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Design and Final Safety Analysis Report for Vertical Fission Product Release Apparatus in Hot Cell B, Building 4501

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Prepared for the
U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
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OPERATED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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Chemical Technology Division

DESIGN AND FINAL SAFETY ANALYSIS REPORT FOR VERTICAL FISSION PRODUCT RELEASE APPARATUS IN HOT CELL B, BUILDING 4501

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ABSTRACT

An existing horizontal furnace and a fission product collection system, used for testing light-water reactor fuel under simulated accident conditions, were rebuilt for operation in the vertical orientation. Major changes in the design of the furnace and in the loading/unloading procedure were required. Modifications to the fission product collection components and the steel containment box for the entire apparatus, however, were relatively minor. Because the fuel specimens, the furnace construction, and the general mode of test operation for this new facility are all similar to those of the previously operated facility, no significant changes in the safety hazards are apparent. Adherence to all quality assurance, personnel training, and operational safety requirements is documented.

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1. EXECUTIVE SUMMARY

Fission product release from light-water reactor (LWR) fuel under simulated accident conditions has been investigated at Oak Ridge National Laboratory (ORNL) for several years. For future testing, it was decided that an existing horizontal furnace and fission product collection apparatus should be rebuilt to permit the fuel specimens to be tested in the vertical orientation, as in an operating reactor. This conversion required major changes in the design and operation of the furnace; concurrently, the capabilities of the fission product collection apparatus were expanded. In order to minimize the potential problems, however, the materials of construction and the general operating techniques were retained to the extent possible. Except for increasing the number of components and making dimensional changes to expand the capacities, the primary fission product collectors (the thermal gradient tube and the filter package) remained unchanged. One new component, an aerosol density monitor, is being designed for utilization in later tests.

An analysis of the potential safety hazards associated with these tests showed that (1) compared to the horizontal apparatus, no additional hazards will be encountered, and (2) the vertical furnace design appears to be inherently safer. As concluded in the previous safety analyses, the maximum credible accident is breakage of the fused silica furnace vessel at a time when it contained mostly hydrogen; this might result in a burn or explosion of ~100 cm^3 of hydrogen but would be insufficient to cause a positive pressure in the experiment containment box, the primary containment.

Careful adherence to all administrative controls, including training and certification of the operators and the documentation of quality assurance and operational safety requirements, should ensure that the tests and the posttest analyses will be conducted in a manner as safe as is reasonably practical.

2. INTRODUCTION

An experimental project — Fission Product Release from LWR Fuel in Steam — has been sponsored at ORNL by the U.S. Nuclear Regulatory Commission (USNRC) since FY 1981. The objectives of this work are to determine the release rates of the most important fission products from highly irradiated commercial LWR fuel and to identify the physical and chemical forms of the released species. As of May 1985, six tests of commercial fuel, four tests of simulated fuel, which contained tracer-level quantities of fission products, and six control tests, in which tracer-level amounts of specific fission product and/or structural material were used,

have been conducted at temperatures up to 2450°C. No significant escape of radioactive material from the horizontal test apparatus in Hot Cell B or personnel exposure has occurred during conduct or analysis of these tests. Experiments in this new, vertical apparatus are a direct continuation of the completed work, which has been documented in ORNL reports[1-7] and open publications.[8-10] In comparison with the successfully completed work, no major changes are anticipated in materials of construction, in the range of experimental conditions, in the types of specimens tested, or in the operating procedures for future tests, which are to be conducted during the next 2 to 3 years.

The purposes of this report are twofold. The design and construction of the test apparatus and the experimental procedures are documented, with emphasis on changes compared to the earlier work. Secondly, the overall safety of these experiments and of posttest sample handling and analysis is discussed; potential problems and consequences of "worst case" accidents are considered. In the interest of brevity, frequent references to the design report for the horizontal test apparatus[11] and to the earlier safety analysis report[12] will be used.

3. APPARATUS DESIGN AND CONSTRUCTION

3.1 DESIGN REQUIREMENTS

In order to modify/convert the existing horizontal test apparatus[11] to a vertical system, the principal requirements were: (a) to change the furnace and thermal gradient tubes (TGTs) from horizontal to vertical orientation; (b) to change from one or two to three TGTs, and utilize a common (rather than individual) temperature control method; (c) to devise completely different methods for loading and unloading the fuel specimen to and from the furnace; (d) to improve the uniformity of steam oxidation of the specimen; (e) to develop new and improved ways for determining and controlling specimen temperature; (f) to relocate and modify the steel containment box to accommodate the above changes; and (g) to maintain the previously specified requirements for safety and containment.[12]

3.2 MAIN COMPONENTS

3.2.1 Furnace

As the key component in the test apparatus, the furnace required a large fraction of the design effort. As shown in Fig. 1, the furnace utilizes a tubular graphite susceptor to heat an inner ceramic (ThO_2 or ZrO_2) furnace tube, which contains the fuel specimen and the flowing steam–helium–hydrogen atmosphere. These furnace internals are surrounded by graphite felt and fibrous ZrO_2 thermal insulation (see Fig. 2). The region containing graphite (both susceptor and insulation) is purged with purified helium at a slightly higher pressure to minimize oxidation by any steam leaking out of the test chamber. One or more thermocouples*

*W–5% Re vs W–26% Re, insulated with BeO.

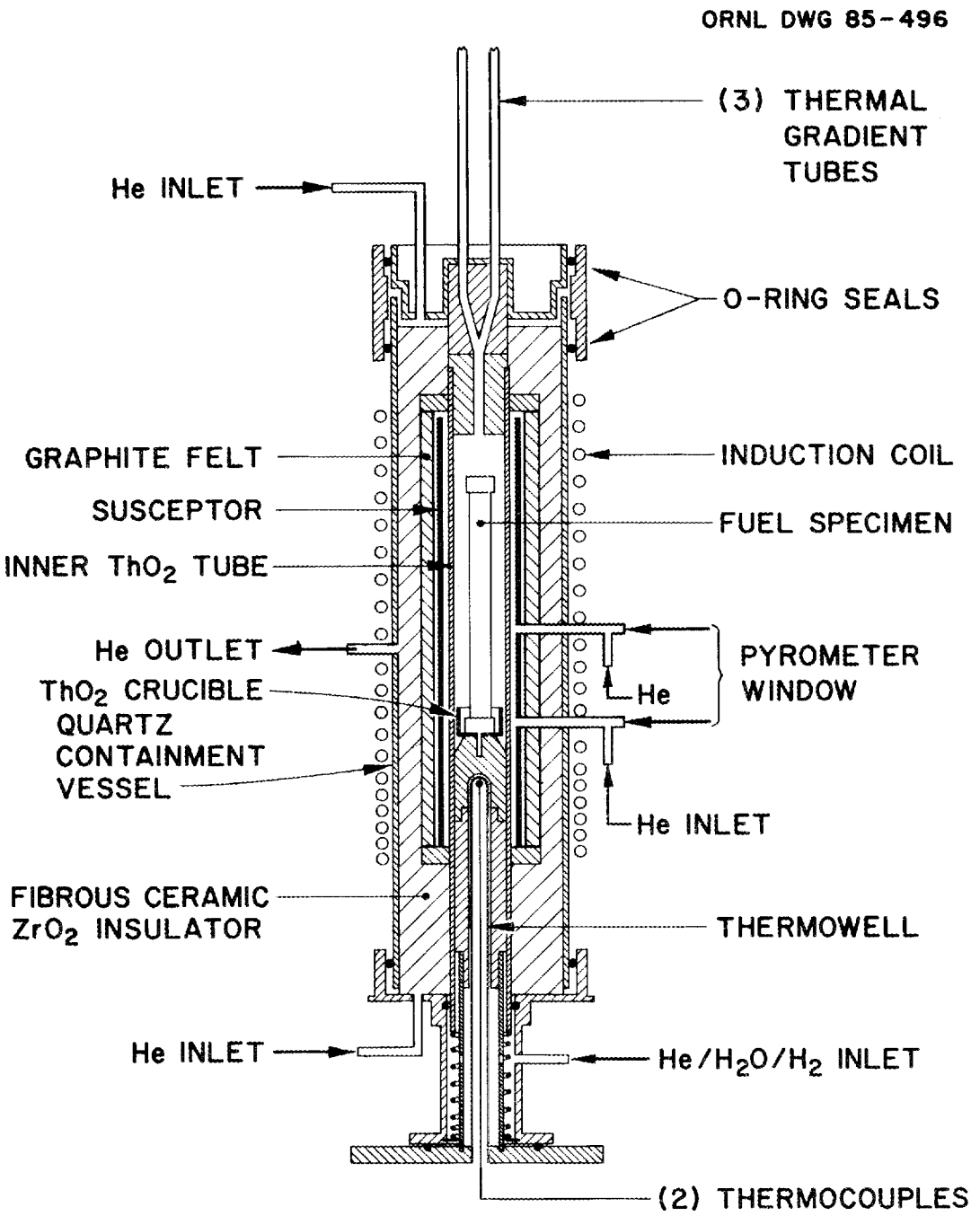

Fig. 1. Vertical fission product release furnace.

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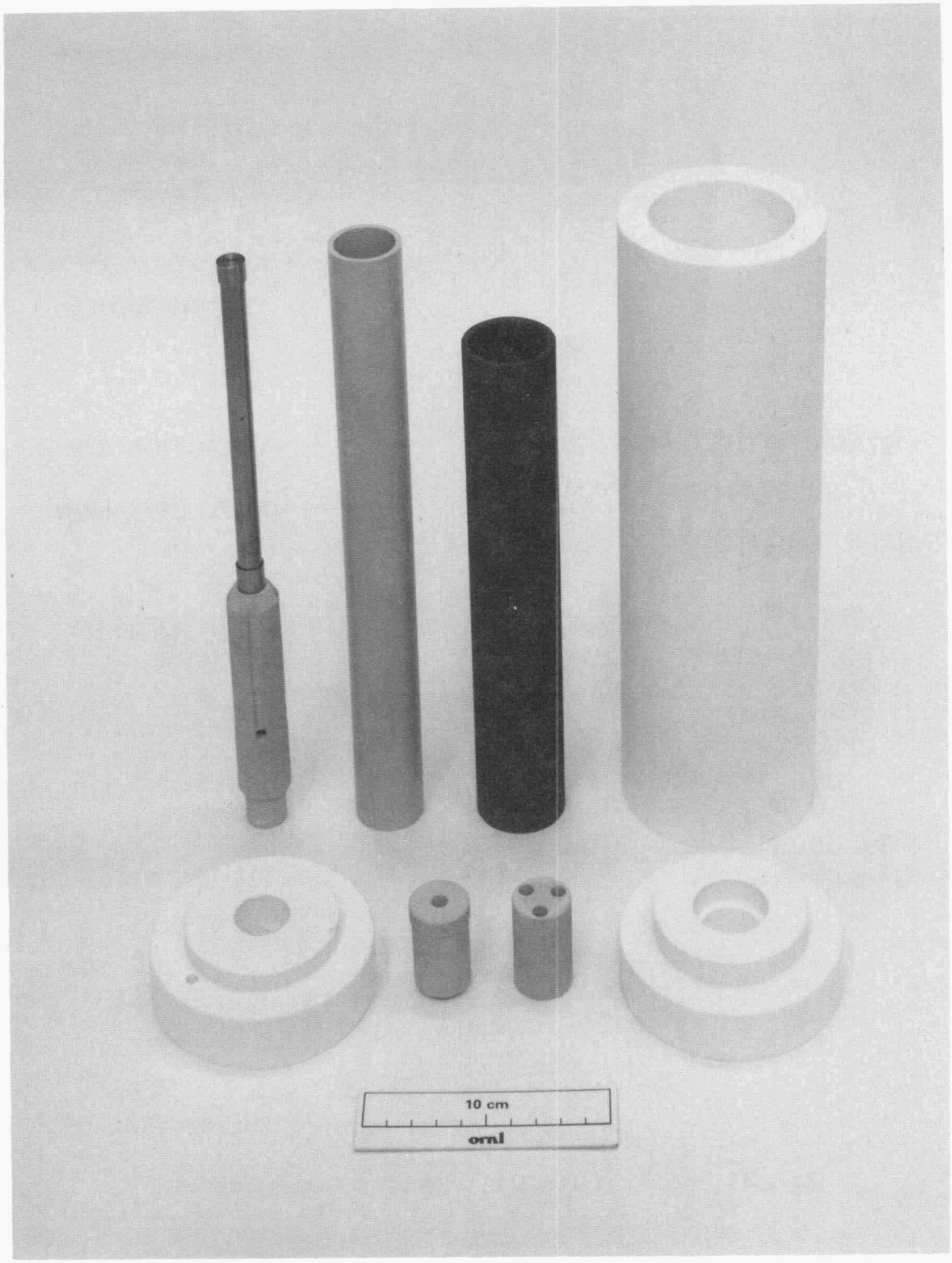

Fig. 2. Components of vertical furnace, in laboratory.

are installed in the inlet (bottom) end of the furnace, and two optical pyrometers* view the inner ceramic tube (through windows and holes in the insulation and susceptor) at elevations near the inlet end and mid-length of the fuel specimen for temperature measurement and control. The furnace vessel is constructed of a fused silica (quartz) tube, 10.16 cm OD × 0.318 cm wall × 40.64 cm long; the stainless steel (bottom) and Inconel (top) end flanges are fitted with water-cooled O-ring seals. The induction coil, of 0.635-cm-OD copper tubing, surrounds the silica vessel and is accurately positioned by vertical Mycalex† supports at 180° (Fig. 3). Purified helium is admitted to the window-support tubes to sweep any condensible material released from the furnace components away from the windows, where it might reduce transmissivity and interfere with temperature measurement. The exiting helium (see "helium outlet," Fig. 1) carries impurity vapors and aerosols to a filter, purification trap, and recirculating pump, from which it is returned to the furnace.

The test atmosphere, which passes over the fuel specimen in the inner tube, is a mixture of helium with controlled fractions of steam and/or hydrogen, depending on the test objectives. This gas mixture, which will be predominantly steam in most tests, is admitted to the furnace near the bottom end (Fig. 1, "steam inlet"). It flows upward and enters the test chamber around the circumference of the bottom ceramic support piece for the fuel specimen. The combination of four grooves at 90° locations and the narrow clearance gap (~0.025 cm) between this ceramic support piece and the surrounding furnace tube should provide good vertical mixing of the incoming gas within the test chamber, thereby improving the uniformity of cladding oxidation as compared to the previous horizontal furnace. This reactive gas mixture carries the fission product vapors and aerosols released from the fuel specimen upward through the top ceramic end pieces and then to one of the three collection trains, as shown in Fig. 4. Flow through the desired train, composed of TGT, aerosol monitor or sampler, and filter assembly, is controlled by operation of the valves further downstream. The remaining gases, which may include helium, steam, hydrogen, carbon monoxide, and the fission gases krypton and xenon, continue and are collected in the condenser and dryer (steam) and the cold charcoal traps (krypton and xenon). A copper oxide conversion bed at 450°C is used to convert H_2 and CO to water and CO_2, which are collected by a condenser and an Ascarite trap, respectively. Hydrogen is generated in the furnace by the reaction of steam with the Zircaloy cladding of the fuel specimen and with the graphite susceptor. Carbon monoxide is also formed by the steam/graphite susceptor reaction. Measurement of the inflowing helium, steam, and hydrogen, of the outflowing helium, and of the collected products (H_2O and CO_2) is used to interpret the rates and extent of Zircaloy oxidation during the test. The commercially supplied equipment, components, and instrumentation for this test apparatus are listed in Appendix A.

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*IRCON, Series R two-color pyrometers.

†Mycalex is a composite of mica and glass, trademark registered by Spaulding Fibre Co.

ORNL-PHOTO 4715-85R

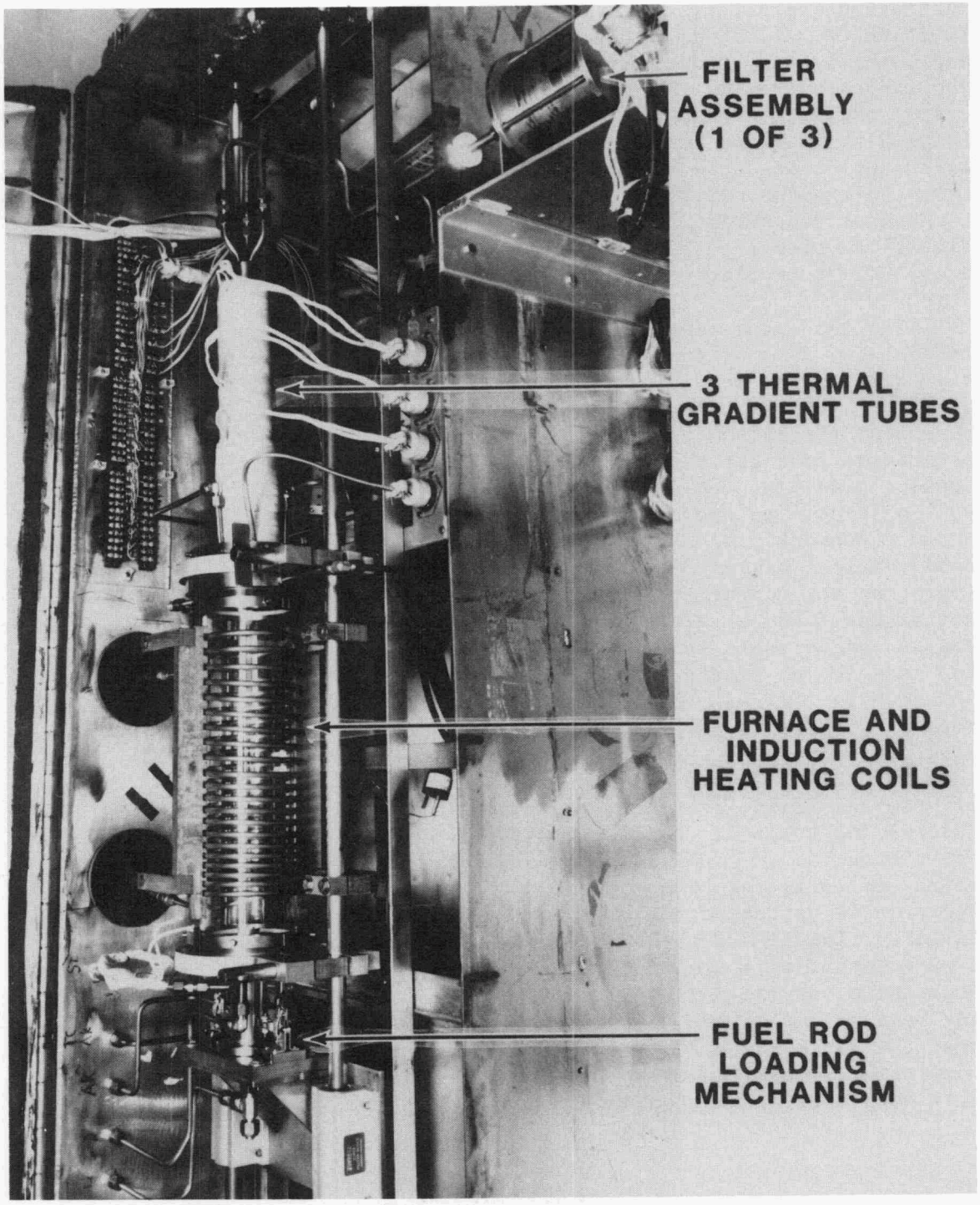

Fig. 3. Vertical furnace assembly, in place in hot cell.

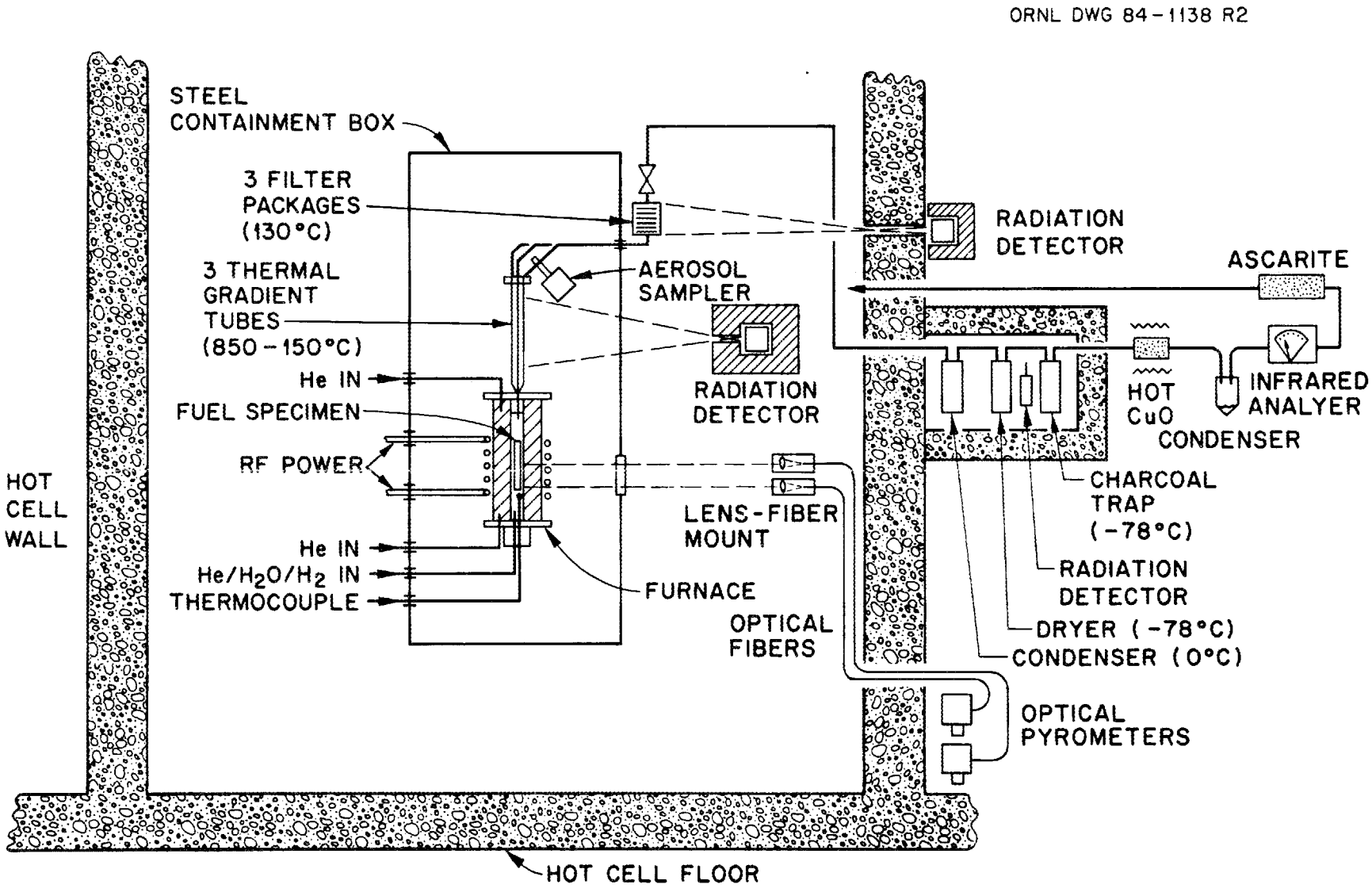

Fig. 4. Vertical fission product release apparatus.

3.2.2 Fission Product Collectors

Upon exiting from the fuel, the released material is swept from the furnace by the flowing helium-steam-hydrogen atmosphere to a series of collectors designed to selectively isolate the various fission product species. These collectors were listed in the previous section and are illustrated in Fig. 5. The TGT liner is made of platinum foil (0.0076 cm thick) and is inserted inside the 0.953-cm-OD Inconel tube; the liner (~0.75 cm ID) serves as a relatively inert deposition surface which can be readily removed and sampled for posttest analysis, as described previously.[11]

The monitor and sampler for examining the aerosols will be installed in selected collection trains; these components are illustrated in detail in Figs. 6 and 7 and provide, respectively, a measure of aerosol density (by the measurement of light attenuation) and representative samples of the material for further examination/analysis by scanning electron microscopy (SEM) and energy-dispersive X-ray analysis (EDX).

The filter package used in the vertical apparatus is a modification of the previously used assembly.[11] The principal change is an increase in effective diameter from 4.60 cm to 8.89 cm compared to the filter packages (Fig. 8) used in tests HI-3 through HI-6. This 270% increase in filter area plus the addition of two additional filter packages for use in different phases of the test, should provide ample capacity for aerosol collection without filter plugging in the highest-temperature tests. (Two of the 4.60-cm filters in simulant test HS-4,[13] which operated 5 min at 2000°C and 15 min at 2400°C, collected 1.45 g of material with only a moderate increase in pressure drop.) The holders for the heated charcoal were enlarged in the new design; up to 2.0 cm^3 (an increase of up to 150% over the amounts used in tests HI-3 through HI-6) may be loaded into the new charcoal holders if needed.

Although no significant amount of ^{85}Kr has been found in the second cold charcoal trap in previous tests, we will continue to use two traps in series as a precaution against overloading or failure of the first trap.

3.2.3 Gas Analyzers

In order to improve our understanding of oxidation reactions in the furnace, components for quantitative measurement of the hydrogen and carbon monoxide produced by high-temperature steam reactions have been added to the collection apparatus (Fig. 8). Downstream from the cold charcoal traps, a hot copper oxide conversion bed (450°C) is mounted to react with the H_2 and CO as follows:

$$H_2 + CuO \rightarrow Cu + H_2O \text{ , and} \tag{1}$$

$$CO + CuO \rightarrow Cu + CO_2 \text{ .} \tag{2}$$

ORNL-PHOTO 4710-85

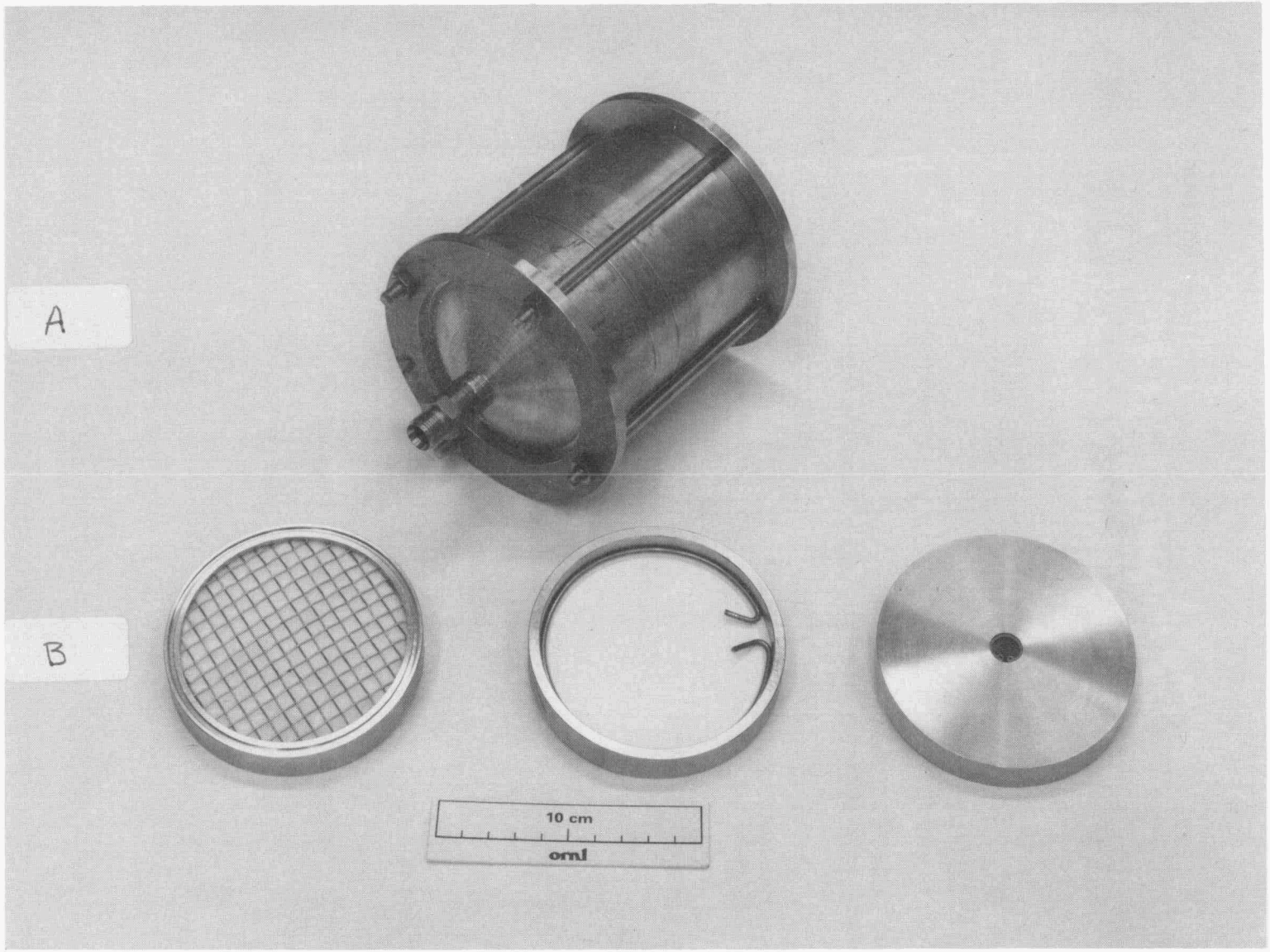

Fig. 5. Filter package, assembly (A) and individual components (B).

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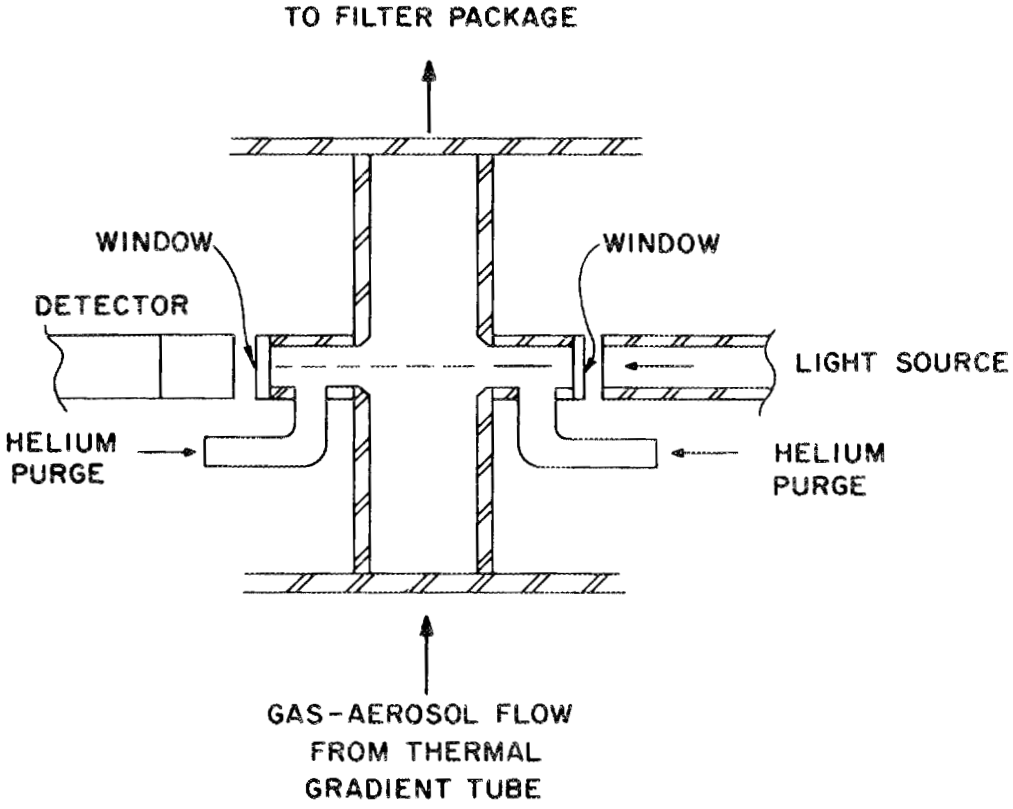


Fig. 6. Aerosol density monitor.

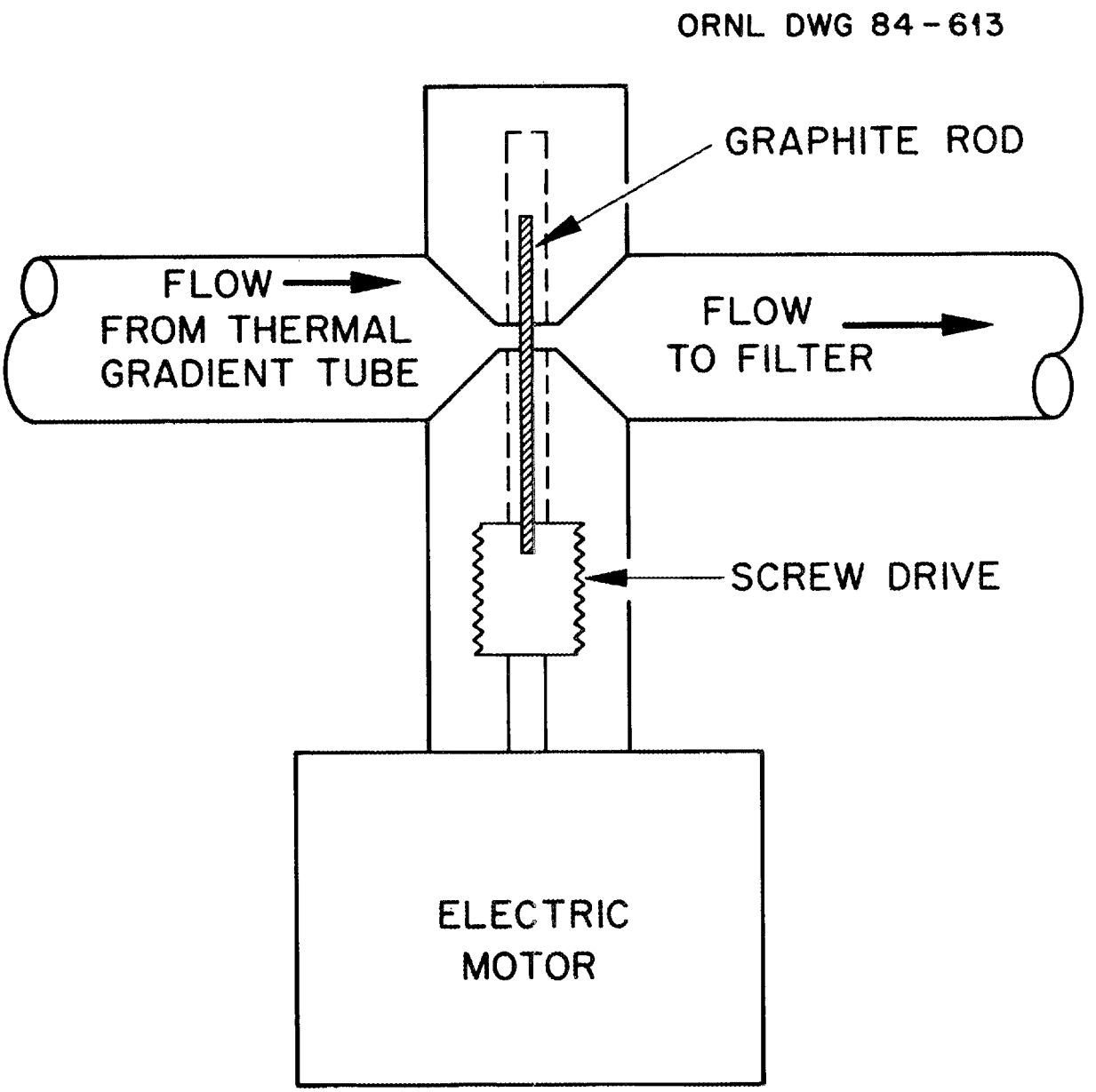


Fig. 7. Schematic diagram of miniature aerosol deposition sampler.

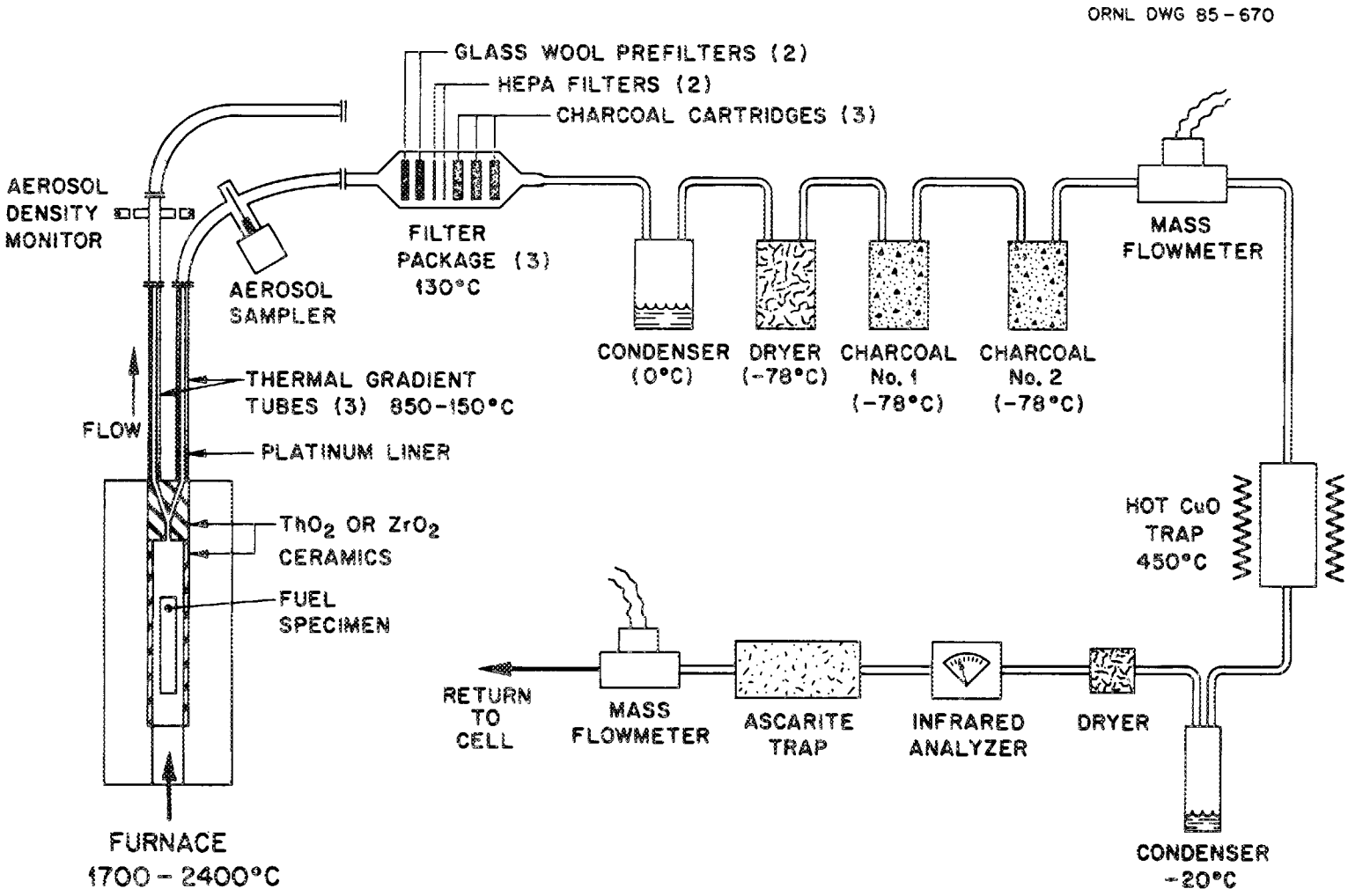


Fig. 8. Components of fission product collection trains.

The products H_2O and CO_2 are then condensed in a cold trap and adsorbed on Ascarite, respectively, where the amounts can be quantitatively measured. The CO_2 flow to the Ascarite trap will also be monitored continuously by a calibrated infrared analyzer.

3.2.4 Instrumentation

Most of the instrumentation changes in this apparatus, compared to the previous horizontal assembly, reflect the change in test orientation. Temperature measurement is accomplished by use of thermocouples and optical pyrometers; gas flow rates and pressures are measured by mass flowmeters and by standard gauges; and radiation is monitored by Geiger-Muller tubes (gross gamma activity) and measured precisely by NaI(Tℓ) and Ge(Li) detectors connected to a multichannel analyzer/computer system; all were described previously.[11]

The details of construction and operation of the aerosol density monitor are not available at this time. The basic design of the instrument used in the severe fuel damage tests at the Power Burst Facility in Idaho will be employed.[14] This concept uses the measurement of light attenuation across the flowing vapor/aerosol-containing exit gas stream. Use of this component, however, is not expected to have any bearing on safe operation of the tests.

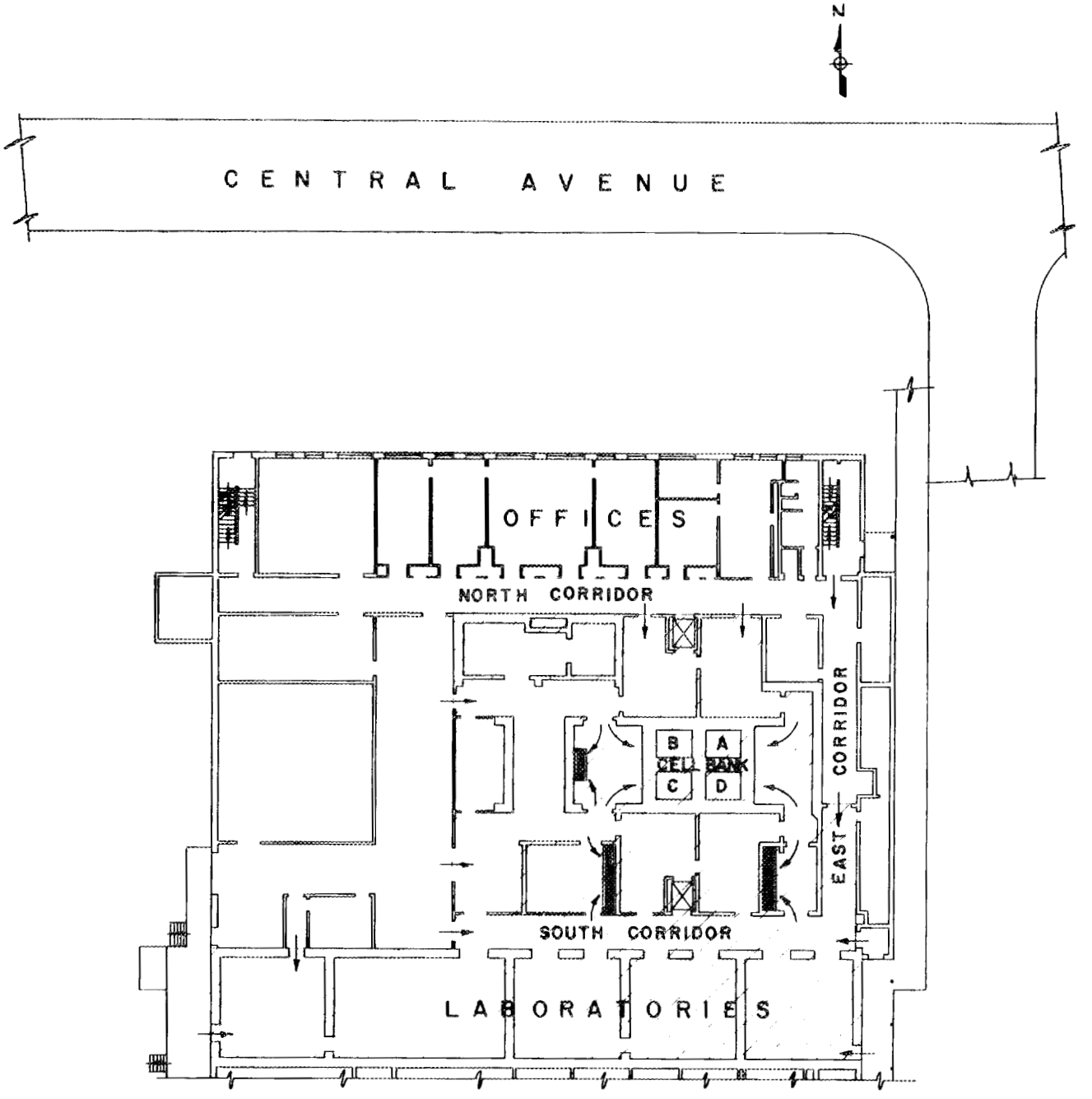
4. OPERATING PROCEDURES

The procedures used in conducting fission product release tests in this vertical apparatus will be very similar to those described and approved previously.[11,12] The principal differences will be in the area of loading/unloading the fuel specimen to/from the furnace. Examples of the general procedure and areas of operator responsibility for a typical test are shown in Appendixes B and C. A floor plan, illustrating the locations of the hot cells and surrounding laboratories in Bldg. 4501, is shown in Fig. 9.

4.1 TEST PREPARATION

As in previous tests, the highly radioactive fuel specimens will be cut to length, capped to prevent fuel loss, and drilled at midlength (to provide a vent during heatup) during specimen preparation in another hot cell. Pretest gamma analysis of the specimen, to verify fission product inventory and distribution, will be carried out at Bldg. 4501 in Hot Cell A and/or in a carrier in Room 220. The specimen will not be transferred into Cell B until the test apparatus has been completely prepared and the cell has been closed and sealed.

Following assembly of the furnace and the fission product collection apparatus, the entire system will be leak-tested (both vacuum and pressure) to ensure proper closure and sealing. Adequate operation of all instruments will be verified by preliminary heating and gas flow and the



NOTE:

1. OUTLINED SECTION IS CONTAINED AREA
2. ARROWS INDICATED DIRECTION OF AIR FLOW
3. ▬ DENOTES EXHAUST HOODS

Fig. 9. First floor plan for Building 4501.

use of radioactive standards. The adequacy of the containment box closure seals will be verified by vacuum and flow rate testing, and all special tools for remote operations — handling of the fuel specimen and casting it in epoxy resin, closing and opening the furnace, and disassembly and transfer of the TGTs and filter packages — will be checked prior to closing and sealing the hot cell. Only then will the fuel specimen be transferred into the cell and loaded into the furnace. (As a safety precaution, the other three cells in this complex are also locked to ensure no personnel access whenever a fuel specimen is in the test cell.) In order to allow hands-on assembly of the fission product collectors (TGTs, aerosol monitor and sampler, and filter packages), it was necessary to develop a procedure for loading the fuel specimen into the furnace from the bottom in this vertical apparatus. An extension pin from one end cap of the specimen fits into a corresponding hole in the ceramic support piece at the inlet (bottom) end of the furnace to hold the specimen in a vertical position (Fig. 1). The inlet end assembly of the furnace is mounted on a support plate that can be driven vertically by an elevator screw to simultaneously insert the specimen and close the furnace. After closure of the furnace and containment box, the seals will be reverified and the test apparatus evacuated and flushed with helium.

4.2 TEST OPERATION

In the interest of safety and reliability, all operations in conducting an actual test will be performed from outside the hot cell. Any use of the manipulators while the high-frequency power supply is activated is prevented by locks.

All parts of the test apparatus that are exposed to steam during the test must be preheated to >100°C (typically 125°C min) to prevent condensation. During this preheating phase, the furnace will be heated very slowly with helium flowing to 250–300°C, and the desired temperature gradient will be established along the TGTs. Steam flow through the test apparatus will then be initiated; stable flow at the planned rate for a minimum of 5 min is required before beginning the test transient, a ramp of 1 to 2°/s. (Unlike previous tests, one or more tests in this series may use significant flow rates of hydrogen, either in place of or in addition to steam. In such tests, the hydrogen flow will be controlled in the same manner as the steam. The hazards of using hydrogen are addressed in Sect. 5.)

During the heatup and high-temperature phase of the test, all instruments will be monitored carefully, and the test apparatus will be observed visually, to the limited extent afforded by the hot cell and containment box windows. Power to the furnace will be controlled manually, based on the temperatures indicated by the thermocouples and the optical pyrometers and on past experience. Upon any indication of a significant problem, the power will be reduced or shut off entirely. Because the high-frequency power has caused inaccurate temperature indications by thermocouples in some past experiments, the power will be

interrupted frequently for 3 to 5 s to allow more reliable comparison with the optical pyrometer. Except for the early, low-temperature (<1000°C) phase of the tests, the optical pyrometers have proven to be more reliable and will be our primary method of temperature measurement. Test temperatures and gas flow rates will be recorded continuously by strip chart recorders. The same data, plus the gamma spectra from detectors observing the TGTs, the filter packages, and the cold charcoal traps, will be recorded at 1-min intervals by a data acquisition system operated by a Hewlett-Packard 9825 computer, as indicated in Fig. 10. The three collection trains, as selected by valves downstream from the filter packages, will permit the collection of material released from the furnace in three phases, which are planned before the test is begun. Following completion of these three high-temperature phases at 1700 to 2400°C, the power will be shut off, and the specimen will be allowed to cool to ~1200°C with no change in the test atmosphere or flow rate. The natural cooling rate will be similar to the heatup rate, 1 to 2°/s. At this point, flow of the reactive component of the test atmosphere (steam or hydrogen) will be stopped, and the entire apparatus will be cooled to room temperature in flowing helium so that it is in a dry, inert condition for opening and disassembly. This test procedure is essentially identical to that used in the six HI tests[1-6] and the four HS tests.[13]

4.3 POSTTEST OPERATIONS

As in previous tests, the disassembly is planned to minimize the possibility of cross-contamination of collectors or of cell contamination. Following cooldown of the apparatus to room temperature, the filter packages, which are mounted outside the containment box (Fig. 4) in the vertical assembly, are disconnected first and transferred to Cell D for disassembly, packaging, sampling, etc., prior to analysis. The individual components of the filter package are shown in Fig. 5. The containment box is opened and the apparatus is examined for evidence of damage; then the aerosol monitor and the aerosol sampler are removed. The platinum TGT liners are withdrawn into preweighed aluminum transfer/storage tubes, then moved to Cell D or to a storage carrier.

Because severe damage — cladding melting and/or disintegration — of the fuel specimen is expected in all tests, no effort will be made to open the bottom of the furnace. (This would almost certainly result in the spilling of damaged fuel and major cell contamination.) Instead, the top end assembly will be removed, thereby allowing limited viewing of the interior with a mirror. Epoxy resin will be poured into the furnace cavity, securing the fuel specimen and ceramic furnace tube into a single mass. (If the ceramic tube is cracked or broken, the surrounding graphite susceptor will be included in this assembly.) After hardening of the epoxy, the entire assembly will be removed from the furnace, placed in a metal transfer/storage can, and moved to Cell D (see Fig. 9). All furnace components expected to be highly contaminated will be removed, packaged remotely, and transferred out of Cell B. (An in-cell ion chamber will be used to measure levels of radioactivity.)

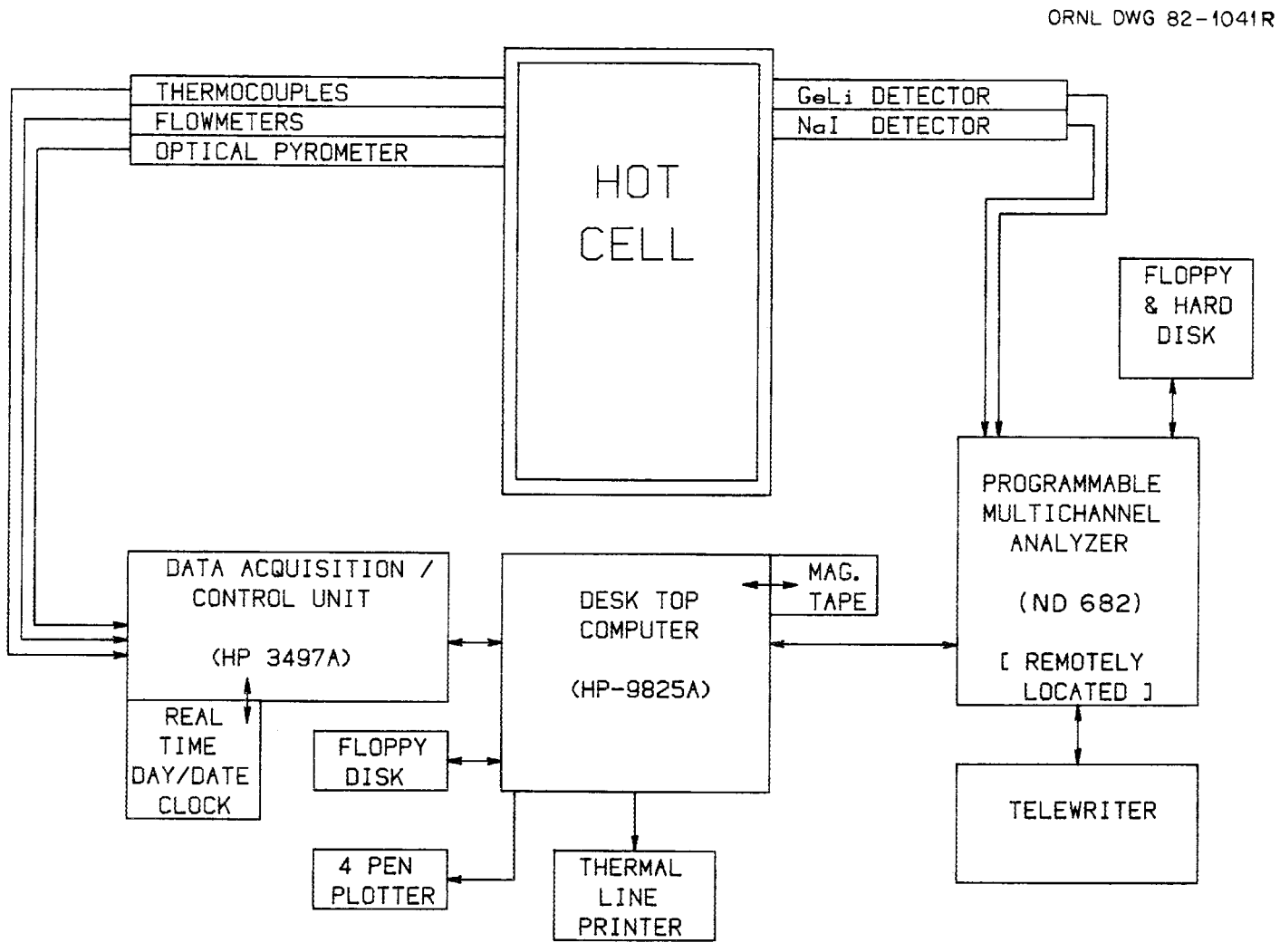


Fig. 10. Data acquisition and processing system for the fission product release test.

At this point, the cell will be opened and surveyed by a health physicist to determine the extent of cell contamination. After the necessary decontamination, the remaining components of the furnace will be removed for analysis and examination.

Posttest gamma analyses of low-level samples and components will be conducted in Room 126A; these are samples (<1 R/h at 3 in.) that can be analyzed safely without shielding, although a shielding may be used during transfer and storage. The high-level samples — the fuel specimen, TGTs, filters, and some furnace ceramics — must be handled remotely and analyzed either in Cell A (through a 15-cm-diam wall hole) or in Room 220 (using a lead-shielded carrier). Analyses of these high-level samples require the use of personnel barricades and supervision by the area health physicist. In addition, these high-level components are examined, sampled, leached, etc., in Cell D, and samples (both solid and liquid) are withdrawn for gamma analysis and/or transfer to Analytical Chemistry Division laboratories for other analyses. Sample selection, dilution, repackaging, etc., is conducted behind lead shielding in a hood in Room 124. All of these operations have been reviewed for safety and are conducted under health physics supervision; no significant laboratory contaminations or personnel exposures have occurred during the previous operations of this project (1982–1985).

5. ACCIDENT ANALYSIS (POTENTIAL PROBLEMS)

5.1 FUEL HANDLING PRIOR TO TESTING

The procedure for handling the fuel specimen prior to testing is discussed in detail in Appendix B. Since all handling of the specimen will be done over a large, resilient roughing filter that will be positioned on a table in front of the containment box, and since the Zircaloy cladding is not brittle at this stage, no breakage of the specimen is likely to occur. Both the table and the portable roughing filter will have sides to help keep the specimen from falling to the floor. However, if it should fall to the floor, there is a possibility of some fuel dust being discharged from the 1.6-mm hole located at the center of the specimen. Although unlikely, it is also possible that one of the pressed-on Zircaloy end caps could be dislodged. In either case, a special vacuum system could be used to retrieve the pellets, particles, and dust. These would be placed in a sealed container and transferred to Cell D for disposal. The floor of Cell B would then be flushed with cleaning solution to remove the contamination. It should also be pointed out that prior to the fuel specimen being lowered into the cell, the cell is carefully sealed and operated under negative pressure (~1 in. H_2O). All air entering and exiting the cell is filtered and controlled.

5.2 FUEL HANDLING AFTER THE TEST

After each test, epoxy will be poured into the cavity of the ceramic tube housing the badly damaged fuel specimen. In many of the tests, the cladding will be melted. Casting the specimens in epoxy will minimize

contamination during subsequent handling steps. An eyebolt partially embedded in the epoxy will be used to remove the specimen from the furnace. Upon removal, it will be placed in a transfer/storage can and sealed. This work will be done over the portable vacuum filter device that will be attached to the containment box close to the furnace. If the assembly should accidentally fall during this operation, the epoxy should contain all fuel, debris, etc., so that the consequences should be much less severe than in the accident case discussed in Sect. 5.1.

5.3 FURNACE MALFUNCTION

In the recently conducted HI and HS test series, ten successful experiments were conducted in the previously discussed horizontal furnace. In the HI tests,[1-6] highly irradiated LWR fuel specimens were heated in steam in the temperature range 1300 to 2000°C. In the HS tests,[13] four simulant (traced) fuel specimens were also heated in steam but at a higher temperature, 1600 to 2400°C. In this heating method, a graphite susceptor (tungsten in two tests) was positioned around the thoria or zirconia tube which housed the fuel specimen. Surrounding the susceptor were layers of graphite felt and fibrous zirconia which served as insulation. The furnace tube components in the vertical apparatus are similar to those in the horizontal apparatus.

Two separate methods for measuring temperature are to be employed. The temperature of the ceramic at the inlet end of the fuel specimen will be indicated by a W-5% Re vs W-26% Re thermocouple in a ceramic thermowell. The external surface temperatures of the ceramic furnace tube at two positions beside the fuel specimen will be monitored continuously with calibrated two-color optical pyrometers. During a test, it has been and will continue to be the responsibility of an operator to watch and record pertinent data or information on the temperature measurement charts. As in previous tests, the normal heatup rate will be 1 to 3°C/s. If a rapid temperature rise were to occur, induction power would be reduced to ensure temperature control.

The induction power supply operator is administratively in charge of the tests. During the test, one of his duties is to closely watch the furnace tube assembly through the cell wall and apparatus box windows. (All cell lights are turned off.) If an abnormal behavior occurs, he will immediately halt the test.

Another event that would signal an abnormal temperature excursion would be an unusually rapid rate of increase in the collection of radioactive cesium and krypton in the collection system. As in previous tests, values will be recorded at 1-min intervals. If anomalous behavior were to occur, the multichannel analyzer operator would inform the other members of the test team so corrective action could be taken.

If, despite all the safeguards, the furnace were to overheat and severe melting of the fuel specimen and some of the ceramics occurred, the melt would flow by gravity toward the water-cooled base of the furnace

assembly where it would be quickly cooled and solidified. Although such an occurrence might mean loss of data from that particular test, little possibility of damage to test apparatus or equipment other than the furnace is apparent. Should a temperature excursion cause breakage of the quartz vessel, the consequences discussed in Sect. 5.4 would apply.

5.4 BREAKAGE OF QUARTZ FURNACE FOLLOWED BY A HYDROGEN EXPLOSION (MAXIMUM CREDIBLE ACCIDENT)

In tests with irradiated fuel, using the vertical furnace, hydrogen will either be introduced to the system as part of the carrier gas or will be generated by the reaction of steam with the Zircaloy cladding of the fuel specimen. The greatest potential for a hydrogen explosion would be in the tests where hydrogen is part of the incoming carrier gas. In these tests, the hydrogen will be mixed with purified helium to give hydrogen and helium flows of <1 L/min (STP) and 0.6 L/min (STP), respectively. If the quartz furnace were to break, the carrier gas mixture would leak out into the stainless steel box, carrying with it fission products as vapors and aerosols.

In order to prevent the buildup of an explosive hydrogen–air mixture in the box as a whole, the box is designed to provide a continuous filtered inleakage of air at a rate of 42.3 L/min which, in the worst case, would dilute the maximum hydrogen inleakage (1 L/min STP) and result in a maximum hydrogen concentration of ~2.4%. A mixture containing at least 4% H_2 in air is required to be flammable. During a test, the negative pressure of the stainless steel box is ~10 in. H_2O relative to the hot cell; the negative pressure of the hot cell relative to the surrounding area is ~1 in. H_2O. If an explosion were to occur, the pressure in the box would remain negative if the amount of H_2 involved was <150 cm^3. The supply of hydrogen will be maintained at a minimum.

If a break were to occur in the quartz apparatus, the outlet flow from the apparatus would reverse, and the inlet flow would increase. This would automatically actuate a solenoid valve in the hydrogen supply line, stopping hydrogen flow to the apparatus and triggering an alarm. The operator watching the pressure readings would then manually close the main valve of the hydrogen supply tank. The induction power supply would also be turned off immediately in response to the alarm. Since the furnace volume is <100 cm^3, a burn or explosion of >150 cm^3 of H_2 appears very unlikely.

The stainless steel end flanges, the induction coil, and furnace ceramic components would serve to protect and contain the fuel specimen during and after the hydrogen burn. Burning would be external to the furnace. No fuel or fuel particles would be expected to be released from the furnace. On the other hand, a small fraction of the fission products could be released to the box.

Table 1 lists the maximum quantities that could potentially become airborne in this type accident. The concentrations in the stack are considerably less than the 40-h industrial maximum permissible concentration

Table 1. Fission product release: maximum credible accident (MCA)[a]

Isotope	Total specimen inventory (Ci)	Amount airborne in MCA[b] (μCi)	Maximum permissible body burden (μCi)	Amount leaving 4501 (μCi)	Amount leaving 3039 stack (μCi)	Concentration in stack (μCi/cm^3)	40-h controlled area MPC[c] (μCi/cm^3)
^{238}Pu	0.37	0.37	0.04	37×10^{-5}	19×10^{-8}	9.9×10^{-18}	2×10^{-12}
^{239}Pu	0.03	0.03	0.04	3.0×10^{-5}	1.5×10^{-8}	0.8×10^{-18}	2×10^{-12}
^{240}Pu	0.055	0.055	0.04	5.5×10^{-5}	2.8×10^{-8}	1.5×10^{-18}	2×10^{-12}
^{241}Pu	12.0	12.0	0.9	1.3×10^{-2}	6.3×10^{-6}	3.3×10^{-16}	90×10^{-12}
^{242}Cm	0.47	0.47	0.05	47×10^{-5}	24×10^{-8}	12×10^{-18}	1×10^{-9}
^{244}Cm	0.34	0.34	0.1	34×10^{-5}	17×10^{-8}	8.9×10^{-18}	9×10^{-12}
^{90}Sr	7.2	72.0	2.0	7.2×10^{-2}	3.6×10^{-5}	1.9×10^{-15}	1×10^{-9}
^{129}I	3.4×10^{-6}	0.102[d]	10^{-5}	3×10^{-5}	1.5×10^{-8}	7.8×10^{-19}	2×10^{-9}
^{134}Cs	9.2	2.7×10^{5}[d]	20	83[e]	0.04	2×10^{-12}	10×10^{-9}
^{137}Cs	10.7	3.2×10^{5}[d]	30	96[e]	0.05	3×10^{-12}	10×10^{-9}

[a]Basis for calculation:
Fraction airborne after MCA = 10^{-6} except Sr, I, and Cs as noted.
Penetration of box of 4501 High-Efficiency Particle Adsorber (HEPA) = 0.001.
Penetration of stack roughing filter = 0.5.
Penetration of 3039 HEPA = 0.001.
Stack flow volume (5 min) = 1.91×10^{10} cm^3.
[b]In stainless steel box.
[c]MPC = maximum permissible concentration.
[d]Represent 3% of fuel specimen inventory.
[e]Assumed that 70% was released as vapor and was condensed on the cooling coils and cool box surfaces. The other 30% was associated with particulate.

(MPC) values. It should be pointed out that the concentration values for ^{134}Cs and ^{137}Cs in the stack are higher than actually expected. There was no allowance given for plateout in the piping to the stack or for the scrubber. Note that the containment box is vented to the off-gas system. Cesium compounds have a tendency to attract water and are sticky and generally reactive, which would enhance their attenuation. In any event, there should be no release from the box (primary containment) to the hot cell (secondary containment).

5.5 LOSS OF ELECTRIC POWER DURING A TEST

A power outage during a test would result in an automatic, safe shutdown of the equipment. Since the exhausts of the hot cell and the stainless steel apparatus containment box are connected to the 3039 stack system, no loss of negative pressure or flow would result. Power to the induction heating system would be lost, but cooling water through the induction cooling coils would continue to flow, ensuring cooling of the furnace and fuel specimen. The helium flow to the apparatus would continue. If hydrogen carrier gas were being used, it would be stopped automatically by a solenoid valve. If steam flow were used, it would be diverted through a bypass line, leaving only helium flowing across the specimen.

5.6 RELEASE OF GASEOUS OR PARTICULATE RADIOACTIVITY

In preparation for a fission product release test, the penetrations for piping, wiring, instrument leads, etc., are checked for adequacy of gamma ray shielding and sealing against airflow. In addition, the personnel access doors (both glass and lead doors) are sealed with heavy plastic tape to minimize air leakage. As a result of the negative pressure maintained in the cell, -1.0 in. H_2O relative to the surrounding laboratory, the probability of release of radioactivity from the cell is very low. In addition, the test containment box is maintained at -10 in. H_2O relative to the test cell, thereby minimizing the probability of significant release from the box to the hot cell. Since small amounts of the inert gas ^{85}Kr and the long-lived β emitter ^{129}I are the only radionuclides in our test specimens that are gaseous at room temperature, no significant gaseous hazard is apparent.

In the event of failure of several of these barriers, so that a significant amount of radioactive material in particulate form were to be released from the hot cell, the normal health physics monitoring instruments (monitrons and constant air monitors) would indicate a hazardous condition immediately. Steam flow would be stopped, and the test would be discontinued, allowing the fuel/furnace/fission product collection assembly to cool to room temperature in an inert atmosphere. No personnel would leave or enter the hot cell area until the nature and extent of the release could be determined and health physics approval granted. Additional information about the location and source of the release would be collected and utilized to the extent possible to mitigate further release and to isolate and confine the released material until its elimination by standard decontamination techniques.

5.7 SAMPLE HANDLING

The apparatus components (TGT, filters, and furnace components) that contain the deposited highly radioactive fission products are handled, disassembled, and chemically leached in Cells B and D (see Sect. 4.3). Only subcomponents of the apparatus and analytical samples (solids or diluted leach solutions) are removed from the cell. This is done by a three-man team, which includes a health physicist. The samples, which are contained in glass bottles, are pulled through a hole in the ceiling of Cell D, with the activity level of each being checked for safety. Each sample is then transferred by means of tongs (over blotter paper) to a specially designed lead carrier (positioned near the hole) where it is double-bagged with minimal personnel exposure. If a liquid sample were to be dropped and its container broken, the consequences would be minimal; only the affected area would have to be decontaminated. If the sample contained solids (like filter particulates), there would be some danger of airborne material, but this too should be minimal because of the airflow into the cell. The team members, wearing protective clothing and masks, would be unaffected.

Over the past few years, many samples have been safely handled as described above with no problems.

5.8 SUMMARY

Twenty-seven successful fission product release experiments with highly irradiated fuel specimens have been conducted horizontally in the stainless steel box located in Cell B; this box was reoriented vertically and will be used in the vertical furnace tests. The box was designed to provide containment under the worst-case accident conditions (H_2 explosion). The probability of this type accident occurring is low, and if it should occur, the consequences would primarily be a matter of box contamination and apparatus damage.

The maximum permissible concentrations of radionuclides in air for occupational exposure[15] are as follows:

	^{239}Pu	^{137}Cs
For 40-h week ($\mu Ci/cm^3$)	2×10^{-12}	10^{-8}
For 168-h week ($\mu Ci/cm^3$)	6×10^{-14}	5×10^{-10}

The calculated in-stack concentrations for our maximum credible accidents are on the order of one million times lower than the above permissible concentrations.

6. QUALITY ASSURANCE

Quality assurance (QA) requirements were a major consideration in all phases of the design, fabrication, assembly, and testing of this experimental apparatus. Only construction materials of proven characteristics were used, and archive samples of the most critical materials, such as

Inconel, ZrO_2, and ThO_2, were retained for possible future examination. All welds were inspected and leak-tested, and all furnace components were (and will be in every case) inspected for proper fit and mechanical quality. The fission product collection media (platinum foil, filter material, and charcoal) are of verified purity and have been proven in previous tests.

All instruments (both new and previously used) were checked and calibrated by Instrumentation and Controls Division personnel prior to installation. All critical instruments are on a regular calibration schedule, and the records are maintained in the QA file for the fission product release project. Prior to beginning any experiment, the entire instrument system is tested to ensure normal operation. The detectors and the multichannel analyzer/computer system are routinely calibrated with National Bureau of Standards radiation sources to ensure accurate, reliable results for both on-line and posttest gamma analysis.

7. VERIFICATION OF OPERATIONAL SAFETY

7.1 ORGANIZATION

Careful planning of test preparation and organization of test procedures with specific duties and responsibilities for each operator are considered to be major factors in ensuring safe, successful operation of these tests. Pretest consideration of potential problems and available alternatives increases the probability for taking the best course of action during test operation. Examples of test procedures and operator responsibilities are included in Appendixes B and C.

7.2 TRAINING OF OPERATORS

To ensure that the test operators are qualified for both normal procedures and for a variety of unexpected events, a formal training program was developed. In addition to the personnel working on the fission product release project, who have developed the test procedures over a period of years, the area health physicist, the building manager, and the Chemical Technology Division safety officer contributed to this program. The details, along with a check list and a written examination, have been documented.[16] Annual recertification of the operators will include (1) a critique of the past year's operating experience, (2) a review of any changes in relevant building facilities, equipment, and operation, and (3) successful completion of the written examination. The training check lists and written examinations are kept on file in the project manager's office, with copies in the building manager's office.

7.3 EQUIPMENT PROOF-TESTING

Testing of the individual components, to the extent possible, as well as integral testing of the assembled apparatus, should identify most potential problems (and allow the required modifications) before high levels of radioactivity are admitted to the system. Many of the components were used in the previous HI[1-6] and/or HS[13] test series, therein

proving their individual reliability. These proof tests will be similar to those conducted on the horizontal test apparatus.[11]

With the use of an instrumented fuel specimen, the vertical thermal gradient in the new furnace will be determined and compared to the temperatures indicated by the optical pyrometers through side windows and the thermocouples in the inlet end ceramic support piece. If needed, the configuration of the induction coil will be modified to obtain the desired uniform temperatures. Preliminary tests of the new TGT furnace design indicated good control; tests of the three-tube assembly, with the furnace at high temperature, will be conducted during furnace testing. The aerosol sampler used in tests HI-5, HI-6, and HS-1 through HS-4 will be modified to better accommodate the higher temperatures and flow rates planned for these tests. In addition, an aerosol density monitor, will be built and installed at a later date. The filter package was modified to improve loading/unloading convenience and to provide increased surface area (270% greater than in HS tests) for these tests, which are expected to generate more aerosol than in previous tests. The increased capacity will be verified in integral tests with unirradiated fuel.

Several new test components, a hot CuO trap, condenser, dryer, and Ascarite trap, are being added downstream from the cold charcoal traps to allow measurement of H_2 and CO generation during the test (Fig. 2 and Sect. 3.2.3). Proper operation of these components will be determined in preliminary tests also. By design, no radioactive material should reach this part of the apparatus. Except for ^{85}Kr, which is collected on the cold charcoal, no radioactive material passes through the filter package.

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APPENDIX A. COMMERCIALLY SUPPLIED EQUIPMENT AND INSTRUMENTATION

1. Electrical power supply for furnace
   RF generator, Model No. T-50-3RS, 50 kW input, 300 kHz, Lepel Corp.

2. Temperature measurement, control, and recording

   2.1 Two-color optical pyrometers, Model No. R-99C05, Ircon, Inc.

   2.2 Digital indicator, Model 2168A, Omega Engineering, Inc.

   2.3 Two-pen strip chart recorder, Model No. 7100B, Hewlett Packard, Inc.

   2.4 Twelve-point strip chart recorder, for thermal gradient tube and filter package, Brown Electronik, 0-1200°C (Type K thermocouples), Minneapolis Honeywell, Inc.

   2.5 Twelve-point strip chart recorder, for steam supply system, Brown Electronik, 0-350°C (Type K thermocouples), Minneapolis Honeywell, Inc.

   2.6 Temperature controllers, for thermal gradient tube, four each, Model No. 527Z, 0-999°C, Barber Coleman Co.

   2.7 Temperature controller, for steam generator, Series 520 digital controller, Barber Coleman Co.

   2.8 Thermocouples, for furnace, Pt vs Pt-10% Rh and/or W-5% Re vs W-26% Re, Omega Engineering, Inc.

   2.9 Thermocouples, other apparatus locations, Chromel-Alumel (Type K), sheathed with stainless steel, Omega Engineering, Inc.

3. Measurement and recording of gas flow

   3.1 Mass flowmeters, for helium and hydrogen inlet flow, 0-1 L/min, Model TDNALL-1KP, Teledyne Hastings-Raydist

   3.2 Mass flowmeter, for helium outlet flow, 0-5.0 L/min with Totalizer, Model TDNALL-5KP, Teledyne Hastings-Raydist

   3.3 Four-pen strip chart recorder, for recording signals from mass flowmeters, Model FL04W6D, Texas Instruments, Inc.

   3.4 Infrared analyzer for continuous measurement of CO_2 passing from the CuO conversion bed to the Ascarite trap, Lira Model 303, Mine Safety Appliances Co.

4. Filtration materials

   4.1 Filters, borosilicate glass fiber, MSF Nos. GA-100 and GA-200, Micro Filtration Systems, Inc.

   4.2 Charcoal, impregnated with triethylenediamine (TEDA), Type NAC-G-618, North American Carbon, Inc.

5. Radiation detection and analysis

   5.1 NaI(Tℓ) detectors, Type 125, Harshaw Chemical Co.

   5.2 Ge(Li) detectors, Model 8101, EG&G ORTEC, Inc.

   5.3 Multichannel analyzer/computer, System 682, Nuclear Data, Inc.

APPENDIX B. GENERAL PROCEDURE FOR FISSION PRODUCT RELEASE TESTS

A. Days before test

1. Prepare system — furnace ceramics, TGTs, filter packages, tools, traps, etc., in both Cell B and Cell D.

2. Check operation of heaters, thermocouples, recorders, flowmeters, etc.

3. Prepare fuel specimen in Cell D for transfer into Cell B. Do gamma spectrometry in Room 220.

4. Verify in-cell remote handling procedures and furnace loading/unloading.

5. Collect fuel specimen data and specify test operating conditions.

6. Fill steam generator.

7. Assemble, evacuate, and leak check test apparatus.

8. Check operation of all radiation detectors; calibrate with standard or accurately known sources.

9. Prepare and check posttest examination equipment in Cell D and scanner above Cell B.

B. Day of test

1. Recheck all radiation detectors, MCA, data recording program, and data acquisition system.

2. Close and lock all cells, tape doors, and set Cell B vacuum (-1.0 in. H_2O).

3. Bring in fuel specimen, install in furnace, and connect lines.

4. Evacuate, purge, and leak check test apparatus with steam line heat on.

5. Close box; set vacuum to -10 in. H_2O and 40 L/min airflow.

6. Set He flow rates: MFM-1 = 0.1 L/min maximum
   MFM-2 = 0.3 L/min.

7. Preheat furnace slowly to ~300°C.

8. Heat steam generator, begin flow to vent at 0.3 L/min He (MFM-3) and T_{SG} = 95.6°C (for 1.0 L/min).

9. Verify proper TGT temperatures.

10. Begin steam flow through furnace; record flow rates and back pressures, and adjust TGT furnaces as needed.

11. Set data acquisition system (DAS) to 1-min recording cycle.

12. When all flows stabilize (minimum 5-min steam flow), begin planned heatup cycle, ~300° to test temperature.

13. Considering correction factors for thermocouple and optical pyrometer, reduce power when test temperature is reached to maintain for desired time period.

14. Monitor all instruments and chart recorders and mark at regular intervals during test, each experimentalist having specific responsibilities.

15. At end of planned period, switch collection trains and heat to new temperature.

16. Turn power off at end of test period, continuing steam flow until temperature drops below 1200°C.

17. Turn steam generator power off and switch steam flow to vent, with MFM-3 helium bypassing steam generator.

18. Continue helium flow through furnace ~30 min to dry system, then turn off power to line heaters and TGT and filter furnaces.

19. Reduce helium flow to MFM-2 = 0 and MFM-3 = 0.1 L/min, and bypass condenser, dryer, and cold charcoal traps.

20. Turn on vacuum pump and reduce pressures in cold traps to ~0.5 atm; then close individually and remove from system for analysis.

C. <u>Days following test</u>

1. Disconnect filter packages and transfer from Cell B to Cell D for disassembly.

2. Record another set of gamma spectra for background correction.

3. Reduce vacuum on containment box, open, and inspect furnace assembly; begin off-gas flow to prefilter at furnace inlet.

4. Remove aerosol sampler and TGT to filter lines.

5. Remove TGT liners, load into transfer tubes, and remove to scanner above Cell B.

6. Record another set of gamma spectra for background correction.

7. Disconnect coolant tubes and remove top flange/TGT assembly from furnace.

8. Remove ceramic end pieces from top end of furnace.

9. Using mirror, inspect specimen and furnace to extent possible.

10. Pour ~20 cm^3 epoxy resin into furnace, allow time to set, then finish filling chamber to top with epoxy and insert lifting eye-bolt. Leave overnight for firm setting.

11. Carefully remove fuel/furnace tube assembly, place in transfer/storage can, and move to Cell D.

12. Using remote ion chamber, monitor furnace and box for high levels of radioactivity.

13. Using manipulators, clean and remove radioactive materials and components.

14. Open cell door for more specific survey by health physicist, including smears for both alpha and beta-gamma analysis.

15. Depending on levels of radioactivity, decontaminate cell, and remove remaining furnace components for analysis.

16. Proceed with disassembly, inspection, photography, sampling, and analysis of all test components.

APPENDIX C. PRIMARY AREAS OF RESPONSIBILITY OF OPERATORS IN FISSION PRODUCT RELEASE TESTS

Operator	Primary responsibilities
M. F. Osborne	— Plan and coordinate activities — Maintain RF power control, heatup rate, and furnace temperature control — Watch cell for any problems — Monitor furnace and TGT temperatures
J. L. Collins	— Monitor and record thermocouple and optical pyrometer temperatures — Record time of all events on chart — Monitor and control TGT and filter temperatures
R. A. Lorenz	— Monitor flow recorder, note events and times — Monitor TGT and filter temperatures — Observe and interpret gamma spectra and flow data
J. R. Travis	— Monitor flow rates and record volume and pressure data — Monitor furnace flange temperatures, advise of need for coolant — Watch for any unusual flow/pressure behavior — Maintain communication by intercom with Osborne and Collins
C. S. Webster	— Operate multichannel analyzer and data acquisition systems — Monitor gamma spectra — Watch for RF interference with spectra — Maintain communication by intercom with Osborne and Collins

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11a. TYPE OF REPORT

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12. SUPPLEMENTARY NOTES

13. ABSTRACT (200 words or less)

An existing horizontal furnace and a fission product collection system, used for testing light-water reactor fuel under simulated accident conditions, were rebuilt for operation in the vertical orientation. Major changes in the design of the furnace and in the loading/unloading procedure were required. Modifications to the fission product collection components and the steel containment box for the entire apparatus, however, were relatively minor. Because the fuel specimens, the furnace construction, and the general mode of test operation for this new facility are all similar to those of the previously operated facility, no significant changes in the safety hazards are apparent. Adherence to all quality assurance, personnel training, and operational safety requirements is documented.

14. DOCUMENT ANALYSIS – a. KEYWORDS/DESCRIPTORS

Fission product release
Radioactivity containment
Induction furnace
Fission product collection

b. IDENTIFIERS/OPEN-ENDED TERMS

15. AVAILABILITY STATEMENT

16. SECURITY CLASSIFICATION

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