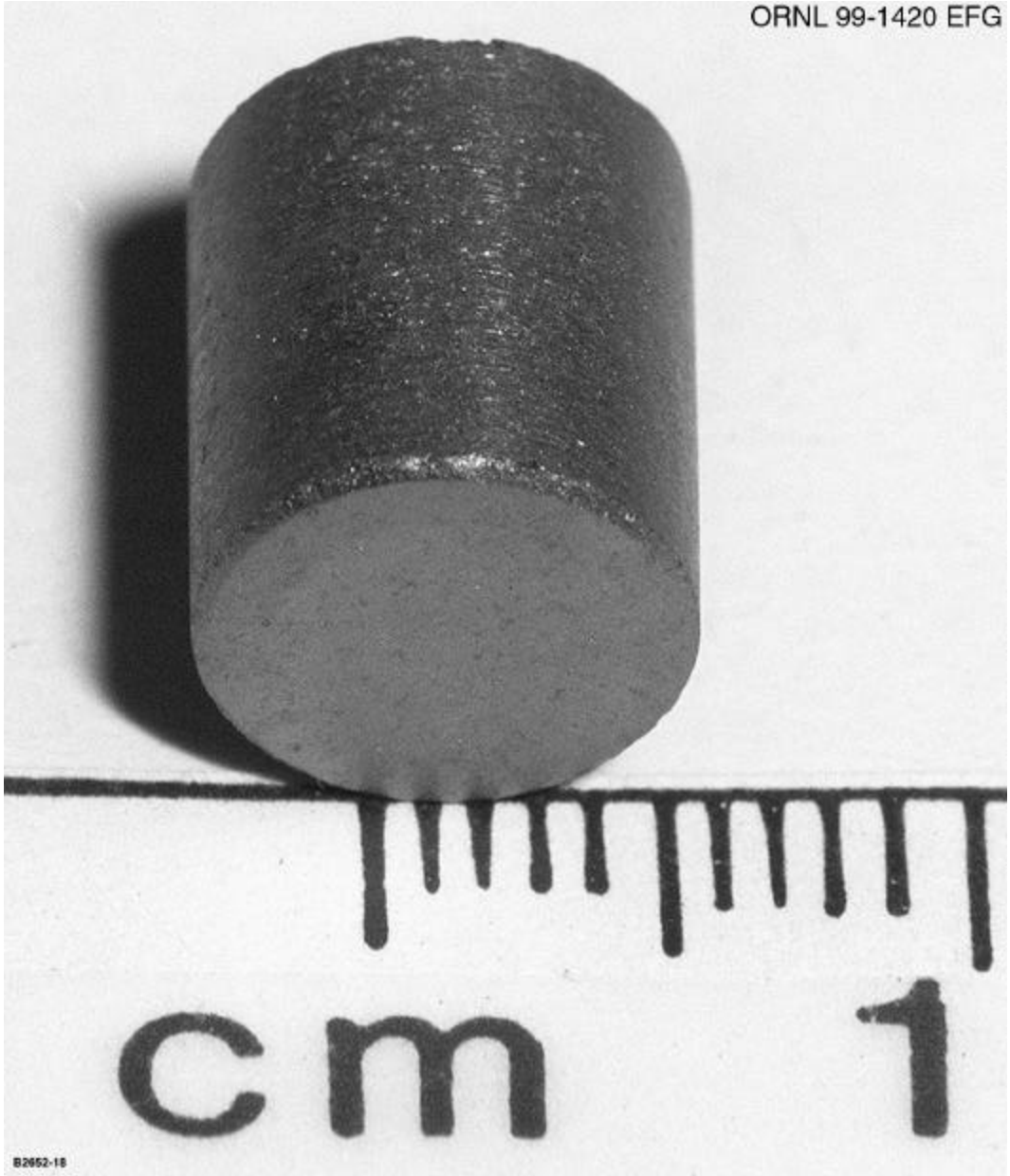

Figure 1 Typical MOX pellet as fabricated at LANL for the average-power test.

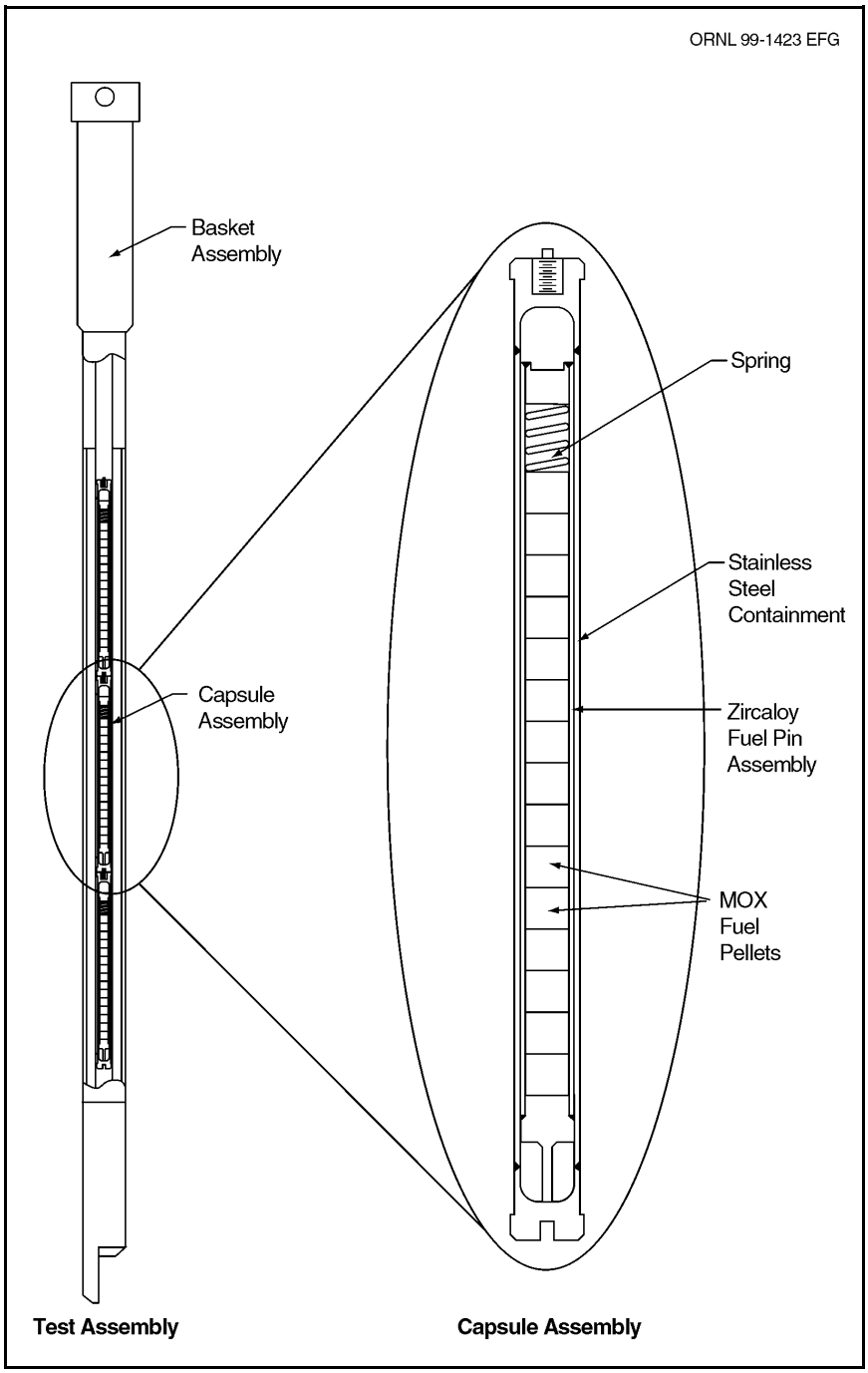

Figure 2 Capsule, fuel pin, and basket assemblies.

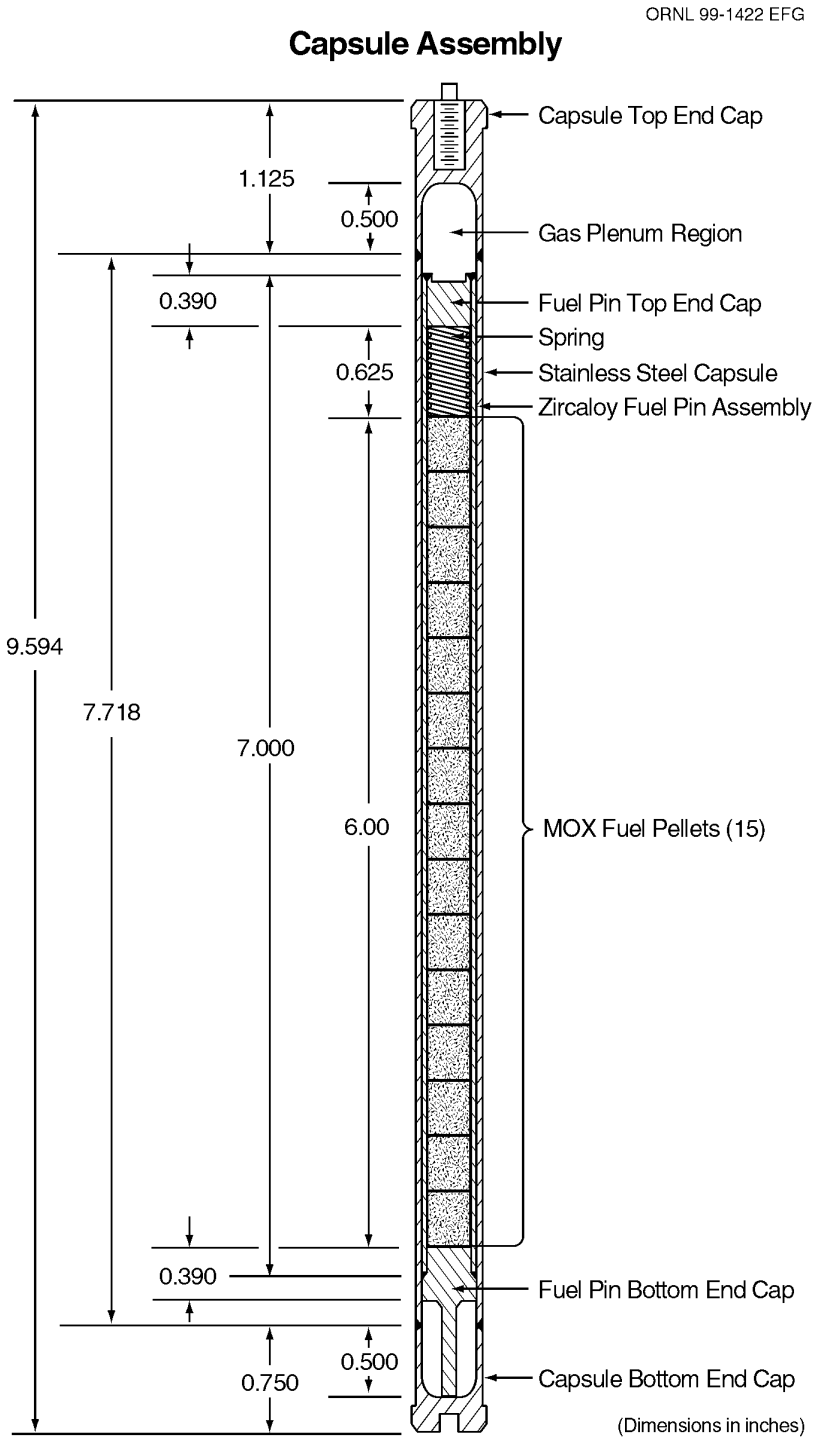

Figure 3 Capsule and fuel pin axial dimensions.

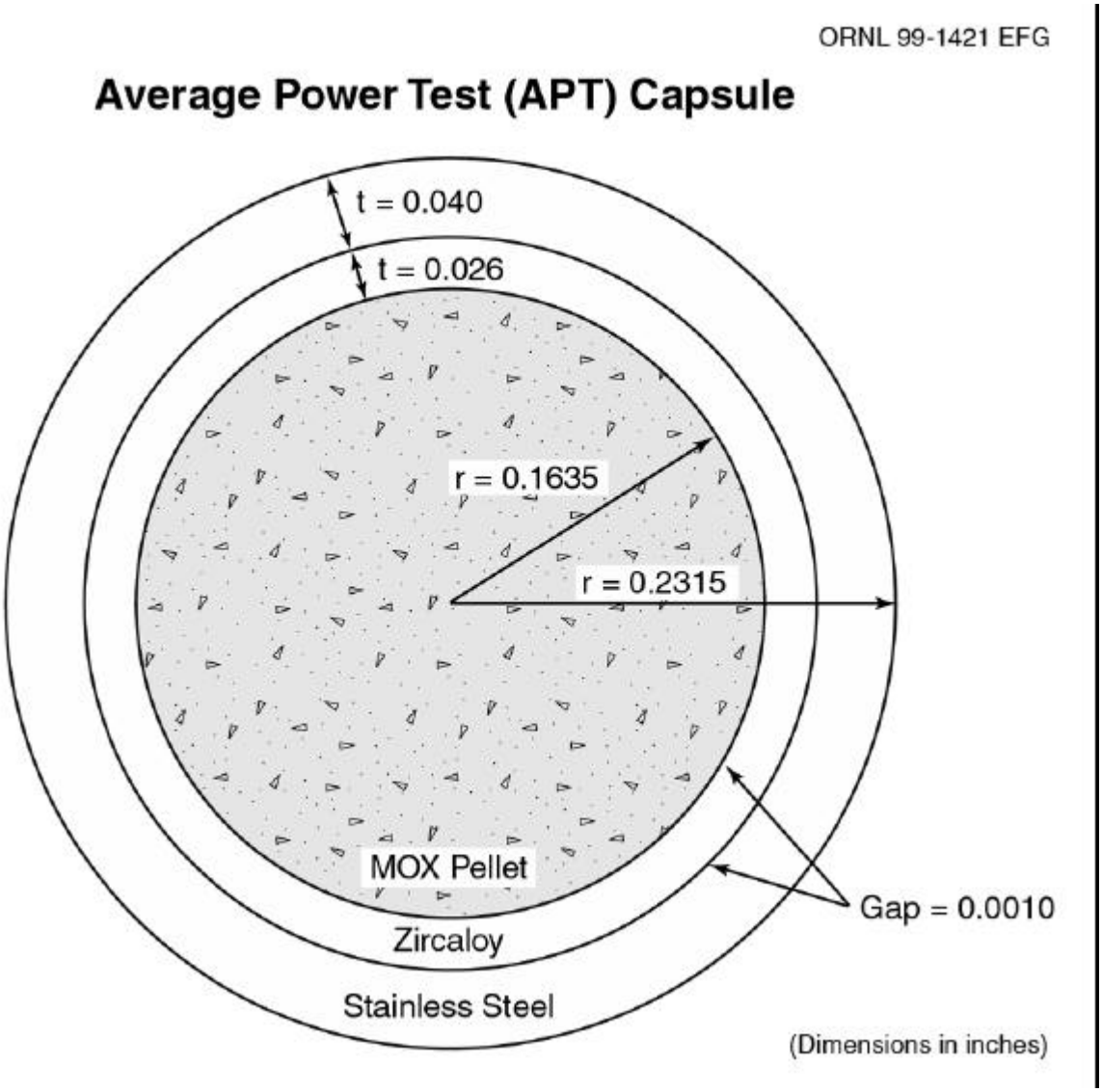

Figure 4 Pellet, fuel pin, and capsule radial dimensions.

TABLE 1 ATR-MOX Capsule Preirradiation Information							
Capsule Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Fuel Pin Number	2	5	6	7	8	9	10
Zr Tube Number	2	5	6	7	8	9	10
Zr Top Number	2	5	1	7	8	9	10
Zr Bottom Number	2	5	6	7	8	9	10
Zr Tube OD (inches)[1]	0.3806 0.3808	0.3806 0.3808	0.3805 0.3808	0.3805 0.3807	0.3806 0.3808	0.3805 0.3809	0.3806 0.3808
Zr Tube ID (inches)[1]	0.3290 0.3292	0.3290 0.3292	0.3290 0.3293	0.3291 0.3294	0.3290 0.3294	0.3290 0.3292	0.3290 0.3294
SS Tube OD (inches)[1]	0.4643 0.4649	0.4643 0.4649	0.4643 0.4649	0.4643 0.4649	0.4643 0.4649	0.4643 0.4649	0.4643 0.4649
SS Tube ID (inches)[1]	0.3830 0.3835	0.3830 0.3835	0.3830 0.3835	0.3830 0.3835	0.3830 0.3835	0.3830 0.3835	0.3830 0.3835
SS Top Number	1	2	3	4	5	6	7
Fuel Stack Height (inches)	5.821	5.833	5.859	5.816	5.816	5.829	5.823
Fuel Mass (grams)	81.41	81.63	80.51	81.40	81.31	81.66	81.47
Pellet Batch[2]	A	A	A	A	A	A	A
Burnup (GWd/MT)	8.6	21	30	40 (Planned)	50 (Planned)	50 (Planned)	None (Archive)

TABLE 1 (Cont.) ATR-MOX Capsule Preirradiation Information						
Capsule Number	**8**	**9**	**10**	**11**	**12**	**13**
Fuel Pin Number	11	12	13	14	15	16
Zr Tube Number	11	12	13	14	15	16
Zr Top Number	11	12	13	14	15	16
Zr Bottom Number	11	12	13	14	15	16
Zr Tube OD (inches)[1]	0.3806 0.3808	0.3806 0.3808	0.3805 0.3808	0.3805 0.3807	0.3805 0.3807	0.3806 0.3808
Zr Tube ID (inches)[1]	0.3290 0.3293	0.3290 0.3294	0.3292 0.3293	0.3292 0.3294	0.3290 0.3293	0.3291 0.3294
SS Tube OD (inches)[1]	0.4643 0.4649	0.4643 0.4649	0.4643 0.4649	0.4643 0.4649	0.4643 0.4649	0.4643 0.4649
SS Tube ID (inches)[1]	0.3830 0.3835	0.3830 0.3835	0.3830 0.3835	0.3830 0.3835	0.3830 0.3835	0.3830 0.3835
SS Top Number	8	9	10	11	12	13
Fuel Stack Height (inches)	5.810	5.810	5.813	5.810	5.795	5.790
Fuel Mass (grams)	82.26	82.23	82.29	82.20	82.00	81.84
Pellet Batch[2]	B	B	B	B	B	B
Burnup (GWd/MT)	8.6	21	30	None (Archive)	50 (Planned)	40 (Planned)

[1] Numerator is the smallest measurement, denominator is the largest measurement.
[2] Pellet batch A was fabricated with PuO_2 that was not treated. Pellet batch B was fabricated with PuO_2 that was thermally treated ("TIGR") for Ga removal prior to pellet fabrication.

3. POST IRRADIATION EXAMINATION TASK

3.1 Capsule Visual and Dimensional Inspection

Once the selected capsules have been moved to the examination area, the ID number(s) (and any engraving on the capsule side) will be checked to ascertain that the correct capsules have been received. Figure 5 illustrates the ID numbering system.

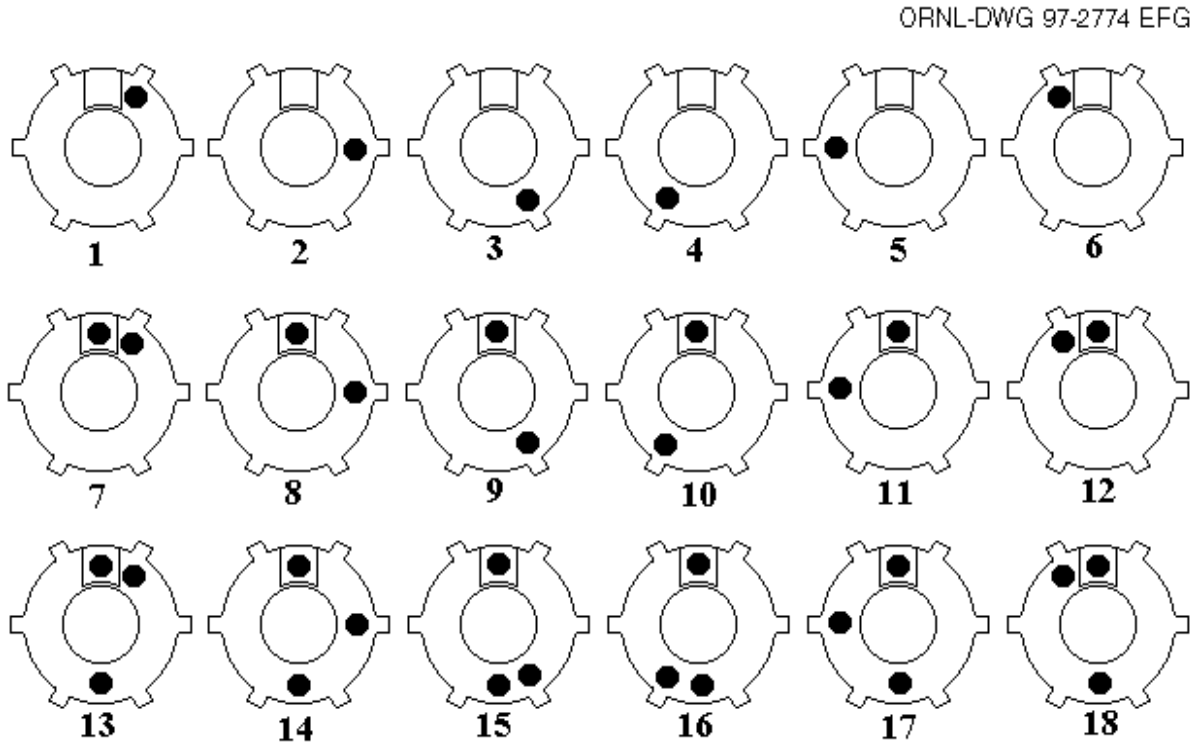

Figure 5 Capsule ID numbering code.

The PIE will begin by visually inspecting the capsule assemblies for physical abnormalities such as blisters, cracks, unusual or heavy oxide layers, weld failures, or distortions. Any abnormality and its location on the capsule assembly will be recorded by photographs and with logbook entries. Should any major problem be noted such as breeched containment, broken welds, or large physical distortions, the project manager will be consulted before proceeding with further PIE tasks. Each capsule assembly is to be weighed, and its mass recorded in the PIE logbook.

The capsule will be checked for bowing either by comparing with a straight edge, by an indicator and a Vee block, or by a three dimensional measurement. If bowing exists, the disassembly

method will be reviewed to determine if the distortion will cause handling and disassembly problems; if so, the project office will be consulted before proceeding.

The length of the capsule assembly from end to end will be measured with a tolerance not to exceed 0.010". The diameter of the capsule assembly will also be measured at a minimum of three longitudinal locations (near top weld, center of capsule, and near bottom weld) with a tolerance of not to exceed 0.0005". Each diameter measurement will consist of at least two measurements 90° apart so that an out of round condition may be detected.

All measurements will be recorded in the PIE logbook or on a special form; any physical problems, such as gross distortion, that may interfere with the removal of the fuel pin assembly from the stainless steel capsule will be reported to the project office immediately so that the situation may be evaluated and future PIE work modified as necessary.

3.2 Initial Gamma Scan

After the initial visual and dimensional inspections have been completed, the capsule assembly will be mounted on the in-cell gamma scanner and gamma scanned from one end of the fuel column to the other. [Note: the capsule may be gamma scanned prior to the dimensional inspection to save time if scheduling conflicts occur] The scanner will use the smallest collimator possible to reveal the greatest detail. The gamma scan will show the activity of the capsule and fuel pin which can then be used to infer the internal mechanical integrity and the length of the fuel stack. Since flexibility exists in the equipment and the exam is nondestructive, details concerning the gamma scanning, such as the best energy range to count, can be determined or modified during the performance of the task.

Once the scan is complete, an axial map of the relative activity of the fission products will be constructed. The gamma scan concept is shown schematically in Figure 6. A raster scan of the capsule can also be prepared by using a color plot map. This map may be used to determine the fuel stack length, provide an indication of fuel pellet gaps, estimate relative burnup, and determine if any gross migration of the fission products has occurred. If there are indications of a serious problem such as gaps in the fuel stack or massive fission product migration, the project manager will be consulted before proceeding. If there are signs that the fuel was damaged during irradiation, disassembly procedures will be reviewed to determine if they require revision.

3.3 Iodine Decay

Before the capsule boundary can be penetrated, hot cell limits require that the fuel pin ^{131}I inventory be 5 mCi or less. This entails an approximately 3 to 4 month waiting period (after the end of irradiation) before any destructive examination can begin.

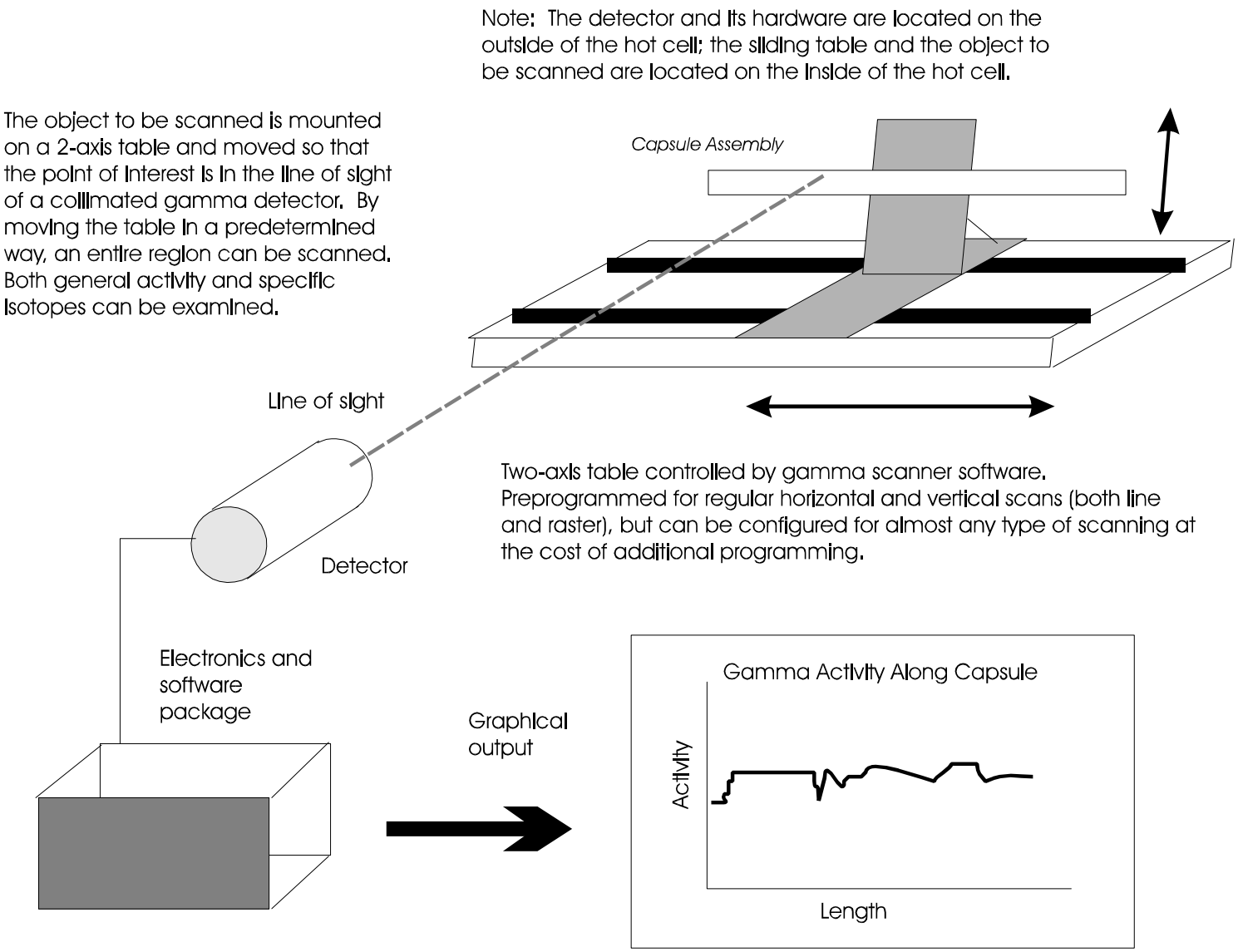

Figure 6 Illustration of the gamma scanning.

3.4 Capsule and Fuel Pin Pressure

The capsule pressure will be measured by drilling into the capsule through the top and capturing and measuring the pressure of the released gasses in a calibrated volume. The capsule pressure can then be determined by the known capsule volume and the ideal gas law. Any captured gasses will then be measured for their ^{85}Kr content. Together, the pressure and radioactive krypton (the only source is the fuel pin inventory) provide a sensitive measure of the fuel pin integrity.

Once the capsule measurement has been completed, drilling will continue into the fuel pin. These gasses will also expand into a calibrated volume and a measurement of the pressure taken. The actual pressure will again be determined by the fuel pin volume and the ideal gas law. The captured gasses will be measured for their ^{85}Kr content and the fuel release fraction determined by the ratio of the measured ^{85}Kr content to the fuel ^{85}Kr inventory (computed by INEEL).

The apparatus to be used and its calibration procedures are detailed in Reference 6. The capsule will be prepared for the apparatus by cutting off a portion of the upper endcap. Figure 7 illustrates the apparatus.

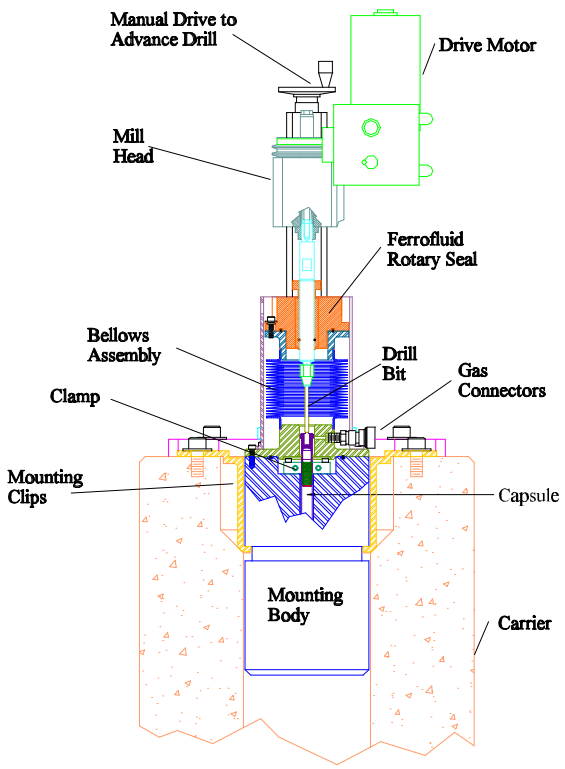

Figure 7 Illustration of the apparatus to measure the fission gas pressure. See reference for details.

This apparatus was successfully used in the intermediate capsule PIE where the capsule pressure was found to be subatmospheric (as expected) and the fuel pin pressure was found to be near the predicted value. Measurement of the ^{85}Kr confirmed no fuel pin leakage.

3.5 Fuel Pin Visual and Dimensional Inspection

After the results of the capsule inspections, gamma scanning, and fission gas measurements have been evaluated, the fuel pin will be removed from the capsule by cutting off the bottom and sliding the fuel pin out (Release of the relatively low fission gas pressures will not significantly alter the fuel pin diameter). Simple sliding of the fuel pin from its stainless steel containment will only prove successful if clearance remains between the fuel pin and the capsule (the expected case). If this is not the case, the fuel pin will have to be cut out of the capsule body.

To cut the fuel pin out, the capsule must be clamped in a fixture and a longitudinal cut made along the containment at two locations 180° apart. The fixture will be carefully set up and the cuts made in multiple passes to minimize any scoring of the Zircaloy clad. Once the cuts have been made, the capsule halves may be pried away from the fuel pin. The project office will be notified beforehand if the capsule must be cut apart to remove the fuel pin.

The fuel pin will be checked for bowing either by comparing with a straight edge, by an indicator and a Vee block, or by a three dimensional measurement of the fuel pin.

The length of the fuel pin from end to end will be measured with a tolerance not to exceed 0.010" [Note: during the removal process part of the fuel pin end pedestal may be removed; this should be taken into consideration during the length measurements; the removed pedestal segment may need to be measured for consistency] .

The diameter of the fuel pin will be measured at a minimum of 150 longitudinal locations (distance between measurements of no more than 0.040") in the fueled region to a tolerance not to exceed 0.0003" so that any bambooing will be noted. Each diameter measurement will consist of at least four measurements 90° apart so that an out of round condition may be detected. The pin’s weight and any unusual characteristics will be recorded.

All measurements will be recorded in the PIE logbook, on a special form, or with electronic media.

3.6 Quick Look Report

At the completion of the items in Sections 3.1 through 3.5, a Quick Look report will be issued detailing the results and describing any abnormalities. Any significant discrepancies between the measurements and the predicted results will be noted and evaluated.

3.7 Fuel Pin Segmenting and Analysis

One option before segmenting the fuel pin is to gamma scan it. This was not found necessary for the intermediate withdrawal capsules, but it may be useful if abnormalities are found as the withdrawal from the capsule may allow an opportunity to examine the fuel pin without the interference of isotopes from the stainless steel containment.

Irradiation-induced swelling of the fuel may cause the pellets to be locked in the clad, especially for the PIE to be performed at 50 GWd/MT burnup. If this occurs, segmenting the fuel is probably the only option for fuel examination. Before cutting the fuel pin, a cutting and specimen plan will be formulated and agreed upon by the program office so that items of current interest may be included in the examination. Prior to cutting the fuel pin into segments, it is intended that the end containing the spring be cut off first to minimize the risk of losing components.

The major difficulty to be encountered in the sectioning will be integrity of the fuel. If it is very friable, sectioning will be difficult. Epoxy potting will be used to stabilize samples that are not to be subjected to radiochemical analysis. No foreign materials will be introduced into radiochemical samples.

At the present time, three types of specimens are of interest for the program: metallographic mounts, radiochemical specimens (pellet and clad), and ductility specimens. All can be prepared by cross cutting of the fuel pin. Additionally, an SEM mount may be prepared to examine the fuel in greater detail.

The metallographic mounts will be prepared by potting the cut off segments in epoxy and polishing. The radiochemical specimens will be prepared by removing the fuel from segments by use of a jig and punch. Each segment will then yield two specimens, one clad and one (crushed) fuel. The ductility specimen (clad only) will be prepared in a similar manner as the radiochemical specimen, but may also be cleaned in an acid solution to remove any fuel residue.

Radiochemical analysis will focus on gallium content and burnup analysis. A scanning electron microscope (SEM) specimen may also be prepared in a manner similar to that of a metallographic mount and analyzed for selected elements. Burnup mapping is the major interest along with an examination of the MOX agglomerates and their relative burnup. A gross burnup map may also be prepared by gamma scanning a metallographic mount.

To the extent possible, the metallographic and SEM mounts will be used to estimate the pellet-clad gap and pellet swelling as well as to assist in the examination of any possible fuel clad interactions.

3.8 Ductility Testing

The ductility specimens will be prepared in the manner as detailed in Section 3.7 with the specific dimensions to be determined at the time of preparation (current approved cutting and

specimen plan). Once prepared and cleaned, the specimens will be placed in archival storage if not immediately transferred to the location of the testing apparatus. Since this apparatus has not been installed at this writing, the details of the testing will be defined at a future date.

4. STORAGE OF CAPSULE CONTENTS

All of the fuel pellets, cladding, and specified pieces of the fuel pins will be stored in suitably numbered hot cell containers unless the project requests that they be discarded during the PIE task. A list of the PIE objects, their locations, and disposition, will be kept. The identification and contents of each container will be recorded in a hot cell logbook and in the test engineer's laboratory notebooks. The facility manager will be kept aware of the containers and their contents, especially the fissile material.

5. DOCUMENTATION

Observations, photographs, videotapes, digital files, and other data will be recorded on the appropriate medium and documented in ORNL laboratory notebooks as the examination proceeds. Progress of the PIE effort will be described in the project monthly reports. The final results of this PIE examination will be documented in an ORNL topical report.

6. COSTS AND SCHEDULES

The cost and schedule for the PIE is specified in Reference 1 and is shown in Tables 2 and 3 for convenience. A Quick Look report will be delivered approximately 6 months after receiving the Test Capsule set at the hot cell. A Final PIE report will be delivered approximately 12 months after the receipt of the Test Capsule set.

TABLE 2
Estimated PIE costs (K)

FY Year	PIE Cost	Comments
2001	$1,100	30 GWd/MT PIE
2002	$1,200	40 GWd/MT PIE
2003	$1,300	50 GWd/MT PIE
2004	$1,300	50 GWd/MT PIE
2005	$800	Conclusion of ATR MOX Test PIE

TABLE 3
Schedule

Activity	Start Date	Completion Date
Fuel removal at 30 GWd/MT	Jul. 2000	Jul. 2000
Quick Look report (30 GWd/MT)	Nov. 2000	Feb. 2001
PIE report on 30 GWd/MT withdrawals	Feb. 2001	Sep. 2001
Fuel removal at 40 GWd/MT	Apr. 2002	Apr. 2002
Quick Look report (40 GWd/MT)	Aug. 2002	Nov. 2002
PIE report on 40 GWd/MT withdrawals	Nov. 2002	Jun. 2003
Achieve burnup of 45 GWd/MT	Mar. 2003	Mar. 2003
Final fuel removal at 50 GWd/MT	Nov. 2003	Nov. 2003
Quick Look report (50 GWd/MT)	Mar. 2004	Jun. 2004
PIE report on 50 GWd/MT withdrawals	Jun. 2004	Jan. 2005
Prepare final test summary report	Jun. 2004	Apr. 2005

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