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MCC

Materials Characterization Center

**Design and Operation of Gamma
Scan and Fission Gas Sampling
Systems for Characterization of
Irradiated Commercial Nuclear Fuel**

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September 1989

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DESIGN AND OPERATION OF GAMMA SCAN
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FOR CHARACTERIZATION OF IRRADIATED
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SUMMARY

One of the primary objectives of the Materials Characterization Center (MCC) is to acquire and characterize spent fuels used in waste form testing related to nuclear waste disposal. The initial steps in the characterization of a fuel rod consist of gamma scanning the rod and sampling the gas contained in the fuel rod (referred to as fission gas sampling). The gamma scan and fission gas sampling systems used by the MCC are adaptable to a wide range of fuel types and have been successfully used to characterize both boiling water reactor (BWR) and pressurized water reactor (PWR) fuel rods. This report describes the design and operation of systems used to gamma scan and fission gas sample full-length PWR and BWR fuel rods.

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J. O. Barner - Developed many of the design criteria for the systems and provided technical supervision during the design and fabrication of the equipment.

D. N. Berger - Developed the detailed design of most of the hardware.

R. W. Goles - Provided technical guidance for the equipment specification, process design, and procedure development for the gamma scanning system.

M. L. Elliott - Executed the troubleshooting and startup of the gamma scan system.

R. S. Holeman and L. J. Dunn - Installed and operate these systems.

D. A. King and R. W. Truitt (Westinghouse Hanford) and **J. W. McNeese** (PNL) - Developed the computer program which controls the gamma scan process.

D. A. Nelson - Provided technical guidance and operator training on the alignment and use of the fission gas system laser.

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INTRODUCTION

The Materials Characterization Center (MCC) has the responsibility to provide well-characterized testing materials for use as test specimens in nuclear waste disposal-related testing. These materials are designated as approved testing materials (ATMs); the test data generated through the use of these materials will be used in the license application for a geologic repository. Increased emphasis on testing of spent fuel as a waste form brought out the need to acquire multiple spent fuel ATMs that exhibit the variety of spent fuel characteristics that are expected to be encountered in the emplacement inventory. These materials would be used to develop a quality data base of spent fuel test performance that encompasses the range of behavior of commercial spent nuclear fuel that could be disposed of in a repository.

To efficiently characterize multiple spent fuel ATMs, a capability was needed to receive assemblies and/or full-length fuel rods, gamma scan and fission gas sample the rods and then complete detailed chemical and metallurgical characterizations. The requirements for gamma scanning, fission gas sampling, and detailed characterizations were documented in a characterization plan for spent fuel ATMs that was prepared by the MCC and concurred with by the repository projects in 1986. Equipment required for gamma scanning and fission gas sampling full-length PWR and BWR fuel rods was designed and fabricated. The arrangement of the gamma scan and fission gas sampling systems is illustrated in Figure 1.

At this time, several rods from four different types of fuel have been gamma scanned and fission gas sampled. At least one rod of each type has undergone additional detailed characterization. The results of this work are periodically published according to type of fuel or specific ATM (Guenther 1988).

FIGURE 1. Fission Gas Sampling and Gamma Scan Systems Arrangement

GAMMA SCAN SYSTEM

Each ATM fuel rod is gamma scanned axially to determine whether regions of unusual activity are present that may be due to radial transport of fission products or axial fission product migration. The gamma scanning results are also used to provide a basis for determining the radionuclide inventory of a fuel rod at any point along its length.

The objective of the gamma scanning operation is to determine the axial distribution of gamma emitting radioisotopes (primarily ^{134}Cs and ^{137}Cs) in a spent fuel rod. The gamma scanning system is designed to measure gamma activity relative to an arbitrarily selected reference rod of each particular ATM, rather than to acquire absolute values of gamma activity. Thus, for each ATM, one rod is selected as the gamma scanning reference rod. A 5-cm section near the mid-plane of the fuel region of this rod is scanned before and after a full-rod scan of each rod of the same ATM. A difference of less than 5% in measured ^{134}Cs or ^{137}Cs gamma activity for these 5-cm scans was deemed adequate for an acceptable full-rod scan. However, the absolute values of these 5-cm scans may vary considerably over time due to a number of factors (e.g., decay of Cs activity, replacement of system components, minor differences in configuration geometry, etc.). This variation in absolute gamma activity (corrected for decay) is used to bias correct the gamma scanning results obtained for each non-reference rod of that ATM type.

The criteria upon which the design of the system is based are discussed below as are the design, qualification, and operation of the system.

DESIGN CRITERIA

A system was needed that would allow axial gamma scanning of full-length BWR and PWR fuel rods using a commercially available gamma detector and multi-channel analyzer (MCA). Gamma scans were to be performed in small increments or steps along the entire length of a fuel rod. Thus, hardware had to be designed and built that would move a fuel rod in discrete steps past a collimated gamma ray detector assembly. This hardware is shown in Figure 1. The gamma ray detector would, of course, need to be located

outside the hot cell. Software had to be developed to provide communication between the MCA and in-cell hardware to control fuel rod positioning, as well as to provide data storage and retrieval capabilities. Because of facility dimensional constraints, it was necessary to design a system that would scan half of a rod at a time. The rod could then be pivoted 180° to scan the second half.

Specifically, the design criteria require the gamma scanning system to provide the capability to:

- scan full-length fuel rods of various lengths up to 4163 mm (164.0 in.) long (length of commercial BWR fuel rods).
- scan commercial fuel rods of various diameters in the range 9.5 to 14.5 mm (~0.40 to 0.60 in.).
- pause at each step for a specified counting time, which could be varied depending on the gamma activity levels in the fuel rod.
- axially gamma scan all rods in 2.5-mm (0.10-in.) steps using a 2.5-mm (0.10-in.) slit width or in 0.25-mm (0.010-in.) steps using an 0.25-mm (0.010-in.) slit width. Note: 2.5 mm (0.10 in.) was selected as the nominal operating value because the individual fuel pellets are approximately 12 mm (0.5 in.) long. This step size permits the activity to be counted in approximately five locations in each pellet, which permits gross detection of pellet-pellet interfaces (the activity changes at the interface). Finer analysis is possible with the smaller slit width.
- enable the operator to physically position the fuel rod vertically and horizontally relative to the detector. The vertical and horizontal positioning should be accurate to ± 2.5 mm (0.10 in.).
- permit the operator to position the fuel rod axially relative to the detector with sufficient accuracy (± 13 mm or 0.5 in.) so that two half-rod scans could be combined to yield a single, continuous scan.
- identify and quantify gamma-emitting radionuclides of interest in spent fuel rods using a high-resolution germanium detector and associated pulse height analysis electronics with

- a useful energy range between 0.06 MeV and >2 MeV
  - an energy resolution $\leq 3\text{keV}$ full width, half maximum (FWHM) (^{137}Cs) at all allowable ($\leq 35\%$) system dead times
  - automatic compensation for electronic dead time, pulse pileup conditions
  - variable counting times to maintain fixed statistical significance (maintain $\leq 1\%$ statistical uncertainty for the selected isotopes)
  - an efficiency calibration source.
- minimize operator interaction during the scanning process.

SYSTEM DESIGN

The gamma scan system consists of four major components: 1) the data acquisition and analysis (DA&A) system, 2) a computer that supervises and controls the gamma scan process and logs all pertinent data, 3) the wall plug penetration assembly, and 4) the in-cell hardware.

A detailed description of each of these components is found in the following sections. Appendix A contains a list of applicable design drawings.

Data Acquisition and Analysis System

The DA&A system is used to identify specific gamma-emitting radionuclides and determine their relative concentrations in spent fuel rods. The system is composed of a high-resolution germanium detector and a programmable multi-channel pulse height analyzer (with live time correction/pulse pileup rejection circuitry). Radionuclide identification is established by the relative position(s) of gamma-ray peak(s) in the gamma energy spectrum. Counting data are directly related to net peak area and inversely proportional to live time under fixed scan conditions. A fixed ^{60}Co gamma-ray source is used as an internal intensity standard in all collected spectra. This system has a useful energy range of 0.06 MeV to >2.0 MeV with energy resolution $\leq 3.0\text{ keV}$ FWHM (^{137}Cs) at all allowable ($\leq 35\%$) system dead times.

The system is programmed to vary counting times to maintain $<1\%$ statistical uncertainty for the selected isotopes until counting times become excessive. At that point the counting time becomes fixed at 5 minutes. The

use of the <1% uncertainty criterion is a conservative approach to minimize the effect of data scatter on the final reported values. It has also been used as a criterion for selecting which isotopes to monitor. Within the current suite of MCC spent fuel ATMs, the only radionuclides that can be counted with <1% uncertainty are ^{134}Cs and ^{137}Cs . Thus, these are the radionuclides of primary interest during gamma scanning of currently available fuels. However, if fresh fuels are acquired as ATMs, it should be possible to obtain gamma scan data for additional radionuclides with shorter half-lives.

The multi-channel analyzer (MCA), which is fully programmed and controlled by computer, records the fuel rod gamma spectra, strips the pulse counts for the gamma energies characteristic of pertinent isotopes, and transmits the data to the computer. The detector and the MCA were procured from commercial vendors. The detector is an EG&G Ortec coaxial lithium-drifted germanium detector. The MCA is a Nuclear Data Model ND65B, which is a microcomputer-based system with a BASIC language interpreter.

IBM Computer

The computer is an IBM PC-XT computer with a 20 MB hard disk and 360 KB floppy disk drive, two internal indexer cards, and a color monitor. The computer has been programmed to provide the operator with step-by-step instructions for scanning fuel rods; control the draw table and gaging table stepping motors through the indexer cards; control the MCA and records the scan data measured by the MCA; store data on hard disk for later use; and monitor solenoid and limit switch activation. The computer controls the functions of the MCA. Initialization parameters are sent to the MCA and all of the gamma scan data are received from the MCA. During a scan, the computer screen displays the starting and ending scan locations, along with the progress of the scan. The computer stores the fuel rod parameters, MCA parameters, gamma spectrum, and locations of regions to be scanned. Data printing and storing are completed automatically during a gamma scan.

The program written for the gamma scan system is a user-interactive program that prompts the user for input, displays step-by-step instructions,

and asks if a step has been completed before proceeding. The operator interacts with the computer by inputting data, supplying a yes or no answer, or by pressing a function key to control program operation. The computer will also prompt the user to perform certain tasks at the appropriate time, such as opening and closing the chuck or moving the chuck onto the fuel rod. These tasks can then be done using the keyboard, switches, or the remote manipulators.

Wall Plug Penetration Assembly

Three connections are needed between the operating gallery and the hot cell to conduct gamma scanning and fission gas sampling:

- one to provide a path between the fuel rod and the gamma detector for conducting gamma scans
- one to permit the firing of a laser beam onto the fuel rod to breach the cladding for fission gas sampling
- one to permit the flow of fission gas from the fuel rod into sample bottles located in the operating gallery.

A shielded wall plug was designed and fabricated to provide all three of these connections. The wall plug is illustrated in Figure 2. It is constructed from stainless steel and is filled with lead to reduce the radiation field from the hot cell to acceptable levels for operations personnel in the cell gallery. The top penetration in the wall plug provides the interface between the fuel rod in the hot cell and the fission gas sampling hardware in the gallery (this portion of the wall plug is further described in the section of this report that deals with fission gas sampling); the bottom wall plug penetration contains a collimator for the gamma scan system. This portion of the wall plug is illustrated in Figure 3.

The function of the collimator is to adjust the line of sight of the gamma detector so that it selectively "views" only the desired object (i.e., the fuel rod) and screens out other gamma sources in the hot cell. Two collimators were fabricated to provide optional slit widths of either 2.5 mm (0.10 in.) or 0.25 mm (0.010 in.). The 2.5-mm (0.10-in.) slit width is used for routine axial gamma scanning; the 0.25-mm (0.010-in.) slit width is available for special applications, such as identifying any redistribution of

FIGURE 2. Wall Plug Assembly

FIGURE 3. Gamma Scan System Collimator Portion of Wall Plug Assembly

fission products to pellet-pellet interfaces. The height of the slit in each collimator is 12.7 mm (0.50 in.), which is slightly larger than the fuel pellet diameter in any fuel rod anticipated to be characterized. Lead shielding is located behind the spent fuel rod to minimize detection of extraneous gamma rays. A tube attached to each collimator is used to position the collimator at the end of the wall plug and to retrieve it for collimator exchange.

The fuel rod is located approximately 6.4 cm (2.5 in.) from the end of the collimator. This results in an effective slit width (i.e., width of fuel rod actually being measured) of 3.1 mm (0.12 in.) rather than 2.5 mm (0.10 in.). This additional slit width, however, has no effect on the utility of the data because this system is used to obtain data that is relative to a "reference" rod rather than absolute gamma scan data.

In-Cell Hardware

The in-cell hardware consists of two major components: the draw table and the gaging table. All components of the hardware are modular in design. An operator can remotely replace any item (i.e., motor, chuck, or limit switch) easily and quickly. This reduces system down time for maintenance and repair.

The draw table, which is illustrated in Figure 4, physically holds the fuel rod, positions the rod axially prior to a scan, and moves (or draws) the rod past the detector in discrete steps. The primary components of the draw table are the carriage assembly with the fuel rod chuck, the ball screw, and the stepping motor with encoder.

The air-activated chuck, which is mounted on the carriage assembly, physically engages fuel rods with the specified range of diameters (9.5 to 14.5 mm). The control computer automatically controls the draw table motor to move the draw table carriage assembly to each scan position. The gamma scan step size, which is inputted to the computer, is translated by the encoder and stepping motor to a controlled rotation of the ball screw. The rotation of the ball screw moves the carriage assembly up or down the length of the draw table. This movement of the carriage is the mechanism for positioning the fuel rod and for moving it in discrete steps.

FIGURE 4. Draw Table

Limit switches are located at both ends of the draw table (Figure 5). When the chuck reaches a limit switch, the switch is activated, thus stopping the stepping motor and halting further movement of the carriage assembly. This is a safety feature to prevent damage to fuel rods or to the equipment in the event of a system malfunction.

The design criteria require that it be possible to move the fuel rod axially in increments as small as 0.25 mm (0.010 in.). A stepping motor can be controlled to a single "step". There are approximately 10,000 steps per revolution of the ball screw. Each revolution of the ball screw translates to 5.1 mm (0.20 in.) of axial movement. Thus, each stepping motor "step" is equivalent to $0.00051 \mu\text{m}$ (0.000020 in.), providing precision in the control of linear distance that is a factor of 500 greater than required.

The gaging table depicted schematically in Figure 6 centers the fuel rod vertically with respect to the collimator and guides the rod as it is moved by the carriage assembly and stepping motor. The gaging table guide wheels center and guide the fuel rod during a scan. While a scan is being performed, the collimator focuses the detector on the center point between the four guide wheels. The back side of the gaging table is surrounded by lead sheet to minimize the detection of extraneous gamma rays and to minimize radiation damage to the stepping motors. The vertical motion stepping motor with encoder is connected to a ball screw that moves a gage wheel mount up and down to center the fuel rod in the slit window of the collimator. Through the gaging table indexer, the computer controls the gaging table motor to raise and lower the gage wheel mount. An optical encoder linked to the motor shaft provides precise gaging table positioning. The DA&A system is used to measure the activity at each location as the fuel rod is moved vertically. The position with the greatest activity is assumed to be the position with the full diameter of the fuel rod within the collimator window, and is thus the position used for the gamma scanning operation.

The fuel rod's length must be known to correctly position the fuel rod relative to the gamma detector. The fuel rod length is measured using the stepping motor system and the fuel rod limit switch mounted on the carriage

FIGURE 5. Draw Table Limit Switch

FIGURE 6. Gaging Table

assembly. First, a "dummy" rod of known length is placed on the gaging table in the V-trough and is butted against a mechanical stop at the end of the V-trough opposite the fuel rod positioner. The carriage assembly is then moved toward the opposite end of the dummy rod until the fuel rod limit switch indicates that the carriage assembly has contacted the rod. The position at which this occurred is determined based on information supplied by the stepping motor/ optical encoder. This procedure is then repeated using the fuel rod whose length is to be measured. The position at which the carriage assembly contacts the fuel rod is compared with the position at which the carriage assembly contacted the dummy rod to determine the difference in length between the dummy rod and spent fuel rod. Using the known length of the dummy rod, the computer calculates the fuel rod length and the location of the axial center of the fuel rod. These data are used to position the fuel rod for gamma scanning.

SYSTEM QUALIFICATION

Before installation in the hot cell, the gamma scan system was set up in a testing laboratory. At that time the function and fit of each of the components was tested, the operating procedure was qualified, and the operators received preliminary training. The software routine was repetitively tested using known lengths of zircaloy tubing and two specially fabricated "calibration" rods to simulate fuel rods and verify that the proximity sensor, limit switches, and stepping motors functioned correctly. The function of the DA&A system could not be fully evaluated in this facility although ^{60}Co sources were used to check the operability of the detector and MCA.

Functional Fit

The testing laboratory was a 1:1 mockup of the hot-cell where the equipment was to be installed. When the gamma scan equipment was set up, it was obvious that the draw table extended past the "wall" of the hot cell and thus was too long. This was the result of using inaccurate historical records on the facility dimensions. Unfortunately, the loss of this additional length did not leave sufficient space to scan one-half the length of BWR fuel rods. The decision was made to modify the equipment to fit in the facility and

develop a separate procedure for scanning small pieces of fuel rods. Thus, the bottom foot of a BWR fuel rod can only be scanned after the rod is sectioned.

Rod Location and Movement Operations

Two "calibration" rods of known length were fabricated for use in qualification of the fuel rod positioning and stepping operations. One rod had a ^{60}Co source installed in the center of the rod, and the other rod had two ^{60}Co sources installed at known distances from the center of the rod. The widths of these sources were less than the collimator slit width. Three tests were completed to verify the correct operation of the fuel rod positioning and measuring operations:

1. The system was operated to measure the length of one of the calibration rods. The measured length was compared with the known length to verify proper operation of the system (to ± 6.3 mm or ± 0.25 in.).
2. The system was operated to align the center of the calibration rod containing the single ^{60}Co source with the collimator. By using the MCA it was demonstrated that the ^{60}Co source was within the slit window. This test demonstrated that the center of a rod could be found with an accuracy equal to the effective width of the slit window (3.1 mm or 0.12 in.). Actual operations require an accuracy of ± 13 mm (0.5 in.).
3. The system was then operated with the other calibration rod to input a specified length of rod to be scanned (equal to the known distance between the two ^{60}Co sources). The MCA was used to verify ^{60}Co sources were within the slit window at the start and end of "scan" operations. This test verified that axial movement of the rod was accurate to within two slit window widths (6.1 mm or 0.24 in.). Actual operations require an accuracy of ± 13 mm (0.5 in.).

Fuel Rod Scans

Subsequent to these tests, the system was installed in the hot cell, and final testing was completed using a full-length PWR fuel rod. A full-length axial gamma scan was completed. During initial radioactive testing of the collimator and wall plug assembly, it was determined that background radiation was "leaking" to the detector. This was due to insufficient collimator length. The portion of the collimator that resides in the wall plug was not

long enough to provide the shielding necessary to attenuate the background gamma rays entering the wall plug at low angles from near the in-cell end of the collimator. A shield sleeve, extending from the wall plug cold face to the back end of the collimator, was fabricated and inserted into the collimator tube to eliminate this problem (see Figure 3).

OPERATIONS

Before initiating the gamma scanning of an ATM, the proper operation of the gamma detection system is verified by calibrating the electronics system using ^{241}Am and ^{60}Co sources. The energies of these sources (0.60 and 1.33 MeV, respectively) represent the upper and lower bounds of the range of gamma energies of primary interest in spent fuel rod gamma scanning, which includes ^{134}Cs (0.6 and 0.8 MeV) and ^{137}Cs (0.67 MeV). The reference rod for the ATM type is then scanned. A scan of the center 5-cm portion of this rod is made using the same procedures utilized for a full rod scan.

Rod identity information (e.g., ATM type, average burnup, rod identification number, etc.) is then inputted to a data file. The ATM rod to be scanned is placed on the gaging table/draw table. The length of the ATM rod is determined by comparing its length to that of a "dummy" rod of known length (as described in a previous section of this report, In-Cell Hardware). The gaging table fuel rod positioner is then used to center the ATM in the collimator slit window. Information regarding the portions of the rod to be scanned is inputted into the computer and the scan is initiated. When the scan has been completed, the process can be terminated or the rod rotated and scanning performed on the remaining half of the rod. Once the entire scan has been completed, a second 2-in. scan of the reference rod is performed. If the two reference rod scans agree within $\pm 5\%$, then the ATM data are accepted.

long enough to provide the shield necessary to attenuate the background gamma rays entering the well from the top of the well and at the collimator. A shield sleeve, extending from the well into the collimator, was fabricated and inserted into the collimator tube to eliminate this problem (see Figure 3).

OPERATIONS

Before testing the gamma scanning of an AIM, the proper operation of the gamma detection system is verified by calibrating the electronic system using ^{60}Co and ^{137}Cs sources. The energies of these sources (0.51 and 1.33 MeV, respectively) represent the upper and lower bounds of the range of gamma energies of primary interest in spent fuel rod gamma scanning, which includes ^{235}U (0.6 and 0.8 MeV) and ^{239}Pu (0.57 MeV). The reference rod for the AIM type is then scanned. A scan of the central 5 cm portion of this rod is made using the same procedures utilized for a full rod scan.

For gamma information (e.g., AIM type, average burnup, rod identification number, etc.) is then required to a data file. The AIM rod to be scanned is placed on the scanning table (see Figure 1). The length of the AIM rod is determined by comparing its length to that of a "dummy" rod of known length (as described in a previous section of this report, in Cell Reference). The scanning table and collimator are then used to register the AIM in the collimator slit window. Information regarding the position of the rod to be scanned is inputted into the computer and the scan is initiated. When the scan has been completed, the process can be terminated or the rod rotated and scanning performed on the remaining half of the rod. Once the entire scan has been completed, a second 5 cm scan of the reference rod is performed. If the two reference rod scans agree within 5%, then the AIM data are accepted.

FISSION GAS SAMPLING SYSTEM

The fraction of fission gas released from the fuel matrix to the void space in the interior of a fuel rod indicates the degree to which a number of thermally induced changes have occurred in that fuel during its operational life. These changes include redistribution of certain volatile fission products (e.g., migration to the fuel-pellet gap and to grain boundaries within the fuel) and microstructural changes such as grain growth within the UO_2 fuel. Because these changes may affect the disposal-related behavior of a spent fuel, it is important that the effects be understood. Thus, fission gas release was adopted as one of the criteria by which spent fuels would be selected for characterization and testing. The results of fission gas sampling are used to help confirm, prior to initiating detailed characterization of a fuel rod, that this characteristic of the rod is consistent with what was expected when the rod was selected for characterization (i.e., low, moderate, or high fission gas release). The results from fission gas sampling also provide data regarding the types and quantities of gaseous radionuclides present in the fuel rod plenum gas.

After an ATM fuel rod is gamma scanned, it is punctured and the internal gas present in the rod is removed and analyzed for fission gas content. The fuel rod void volume is measured and the rod is either sectioned to provide characterization and testing specimens or it is back-filled with argon to a pressure of approximately 20 psi and sealed for storage.

The objectives of fission gas sampling operations are to estimate the quantity of gas present in a fuel rod and to collect a sample of that gas for analysis. When the cladding is breached, the gas flows into a closed, evacuated system of known volume (V_S). The pressure (P_S) and temperature (T_S) in this closed system are measured. The gas is then evacuated into sample bottles that are removed and transferred to a laboratory for analysis. Argon gas is used to measure the fuel rod void volume (V_P), which is very small compared to V_S . The total volume ($V_t = V_S + V_P$) of the system plus the fuel rod is known. The quantity of fission gas can then be calculated from the Ideal Gas Law:

$$n = \frac{(P_s)(V_t)}{(R)(T_s)}.$$

The criteria for the design of the system are discussed below, as is the design and operation.

DESIGN CRITERIA

A system was needed to collect the internal gas from fuel rods for analysis without contaminating the sample (e.g., with air) and to determine the quantity of gas present in the fuel rod. When the system was designed, calculation of rod void volume was not a primary objective as rod void volume can vary by $\pm 100\%$ and still have no significant effect on the calculation of the fission gas quantity. (This is because the rod void volume is very small compared with the system volume-- $\sim 50 \text{ cm}^3$ versus ~ 3000 to $\sim 13,000 \text{ cm}^3$). Subsequent to the installation of the system, however, the need for an estimate of initial fuel rod gas pressure was identified. To calculate this pressure, both the quantity of gas and the rod void volume must be known. Rod void volume measurements are, therefore, made as part of the fission gas sampling process. To accomplish the objectives of the fission gas sampling operations, the system must provide the capability to

- sample commercial fuel rods of different diameters in the range 9.5 to 14.5 mm (~ 0.40 to 0.60 in.).
- sample fuel rods with internal pressures from atmospheric to 700 psi.
- provide a leak-tight connection between the plenum region of the fuel rod and the sample bottles (less than 0.01 mm Hg change in pressure sensor reading over three minutes).
- obtain a sample of the fuel rod interior gas which contains less than $0.5 \text{ mol\%}$ contaminants.
- breach the cladding of a fuel rod to release the gas contained in the fuel rod.

- measure the quantity of internal gas in the fuel rod with an accuracy of ± 0.001 moles.
- reseal the fission gas sampling hole in the fuel rod cladding to a leak tightness of less than 0.01 mm Hg change in pressure sensor reading in three minutes.

SYSTEM DESIGN

The fission gas sampling system consists of three major components: 1) a sampling head and wall plug assembly that provides a leak-tight connection between the fuel rod and the remainder of the fission gas measurement/collection system, 2) a laser that is used to breach the fuel rod as well as to re-seal the rod after fission gas sampling and back-filling with argon has been completed, and 3) a sampling cart that incorporates a leak-tight system of piping, valves, and sample bottles, a vacuum pump, and the means to measure the pressure and temperature of the gas contained by the system.

A detailed description of each of these components is found in the following sections. Appendix A contains a list of applicable design drawings.

Fission Gas Sampling Head and Wall Plug

The fission gas sampling head is shown in Figure 7. The fuel rod is inserted into this fixture, which is clamped to the hot cell side of the wall plug to form a leak-tight connection (as shown in Figure 8). Two sampling heads are currently used -- one for PWR fuel rods [nominal diameter of 10.7 mm (0.4 in.)] and a second one for larger diameter BWR fuel rods [nominal outside diameter of 14.5 mm (0.6 in.)].

The wall plug assembly provides an optical path to permit firing the laser beam onto the fuel rod surface to breach the cladding and release the fission gas from the fuel rod. The wall plug also provides a gas-tight connection between the fission gas sampling head and the fission gas sampling cart located outside of the hot cell. A light source in the inner sleeve of the wall plug enables operators to view the surface of a fuel rod when it is enclosed in the fission gas sampling head.

FIGURE 7. Fission Gas Sampling Head

FIGURE 8. Fission Gas Sampling Head and Wall Plug Assembly (Hot Cell Side)

As shown in Figure 9, a laser focusing lens is located at the end of the lens adjustment tube, which is situated inside the inner sleeve of the wall plug. This lens is moved forward or backward to focus or defocus the laser to permit cladding penetration or resealing of rods of different diameters and cladding thicknesses.

Laser System

The laser system houses two lasers: a YAG high-power solid-state laser capable of penetrating zirconium and stainless steel cladding when properly focused and a He-Ne visible light laser used to align the YAG laser. When properly aligned, a single lens can be moved approximately 1/2 in. to either focus or defocus the laser beam. The laser system is totally enclosed for the safety of operations personnel and observers. The laser is positioned perpendicular with respect to the wall plug inner sleeve. The laser beam is deflected by a 90-degree mirror down the center of the inner sleeve. This configuration allows lead shielding to be placed between the wall plug and the hot cell operating gallery; this shielding minimizes the radiation in the gallery due to the direct line of sight into the hot cell through the wall plug inner sleeve.

Fission Gas Sampling Cart

The fission gas sampling cart is illustrated in Figure 10. Four flasks with calibrated volumes of $1263 \pm 1 \text{ cm}^3$, $1991 \pm 1 \text{ cm}^3$, $3958 \pm 1 \text{ cm}^3$, and $11167 \pm 1 \text{ cm}^3$ are installed on the cart. The volume of the manifold and piping that connect the flasks to the wall plug is $1517 \pm 15 \text{ cm}^3$. The volume of the wall plug plus sampling head is $664 \pm 7 \text{ cm}^3$. The latter two volumes were determined using Boyle's law as discussed in the next section of this report, System Qualification.

The range of volumes incorporated into the sampling cart provides the system with the capability to determine the quantity of gas present in rods with internal pressures between atmospheric and 700 psi. For example, the gas in BWR rods is typically near atmospheric pressure (760 mm Hg). If the gas in such a rod with a void volume of 50 cm^3 is expanded into the system, the system pressure will be equal to

FIGURE 9. Fission Gas Sampling Portion of Wall Plug Assembly

FIGURE 10. Fission Gas Sampling Cart

$$\frac{(760 \text{ mm Hg})(50 \text{ cm}^3)}{(1517+664+50) \text{ cm}^3} = 17 \text{ mm Hg}$$

Such a pressure is within the 0 to 100 mm Hg range of the capacitance manometer used for measuring system pressures. PWR rods typically have high internal pressures and lower void volumes. If the gas in a PWR rod with a void volume of 30 cm³ and an internal pressure of 700 psi was expanded into the system using the 11167 cm³ flask, the resulting system pressure would be approximately 81 mm Hg, again within the capability of the pressure measurement device.

The cart was designed so that connections do not need to be made or broken in order to change the system volume. Such changes might affect the integrity of the leak tightness of the system. Instead, the calibrated flasks can be valved in or out of the system to allow the full range of expected fuel rods to be sampled.

System pressures are measured using an MKS Baratron capacitance manometer pressure sensor. It is accurate to ± 0.01 mm Hg over the range 0 to 100 mm Hg. This unit is compatible with any gas that is compatible with Inconel or 304/316 stainless steel, and is overpressure limited to 5 psi. As shown in Figure 10, the sensor (pressure transducer) is coupled to the system manifold, but may be valved out of the system. This valve is closed when pressures in the system are expected to exceed 5 psi; this ensures that the sensor's overpressure limitation is not exceeded. Fission gas sampling is done at room temperature (approximately 25°C), within the 15 to 40°C recommended operating temperature range for this sensor. Also, this unit is temperature controlled so that changes in operating temperature, within the recommended operating range, do not significantly affect the unit's accuracy.

Gas temperatures are measured using a thermister probe that is located in the system manifold. This probe provides temperature measurements that are accurate to $\pm 0.6^\circ\text{C}$ over the range 0 to 100°C.

The fission gas sampling cart also houses the vacuum pumps used to evacuate the system volumes. These pumps include a mechanical roughing pump and a turbomolecular diffusion pump.

SYSTEM QUALIFICATION

The fission gas sampling system was set up in a nonradioactive laboratory to check functional fit and verify that the system operated as intended. During initial tests with this system it was determined that a roughing pump was not efficient in the low-pressure regions during system pumpdown. Thus, a Turbovac® TMP-50 turbomolecular pump was procured for final stage evacuation of the system. The TMP-50 pump has an ultimate pressure rating of 6×10^{-9} torr. Once installed, this unit provided efficient final evacuation.

The conditions required for fuel rod breaching and resealing were determined using segments of zircaloy tubing with diameters and cladding thickness similar to those found in fuel rods. The tubing was inserted in the fission gas sampling head and the sampling head was clamped to the wall plug. The laser power and laser focusing lens locations were adjusted until the parameters were identified which 1) produced a pin-hole breach in the tubing and 2) permitted the pin-hole to be resealed.

After the fuel rod breaching and resealing parameters were determined, "dummy" rods were "sampled" to verify proper operation of the system, check out the operating procedure, and train the operators. These rods were pressurized with argon to simulate intact fuel rods. Each rod was punctured to evacuate the argon; a mass spectrometer analysis of the evacuated gas sample was completed to verify there was no air inleakage; the rod was resealed and the leak tightness of the rod was confirmed.

Subsequently, the system was installed in the hot cell. Several additional dummy rods were sampled, followed by sampling of a "test" fuel rod

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(i.e., an actual fuel rod that was not scheduled for characterization). Upon satisfactory completion of these activities, fission gas sampling operations were initiated on ATM fuel rods.

The fission gas sampling flasks were calibrated to $\pm 1.0 \text{ cm}^3$ before being installed on the fission gas sampling cart. The volumes of the remaining system components (the manifold and piping that connect the flasks to the wall plug, and the wall plug plus sampling head) were determined, using Boyle's law - $v_2 = (P_1 V_1)/P_2$, by expanding gas of a known volume at a known pressure into these unknown volumes, measuring the new pressure, and calculating the unknown volume. The accuracy and reproducibility of these determinations were checked by using this technique to "measure" the volumes of the calibrated flasks. It was found that the procedure was reproducible and accurate to within $\pm 1\%$.

The ability of the system to accurately determine the quantity of gas in a rod was calculated. This calculation was based on the known uncertainties associated with the temperature and pressure measurements (0.6°C and 0.01 mm Hg , respectively) and associated with the volumes of the sampling cart manifold plus piping (15 cm^3), the wall plug plus sampling head (7 cm^3), and each of the calibrated flasks (1 cm^3). This calculation was also based on an estimated uncertainty of the rod void volume measurement of $\pm 50\%$ (approximately 30 cm^3). Based on these uncertainties, the system should be capable of determining the quantity of gas in a rod to at least $\pm 1.8\%$ if the quantity of that gas is such that the smallest of the calibrated flasks on the sampling cart is used for gas expansion. If the rod contains a greater quantity of gas, such that one of the larger calibrated flasks is used, the uncertainty associated with the gas quantity calculation will be smaller because while the absolute uncertainty in the system volume will remain the same, this uncertainty will be a smaller fraction of total system volume. The absolute uncertainty in the rod gas quantity determination will be in the range of $\pm 3 \times 10^{-4}$ moles (for a PWR rod with an internal pressure of 700 psi and a void volume of 30 cm^3) to $\pm 3 \times 10^{-5}$ moles (for a BWR rod with an internal pressure of 14.7 psi and a void volume of 50 cm^3). These uncertainties are well within the required uncertainty of ± 0.001 moles.

OPERATIONS

Fission gas sampling has been completed on each of the available ATM fuel rods (ATMs-103, -104, -105 and -106). As additional ATMs are acquired, those fuel rods will also be fission gas sampled. Appendix B describes the sequence of operations that is performed during fission gas sampling. This appendix also contains a sample calculation demonstrating how rod gas quantity and rod void volume are determined.

The fission gas sampling system requires minimal maintenance. Periodically, the lenses in the optical train must be cleaned (or replaced if browning has occurred as a result of radiation damage). This maintenance is required when the laser cannot be focused to penetrate the fuel rod cladding. Similarly, the O-rings in the fission gas sampling head are also susceptible to radiation damage and must be replaced whenever a leak-tight connection cannot be obtained between the head and the wall plug assembly. The system volumes are remeasured whenever a change is made to the system (e.g., a valve is changed out or a new sample bottle added to the system). The pressure sensor is calibrated before each rod is sampled. The temperature probe is calibrated annually.

REFERENCE

Guenther, R. J., et al. 1988. Characterization of Spent Fuel Approved Testing Material - ATM-103. PNL-5109-103, Pacific Northwest Laboratory, Richland, Washington.

APPENDIX A

LISTING OF DESIGN DRAWINGS

TABLE A.1. Design Drawings for Gamma Scanning and Fission Gas Sampling Systems

<u>Drawing Number</u>	<u>Drawing Title</u>
H-3-55357	Gaging Table
H-3-55358	Draw Table
H-3-55360	Gamma Scan/Fission Gas Sampler Wall Plug Assembly
H-3-55361	Laser Drilling Fuel Rod Support
H-3-55363	Laser Mount - Lens and Mirror Assembly
H-3-55368	Fuel Rod Examination Machine Ball Screw
H-3-55369	Fuel Rod Examination Machine Track
H-3-55370	Gaging Table Ball Screw
H-3-55376	Gamma Scanner Calibration Rod
H-3-56402	Fuel Rod Examination Table Wiring Diagram
H-3-56410	Ball Screw Modification
H-3-56412	Laser Drilling Fuel Rod Support BWR
H-3-56413	Gamma Scan Calibration Rods

APPENDIX B

FISSION GAS SAMPLING - SEQUENCE OF OPERATION

APPENDIX B

FISSION GAS SAMPLING - SEQUENCE OF OPERATION

To calculate the quantity of gas in the fuel rod, all the volumes in the fission gas sampling system must be known. This includes the volumes of the sample flasks as well as the volume of the piping, the internal volume of the wall plug and the fuel rod void volume. To determine all of these volumes, a volume, V_1 , is pressurized with argon to a pressure P_1 . This gas is expanded into a second volume, V_2 . The new pressure, P_2 , is measured, and the unknown volume (which may be either V_1 or V_2) is calculated from Boyle's Law:

$$P_1 (V_1) = P_2 (V_1 + V_2)$$

In this manner all unknown volumes in the fission gas sampling system are determined.

The following steps are executed to fission gas sample a fuel rod:

Sample Calculation

1. A leak-tight connection is made between the plenum region of the fuel rod and fission gas sampling cart (located in the hot cell gallery).
2. The system is evacuated, back-filled with argon and reevacuated to remove residual air and other contaminants.
3. The sample bottles and calibrated flasks are valved out.

Sample Calculation

4. A laser beam is focused and fired on the plenum region of the fuel rod to breach the cladding and release the fuel rod gas.
5. Valves are opened as required to the evacuated flasks until the Baratron gauge is on scale (i.e., system pressure is below 100 mm Hg) and the pressure is stabilized so a pressure reading (P_s) can be made (the total volume of calibrated flasks required depends on the total volume of fission gas present in the fuel rod). The temperature of the gas (T_s) is measured. The system volume is V_s .
6. Valves are opened to the evacuated sample bottles.
7. After the pressure stabilizes, one (or more) sample bottles are removed and transferred to the analytical laboratory for chemical and radiochemical analyses.
8. The system is reevacuated, the piping to the fuel rod is valved out, and a known volume (V_1) is pressurized with argon to pressure P_1 .
9. The argon is expanded through the wall plug into the fuel rod, and the system pressure, P_2 , is measured.

$$P_s = 86.88 \text{ mm Hg}$$

$$T_s = 26.5^\circ\text{C}$$

$$V_s = V_w + V_m + V_f = (664 + 1517 + 5949) = 8130 \text{ cm}^3$$

where

V_w = volume of wall plug plus sampling head (664 cm³)

V_m = volume of sampling manifold cart and piping (1517 cm³)

V_f = volume of calibrated flasks (3958 + 1991 cm³)

$$V_1 = V_m = 1517 \text{ cm}^3$$

$$P_1 = 80.51 \text{ mm Hg}$$

$$P_2 = 55.32 \text{ mm Hg}$$

$$V_2 = V_w + V_p + V_1 = (664 + V_p + 1517) \text{ cm}^3$$

where

V_p = fuel rod void volume

Sample Calculation

10. The fuel rod void volume is calculated from

$$V_p = \frac{P_1(V_1) - P_2(V_1 + V_w)}{P_2}$$

$$V_p = \frac{(80.51)(1517) - 55.32(1517 + 664)}{55.32}$$

11. The amount of gas originally in the fuel rod (which is primarily the inert gas used to pressurize the rod during fabrication) is calculated from the Ideal Gas Law:

$$n = \frac{P_S V}{RT}$$

$$= 27 \text{ cm}^3$$

$$n = \frac{86.88 (8130 + 27)}{(62360)(273.15 + 26.5)}$$

- where P_S = pressure measured in the sampling system after fuel rod puncture (from step 5), mm Hg
 V = total system volume filled with gas at pressure P_S (V_s from step 5 + V_p from step 10), cm^3
 T = gas temperature (T_S from step 5), K

$$= 0.038 \text{ moles}$$

12. The system is pressurized with argon, and the laser is defocused and fired to "reweld" and seal the laser hole in the cladding.

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