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MARTIN MARIETTA ENERGY SYSTEMS, INC.
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Metals and Ceramics Division

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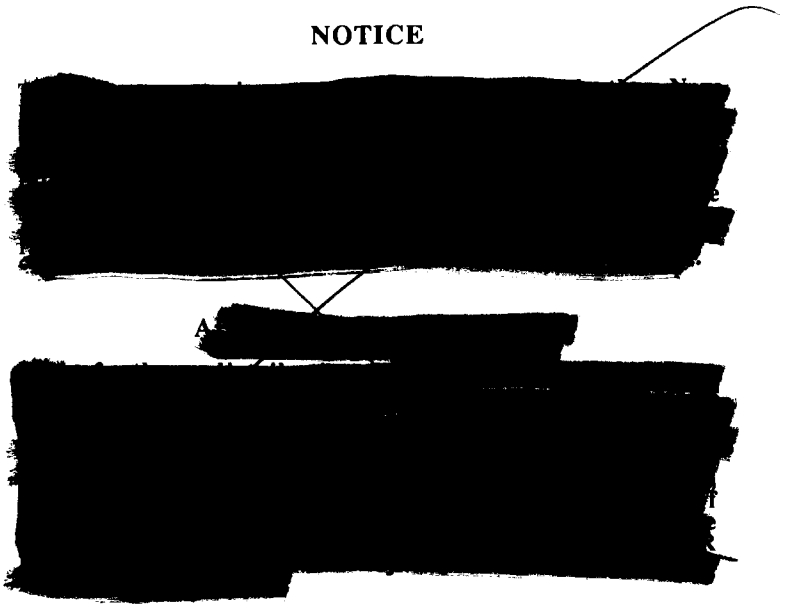

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THE CORE CONDUCTION COOLDOWN TEST FACILITY: CURRENT STATUS AND ISSUES*

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ABSTRACT

The Core Conduction Cooldown Test Facility (CCCTF) will allow the testing of modular high-temperature gas-cooled reactor (MHTGR) candidate fuel specimens under both normal and off-normal conditions. The facility will be capable of exposing irradiated fuel specimens to a variety of temperature time histories with a maximum temperature of 2000° C and experiment duration times of up to 1000 h. In addition, with appropriate modifications, the test atmosphere can be adjusted to suit programmatic demands from completely inert to a variety of chemically active agents. The fission products released by the fuel specimen will be collected and quantitatively analyzed by the use of a cold finger and a cooled charcoal trap. Some materials and operational issues need to be optimized for the long term. However, interim design and materials selection have been made in order to initiate near-term testing of irradiated highly enriched uranium (HEU) uranium oxycarbide (UCO) TRISO particles.

1. PURPOSE AND SCOPE

The goal of the Fuel Performance Off-Normal Task in FY 1991 is to demonstrate the capability of irradiated highly enriched uranium (HEU) fuel composed of uranium oxycarbide (UCO) TRISO particles to retain fission products under accident conditions. The purpose of this report is to document the progress made to date on the design, installation, and testing of the Core Conduction Cooldown Test Facility (CCCTF), which will be used for heating

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particles. The scope of this document will include the major design details of the CCCTF, the results of the furnace component material tests and their future direction, a brief outline of the operational procedure for the CCCTF, an outline of possible furnace failure modes, and a brief safety summary.

2. INTRODUCTION

The ceramic fuel concept of the Modular High-Temperature Gas-Cooled Reactor (MHTGR) has been studied for nearly three decades, and the fundamental performance and fission product release characteristics are understood to a usable degree, but excessive uncertainty in predicted fission product releases still remains. Reduction of prediction uncertainty and validation of the fuel performance models that are used to predict the coated particle integrity are the primary tasks remaining to be accomplished.[1-3]

The upcoming generation of MHTGRs such as the New Production (NP) MHTGR uses an advanced fuel design to accommodate high burn-up requirements and provide a reduced level of particle defects and heavy metal contamination. More advanced designs such as the Direct Cycle Gas Turbine MHTGR and space applications will push the operating limits of the fuel even further. The existing fuel performance models are based on extensive data, both United States and German, obtained prior to the advancement in design. Thus, certain assumptions and extrapolations were required so that the existing data base for the MHTGR could be used in conceptual designs. In the case of particle coating failure fraction, the uncertainty is unacceptably large with regard to compliance with the desired fuel accident behavior. Reduction of this uncertainty to acceptable levels and increased insight into fuel behavior under accident conditions are necessary. This will be accomplished by two tasks. The first is a series of accident condition simulations in the CCCTF. The second is to use the information from these tests to provide a statistically significant evaluation of the models in comparison with the data.

A series of capsule experiments will provide reference irradiated samples for use in the CCCTF experiments. Although there is an extensive data base from the prior core heat-up simulation testing (CHST) program, the CHST program was intended to simulate the conditions for a loss of cooling event in a large (> 2000 MWT) High-Temperature Gas-Cooled Reactor (HTGR) design. Typically, the CHST simulation transients consisted of heating ramps

from 1100 to 2500°C in time periods of about 30 h where complete failure took place in a relatively short time. In contrast, many MHTGR events involve temperatures of less than 1600°C, where failure is not expected except at times well beyond the duration of the accident. Thus, the U.S. data base that was developed for the large HTGR is lacking in the intermediate temperature range, 1200 to 1600°C, that is of most interest for designs such as the NP MHTGR. Investigators at Forschungszentrum Jülich GmbH (KFA) have examined this temperature regime for their reference fuel, and these results have been used to develop U. S. and Germany fuel failure models. Testing of the U.S.-made fuels is needed to validate the models for the U.S. program.[4-8]

2.1 CORE CONDUCTION COOLDOWN TEST FACILITY

The CCCTF will allow the thermal testing of irradiated MHTGR fuel specimens under demanding off-normal conditions. The completed facility will contain two independent furnace and data collection systems capable of simultaneous operation. The facility will be capable of exposing irradiated fuel specimens to a variety of temperature time histories with a maximum temperature of 2000°C and experiment duration times of up to 1000 h. In addition, the test atmosphere can be adjusted to suit programmatic demands from completely inert to a variety of chemically active agents. The fission products released by the fuel specimen will be collected and quantitatively analyzed. Finally, the particles themselves can be nondestructively examined, in detail, both before and after heating by an Irradiated Microsphere Gamma Analyzer (IMGA) system also in operation at Oak Ridge National Laboratory (ORNL).[3]

The specimen heating will take place in an instrumented graphite resistance heated furnace with a computerized temperature control and data collection system. The fuel specimen will be located in the central hot zone of the furnace, and a sweep gas of predetermined composition will slowly flow past the specimen upwards toward the fission product collection systems. The furnace and some of its support systems will be located in a hot cell during heating.

Two different and independent systems are available for the collection of the fission products released from the test specimen. The first is a cold finger assembly that is located within the furnace just above the fuel test specimen. This assembly is water cooled and provides a cool surface for the condensable fission products to plate-out on. During furnace

operation, the cold finger assembly can be withdrawn from the furnace, the deposition surface removed and replaced, and the cold finger assembly reinserted into the furnace. A combination of valves and purging systems will prevent interruption of furnace operation or the introduction of contaminates. This capability will provide information on the time release history of the fuel in addition to the aggregate metallic fission product release. The second fission product collection system is an external cold trap assembly for the collection of the noble fission gases. The sweep gas from the furnace will be routed through a cryogenically cooled charcoal trap that will adsorb the inert fission gases. The traps will be constantly monitored for their activity, providing a time record of the total fission gas release. The traps will be located in shielded containers outside the hot cell to keep the background radiation levels as low as possible.

The entire system is highly automated, with computer-controlled temperature data collection and furnace temperature control. The data collection times can be varied to suit the demands of the experiment, and the collected data are stored on a computer hard disk in a format that will allow easy access to the information. After completion of the experiment, the data will be copied and stored outside the computer system to prevent possible loss of information due to later computer problems. Temperature control input can be selected from three different furnace temperature measuring devices. Available for the control loop are two internal thermocouples of differing types and an external optical pyrometer.

Automation of the many CCCTF operations will aid in the execution of routine tasks and will reduce the possibility of operator fatigue and errors during long run times. Computer sequencing of the initial furnace purge and fill operations of the furnace will aid in the assurance of a clean initial atmosphere. Fuel specimen elevators will simplify furnace loading and unloading operations, and computer-scanned alarms will notify the operator in case of problems.

A system diagram of the CCCTF is shown in Fig. 1. Note that the furnace is contained in the hot cell. The cold traps are located outside the hot cell to aid in the reduction of the background radiation. The furnace and its sensors, along with the cold traps, are tied into the computer control and data collection system; the detectors have their own computer and storage system. The purge gas is a once-through system with the hot cell ventilation system handling the exhaust from the traps.

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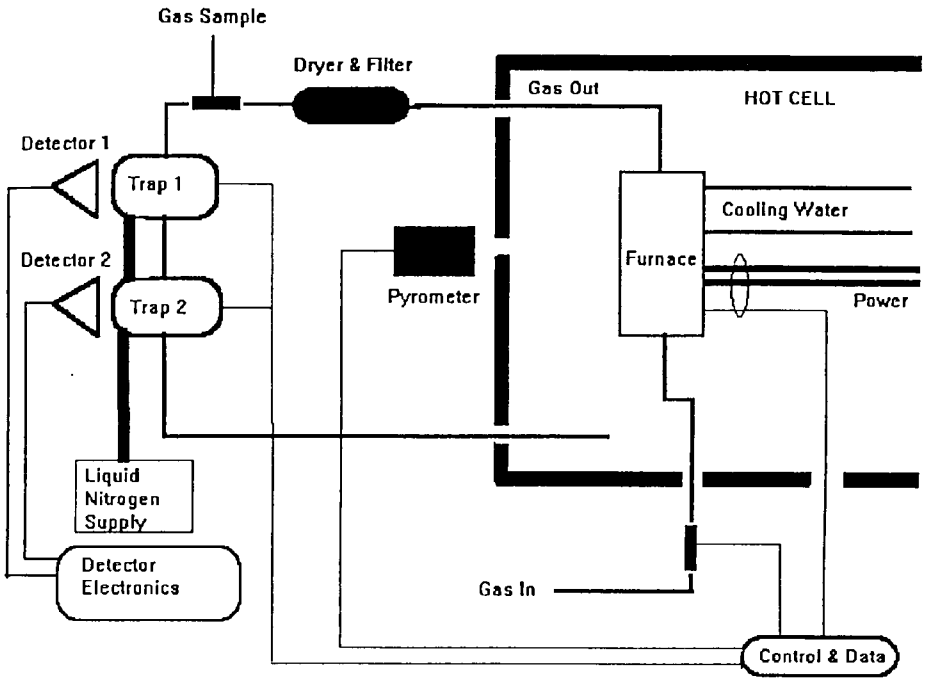

Fig. 1. CCCTF system diagram.

3. MAJOR CCCTF COMPONENTS, EQUIPMENT, AND SUPPORT

A host of components and subsystems make up the CCCTF along with several support services. The CCCTF is located in a hot cell facility at ORNL. The furnace and its subsystems are located in the hot cell itself, while the controlling systems and cold traps are located just outside the hot cell. The operator can view the furnace during operations through the hot cell window and can verify that the large mechanical components are in their proper locations. The following major components form the backbone of the system:

1. high-temperature graphite resistance heated furnace, cooling water supply, and its power supply;
2. computer/real time processor (RTP) furnace controller and data logger;
3. optical pyrometer;
4. boron graphite thermocouple;
5. tantalum-sheathed type C thermocouple;

6. vacuum system;
7. chilled water recirculator for the cold finger;
8. helium sweep gas supply, purifier, and control;
9. residual gas analyzer (RGA);
10. two NaI(Tl) detectors, their electronics, and cryogenic fission gas traps with their cooling system;
11. cold finger with deposition cup insertion/removal system;
12. deposition cup shield and handling system for removal from hot cell;
13. fuel specimen insertion/removal system; and
14. fuel specimen shield and handling system.

The facility also contains a considerable number of ordinary components such as tubing, valves, filters, connectors, etc.

The major CCCTF components are either stock, commercial items or modified, commercially available items. The use of such items should help prevent long downtimes due to component failure and can save considerable expense. The noncommercial items used in the CCCTF are generally of simple design and made of common laboratory materials such as stainless steel, graphite, and tantalum. As the program progresses to more complex furnace environments, such as high moisture level, more specialized materials may be required for the furnace interior.

To ensure reliable and consistent operation, a number of minor components will be periodically replaced, either after each experimental run, or after a number of runs. These components may become contaminated by the released radioactive materials or may degrade after long-term exposure to high temperatures. Components that may become contaminated with radioactive or chemical agents will be monitored or replaced after each experiment to ensure that cross contamination between experiments does not occur.

At the present time, the planned replacement cycle of the furnace internal components is based on both uncertainties about the nature of the fission product deposition pattern and component degradation. If experience reveals that only the components in immediate contact with the released fission products need to be replaced after each run, then the number of components needing replacement after a run will be reduced considerably. This is favorable from both a hot cell labor cost and reduced test cycle time viewpoint.

Other components will require periodic servicing as necessary to ensure reliable operation. These items are staples such as vacuum pump oil, lines, filters, etc.

Operation of the CCCTF will require standard consumables. The major items are expected to be:

1. electric power,
2. helium sweep gas (selected purity),
3. liquid nitrogen for cold traps,
4. dry nitrogen (or argon) backfill gas (selected purity), and
5. process water for furnace cooling.

None of these items are expected to present any problems as long as care is taken to ensure their supply and quality.

3.1 CCCTF SUPPORTING SERVICES

In general, the CCCTF will require the supporting services of several laboratory groups besides the immediate CCCTF group. Before the fuel sample is placed in the furnace, a preheating examination will be performed by the post-irradiation examination (PIE) group on the specimen to characterize its physical condition and radionuclide inventory. Both destructive and nondestructive testing can be performed on the specimen and samples of the specimen in the preheating examination.

Destructive testing will include the preparation of metallographic mounts to examine fuel particle physical performance and scanning electron microscopy (SEM) mounts to determine the particle internal fission product distribution after irradiation. Also possible is the chemical analysis of the particle; this will provide an estimate of the beta decay radionuclides. Nondestructive analysis on unbound particles will be performed by the IMGA, which will determine the individual irradiated particle inventory of gamma-emitting radionuclides.[10] Compacts will be gamma analyzed as a unit.

After the heating cycle, the sample will return to the PIE group, and the same characterization tests can be performed to determine the effects of the heating cycle. If a significant amount of material was released by the sample, the IMGA system will allow the nondestructive estimation of the amount lost. However, the expected inventory releases for fuel at the exposure temperatures planned for the near future will be a very small fraction, less

than 10^{-4}, of the total inventory. This will be undetectable by the IMGA system. Thus, mass balance calculations comparing the collected fission products and the difference in particle radionuclide inventory may not be possible for high-quality fuel at temperatures below 1800° C, unless a particle failure occurs.

The measurement of the collected fission products is of major importance for determination of fuel quality and performance. This task is easiest with the cold traps because the fission gases are concentrated in a relatively small space that is easily viewed by the sodium iodide detector. Tests using ^{85}Kr will be used to calibrate the cold trap system. The measurement of the fission products plated out on the furnace components will be more difficult because of the large areas and very low expected levels of activity. Several methods have been proposed to do this. The parts can be gamma counted as they come from the furnace, taking care to consider the geometric problems; they can be cut up into small pieces and measured; the radionuclides can be leached off the parts and the liquid counted in a well detector; or some combination of the above methods can be employed. Because it probably will not be possible to obtain an accurate mass balance measurement, great care must be taken in the gamma counting. A cesium tracer test was performed to determine the deposition pattern of the cesium on the cold finger and the furnace interior components. This test will also evaluate the possible gamma activity counting problems and determine the leaching usefulness.

3.2 HIGH-TEMPERATURE FURNACE AND ITS SUBSYSTEMS

The CCCTF furnace is a modified, commercially available graphite resistance heated furnace with an internal muffle tube to provide isolation between the furnace elements and the fuel test region.[12] The axis of the furnace is vertical, allowing access to the heating region from both the top and bottom. In the present configuration, the fuel specimen is loaded from the bottom, and the cold finger assembly is inserted from the top. See Fig. 2 for the basic furnace layout. The basic furnace is expected to be capable of operation to as high as 3000° C, but because of material limitations and the expected use of chemically active atmospheres, the modified version is limited to approximately 2000° C at the present time.

The furnace is composed of four essential components. The first component is the furnace body. This is an aluminum shell with water cooling that encloses the internal components and

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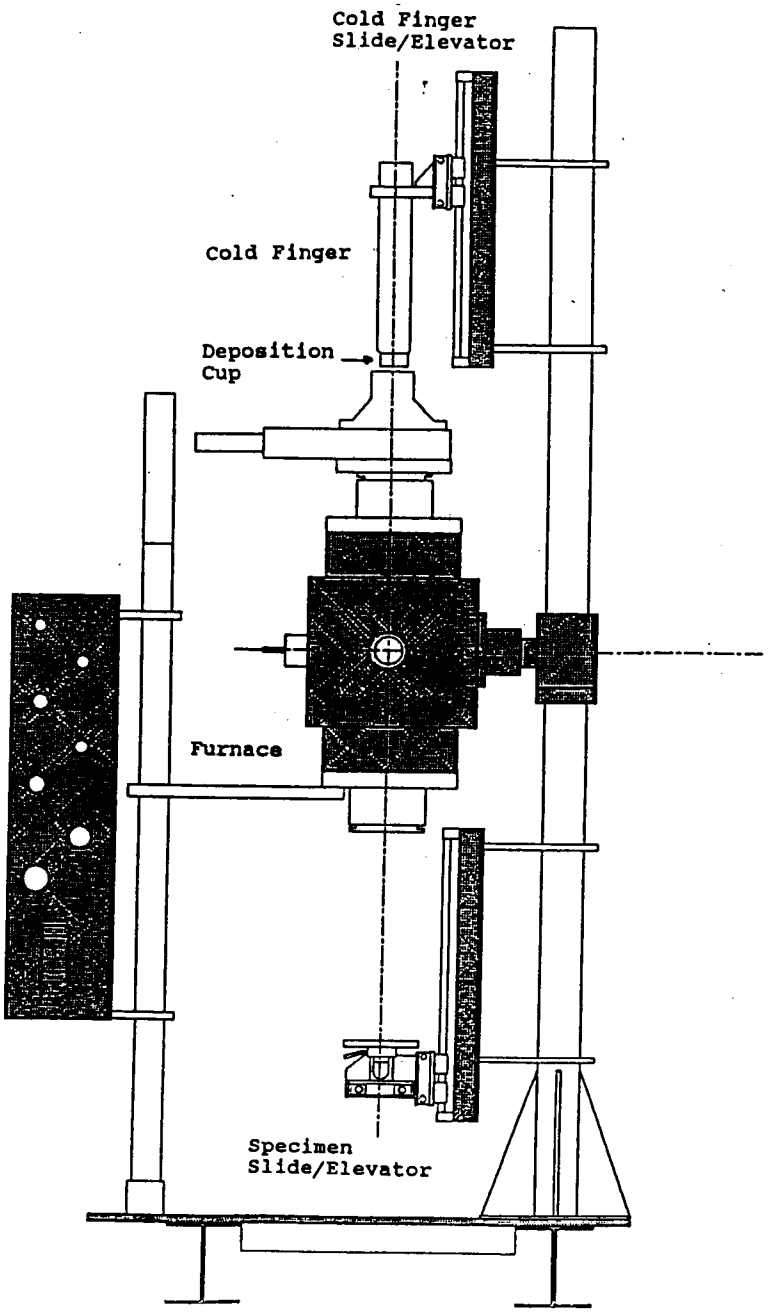

Fig. 2. Basic furnace layout.

provides an isolation boundary. Just inside the shell is a layer of carbon felt insulation and an aluminum insulation shield. Next, moving radially inward, is the cylindrical graphite heating element, separated from the insulation by a small gap. Within the heating element, also separated by a gap, is the muffle tube that provides a barrier between the furnace heating and insulation components and the fuel specimen test region. See Fig. 3 for a cross-sectional view of the basic furnace design.

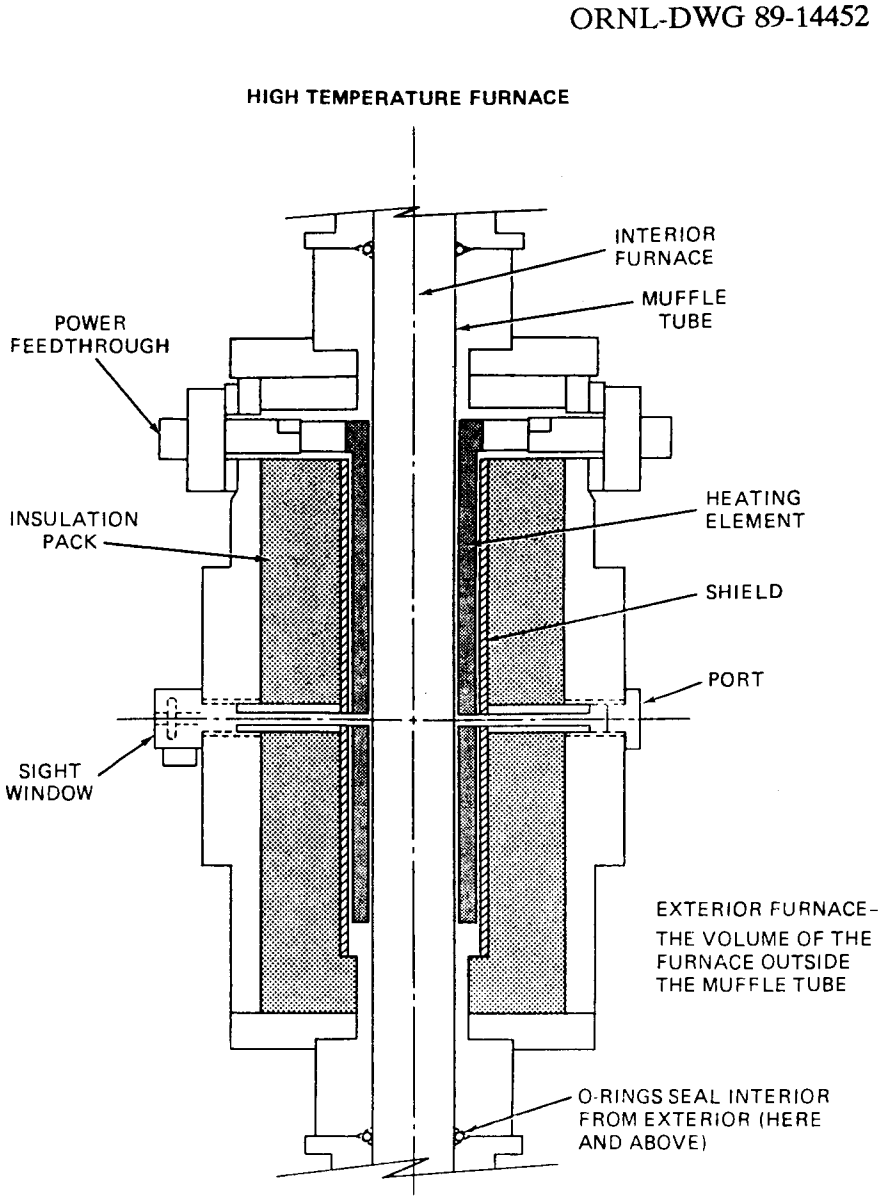

Fig. 3. Furnace cross section.

The major modifications made to the stock furnace include the muffle tube, the control system, and the furnace upper and lower flanges. The heating elements and insulation are unchanged and can be purchased from the manufacturer on a short delivery schedule. The modifications to the furnace flanges are those necessary to accommodate the redesigned muffle tube, the cold finger, and the fuel handling mechanism.

3.2.1 Muffle Tube

The muffle tube is manufactured from refractory materials and is approximately 61 cm long and 7.6 cm OD with a 0.64-cm-thick wall. The purpose of this component is to provide isolation between the fuel test region and the furnace heating elements, insulation, and support components. The releases of interest for this facility are the noble fission gases and the condensable fission products. Since the noble gases do not strongly interact with the furnace materials and are constantly being purged from the furnace by the sweep gas, the muffle tube does not have to form a perfect gas seal between the furnace regions. As long as there is no significant pressure differential between the two furnace regions and an adequate sweep gas flow, the noble gases are expected to be swept from the furnace to the cold traps. Exhaust from both regions of the furnace will be combined together into a single flow path outside the furnace before being routed to the cold traps.

The case for the condensable fission products is quite different from that of the noble gases. They can interact with the furnace material and can diffuse into and be trapped in the muffle tube material. They will also plate-out on the muffle tube as they enter the cooler regions of the furnace which, in effect, form a thermal barrier to the further transport of the condensable fission products. In this situation the muffle tube needs to act as a barrier to the diffusion of these substances only in the hot areas of the furnace, as long as the sweep gas flow is low and a large axial temperature gradient is maintained. Because these substances will have plated out either on the cold finger or the central muffle tube and fuel holder region before they reach the cold ends of the muffle tube, a gas-tight seal is not required on the cooler ends of the muffle tube. Thus, for the inert atmosphere case, the muffle tube can be selected for its ability to retain condensable fission products at the higher temperatures without the need for a perfect seal at the cooler ends of the tube.

These concepts can be exploited in the design of the muffle tube by the use of a two-piece muffle tube. The design selected for initial tests is a muffle tube with an inner liner. The

outer muffle tube provides structural support and limited furnace isolation while the liner is relieved of major stresses and can function as a barrier to the diffusion of condensable fission products into the supporting muffle tube and furnace. This concept also has the advantage that the liner can be more easily removed remotely should it become heavily contaminated. This separation of function, at least in the benign atmosphere cases, offers considerable design and operational flexibility. For high moisture levels where test atmospheres are more hostile to the furnace components, a better gas seal between furnace regions, perhaps by the use of a dense silicon carbide muffle tube, will be required.

Two muffle tube designs were investigated in the development of the furnace: an impermeable, aluminum oxide, one-piece muffle tube and a two-piece muffle tube composed of a semipermeable outer graphite support tube and a loosely fitted tantalum liner tube. Both designs were tested for compatibility with the graphite furnace environment. The aluminum oxide tube underwent carbothermic reduction and failed near the high-temperature graphite heating elements. This result occurred during a high-temperature test that reached a peak temperature of over 1900° C at a helium pressure of 1 atm for a period of several hours. The results of this test are shown in Fig. 4. Both the failed muffle tube and the damaged heating element are shown. The failure of the muffle tube was due to the enhanced decomposition of aluminum oxide in a carbon-rich atmosphere (due to the graphite heating element). The released oxygen and aluminum attacked the heating elements producing carbon dioxide and aluminum carbide. The oxygen concentration in the helium was 25 ppm and is not considered to be responsible for more than minor effects.

Later operation of the furnace revealed that the aluminum oxide muffle tube would not be stable for long-term operation above approximately 1350° C in the desired test atmosphere. Investigators at KFA-Jülich also found that aluminum oxide was not a suitable material for their furnace design even though they used tantalum rather than graphite heating elements.[8]

After the poor results with aluminum oxide, the two-piece graphite/tantalum muffle tube was tested. Tantalum has been used extensively in high-temperature furnace design, and graphite is a common refractory material, so major problems were not expected when operating in an inert atmosphere.[9] The only concern was the rate of the tantalum/carbon reaction. Work by the investigators at KFA-Jülich indicated that the reaction rate was acceptable, although it was not quantified.[8] After approximately 12 h of exposure at 1600° C in a helium atmosphere, in three heatup and cooldown cycles, no degradation of the graphite tube or

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Fig. 4. Failed aluminum oxide muffle tube and damaged heating elements.

tantalum liner was noted. A very light, golden layer of tantalum carbide was observed on the tantalum where it was in contact with the graphite in the high-temperature region.

Because of these results and the need to initiate testing in a timely fashion to support the Record of Decision (ROD), exploration of other options was postponed, and the reference design for the muffle tube was selected to be the graphite outer tube with an internal, loosely fitted tantalum liner. The graphite tube is sealed at both ends to the furnace upper and lower flanges by "O" rings to enhance isolation between the fuel test region and the furnace interior. The liner provides the barrier to metallic fission products and can be removed from the furnace remotely. Noncondensable fission products are not expected to result in contamination problems within the furnace. The ability to remotely remove components likely to be contaminated during operation, such as the liner, is an operational advantage that can speed up turnaround and reduce personnel radiation exposure.

Several muffle tube designs are available for future study or enhancement, and these designs largely favor graphite and tantalum as the structural materials for high-temperature, inert atmosphere operation. The muffle tube design is likely to change as the furnace temperature range and sweep gas composition changes later in the experimental program. As the furnace operational temperature becomes lower and the atmosphere becomes chemically active, erosion and attack of the muffle tube will become important considerations. The options currently identified for use or future consideration are summarized below:

1. A two-piece muffle tube has the advantages that it can provide metallic fission product isolation and the contaminated inner liner can be remotely removed with the current furnace design. In this option, which is the current design, a graphite muffle tube surrounds the loosely fitted, thin refractory metal, internal liner to prevent an exposed graphite surface in all but the very cool parts of the furnace. This liner does not completely cover the muffle tube; a small area on the upper and lower edges of the muffle tube is still exposed, but the area exposed is very small compared to the total wall area and is at low temperature (80°C). This liner acts as a barrier to the metallic fission products and allows only a small leakage of the fission gases, which diffuse around the outlet end of the metal liner into the annulus between the liner and the outer muffle tube. The metals of interest for the liner are tantalum and tungsten. The upper temperature limit of this design is probably determined by the mechanical strength of the liner at the test

temperature—too high a temperature and the liner will sag and buckle. Since the metal is in contact with the graphite, metal-carbon reactions will occur. If carbides form too extensively over the course of the experiment, they may embrittle or consume the liner. This is a concern if the reaction rates and carbon diffusion rates are high enough.

If the chemical reaction/diffusion rates are low enough and the liner does not bind itself to the graphite tube, the ability to remove the contaminated liner remotely from the system is attractive. Short test runs of a few hours using a 0.5-mm-thick tantalum liner revealed only a very light surface film of carbide formation. KFA-Jülich investigators have successfully used tantalum for their fuel testing furnace construction and to support graphite-coated fuel elements during their heatup experiments. They report that the carbide reaction rate is acceptably slow.[8]

2. A one-piece, unlined muffle tube constructed of graphite is a simple and reliable design. This option has the advantages of simplicity, good chemical properties, and very high temperature operation. The drawbacks are the limited isolation between the interior and exterior regions of the furnace due to the material porosity and the high metallic fission product absorption properties of the graphite. The high gaseous permeability and metallic fission product absorption of the muffle tube may limit the collection efficiency of the gas trap and cold finger. Also, this muffle tube cannot be remotely removed with the present furnace design. The permeability and sorptivity of graphite have resulted in rejection of this design, but it can form the basis of a multicomponent muffle tube as discussed above.
3. One way to improve option 2 is to coat the inside of the graphite muffle tube with pyrolytic carbon. In tests at low temperatures, this coating reduced the porosity of the graphite by two or more orders of magnitude. If this result applies at the higher temperatures, this option may greatly reduce the isolation problems associated with the graphite porosity. The present difficulty is that only a thin layer of carbon can be coated on the muffle tube; thick layers appear to spall off easily. The diffusion of metallic fission products remains a concern. If the diffusion of the fission products into the tube wall is reduced by this coating, then the impact on cold finger collection efficiency will be less, and major furnace contamination is much less likely. However, pyrolitic carbon may not be any better than graphite in this respect. One new problem may be the contamination of the muffle tube by a halogen; one vendor claimed that 25 ppm chlorine will be introduced into the surface of the graphite muffle tube during a precoating cleaning process and that it may start to

leach out at 1200°C. Perhaps the chlorine can be baked out at higher temperatures. Finally, with the present furnace design, this muffle tube cannot be removed remotely. This option has not been tested yet.

4. Another option is to eliminate the graphite muffle tube altogether and use a tantalum or tungsten muffle tube. The drawback to this approach is a temperature limitation of < 2000°C and possible embrittlement or creep and buckling of the muffle tube during long runs. It is likely that this system will have the best sealing and isolation of all the options. Since the atmosphere in the furnace is purged with helium (for the first part of the experimental program) and the metal is not in contact with the graphite heating elements or insulation, the chemical reaction and embrittlement problems should be reduced from that of the liner option. KFA-Jülich investigators have used tantalum for their furnace construction and claimed that the furnace was good to 1800°C.[8] The heat conduction losses by the metals are no more than that due to the graphite and, in fact, may be much less. This is because of the much thinner wall used in the construction of the muffle tube and, in the case of tantalum, a lower heat conductivity than graphite. This option has the usual single-tube disadvantage in that it cannot be remotely removed. This option has not been tested.
5. A variation of the above option is a refractory metal muffle tube with a refractory metal liner. This option should be similar to the previous option with the advantage of the remote handling of the liner. This option has not been tested.
6. The refractory metals and graphite may not be suitable for operation in chemically active atmospheres. In these cases the use of other refractory materials may be possible. They could be used as a single-component muffle tube or as a liner for a multicomponent muffle tube. Zirconium oxide is one candidate that can withstand high temperatures and many chemical agents. Its disadvantage may be failure due to thermal shock and carbothermic reduction as with aluminum oxide. This material has been used in other high-temperature experiments at ORNL with chemically active atmospheres.[13] Results have been good, but the duration of the experiments has been no more than a few hours.
7. Silicon carbide is also a possible material for use in both inert and chemically active atmospheres. It has good thermal and chemical properties in the moderate-temperature regimes. It is also known to be compatible with graphite, so that a two-piece muffle tube design is possible. The KFA-Jülich investigators are reported to be using this material for

their water ingress fuel tests with positive results. It has the additional advantage that in tests with only trace amounts of oxidants representing NP-MHTGR dry condition accidents, the oxygen potential is not driven to unrealistically low levels by metallic gettering. This option has not been tested at ORNL.

8. Finally, a vitreous carbon muffle tube is a possibility. At the present time, little is known about this option. The vendor claims ability to withstand very high temperatures, good isolation properties, and good chemical resistance. It is, however, rather expensive and has a long procurement lead time.

Of the eight options, the metallic muffle tubes, metallic liners, and non-graphite ceramic tubes form good barriers to the metallic fission products and are expected to absorb the fission products to a much lesser extent than the graphite. This is expected to help with the cold finger collection efficiency. The simple graphite muffle tube suffers from rapid diffusion of gaseous fission products, sorption of metallic fission products, and potential furnace contamination problems. However, with a properly engineered liner, it is expected to be satisfactory for initial testing, which is needed prior to the ROD.

3.2.2 Sweep Gas

Helium sweep gas will flow through the furnace heating and insulation region, and either helium or a gas mix will flow through the muffle tube. Helium gas will also flow through the optical window region to prevent condensation of impurity vapors on the window. This window will provide visual access to the muffle tube exterior, allowing the use of an optical pyrometer for temperature determination. At the exit of the furnace, the flows will be combined together and passed through a set of filters to remove any particulates. Next, the sweep gases will be passed through the cold trap assembly to collect the noble fission gases. The remaining gas will be routed back to the hot cell and handled by the hot cell ventilation system.

The helium sweep gas circuit includes an upstream helium purifier to ensure that the oxygen concentration is held at very low levels, less than 1 ppm. Oxygen removal is achieved by passing the helium supply gas over a heated (800° C) getter consisting of 425 g of titanium. Low oxygen levels are required to hold material degradation to low levels, so that long experimental run times are possible. The helium purifier has a self-contained oxygen monitoring gauge, so that the quality of the sweep gas may be easily observed. Two mass flow

transducers in the gas distribution and flow system monitor the flow rates into the furnace heating and muffle tube regions. Flow rates are approximately 0.4 L/min through the muffle tube, 0.2 L/min through the furnace heating region, and 0.05 L/min through the window region. These flows appear to be adequate for operational purposes, but they have not been explored in detail and may be changed depending on the experimental conditions. The gas flow circuit also allows the furnace heating and muffle tube (fuel test zone) regions to be isolated from each other for separate purging and filling operations.

3.2.3 Temperature Control and Logging

The furnace temperature will be controlled and monitored by the computerized control system, which represents a major modification to the stock furnace control system. This system consists of three major parts: a computerized controller and its data processing software, the temperature-sensing elements, and the power supply and its electronics. The computer subsystem is composed of a commercially available computer, digital controllers, and a flexible software package.[11] In addition to controlling the furnace temperature, the system also logs the temperature history of the furnace and controls the sweep gas inlet and exhaust valves; at the present time, the flow rates must be manually controlled. The system can be programmed to execute a range of furnace temperature time histories and to log the data on an appropriate monitoring interval. Important operational information is constantly updated and displayed on the video monitor. The display and data formats are flexible and can be easily modified to include new variables as the experimental program develops.

Three independent temperature-sensing elements will measure the furnace temperature. The muffle tube external temperature will be monitored by a boron graphite thermocouple (BGT) and by an optical pyrometer through the furnace window. The internal muffle tube temperature near the fuel specimen will be monitored by a tantalum-sheathed type C thermocouple. The furnace control system can use any one or combination of these sensors as the control input. In practice, the BGT provides the most stable temperature control, although with any controlling element, the temperature fluctuations are only of the order of a few degrees. The temperature difference between the specimen holder and the exterior of the muffle tube is approximately 50°C for the reference muffle tube. Thus, if it becomes necessary to control the furnace by the BGT because of unforeseen temperature sensor problems, a compensation can easily be applied. All temperature readings will be continuously logged, both in computed temperature and actual millivolt readings, so that back calculations and checks will be possible.

3.2.4 Furnace Subsystems

The power supply for the furnace is a solid-state controlled transformer rectifier system capable of delivering the low voltages and high currents needed by the furnace. It is a rather bulky system, and it will be located well away from the rest of the system electronics to minimize any electrical noise or coupling problems. Its physical location will be on the floor above the hot cell, so that the power leads can come directly through the hot cell ceiling to the furnace. This power supply is essentially unchanged from the stock version.

Other subsystem components are also part of the furnace system and represent modifications to the stock furnace. Special sliding tables and elevators aid in the loading and unloading of the irradiated fuel specimen, as well as in the insertion and removal of the cold finger assembly. The location of these devices is shown in Fig. 2. Additional thermocouples will monitor the furnace external surface temperatures, and a process water system will provide cooling for the furnace body. A recirculating, chilled water system will provide the cooling required by the cold finger. This system will also be located above the hot cell with the power supply. A vacuum system, located just outside the hot cell, will aid in the purging of the furnace and sweep gas lines as well as aiding bakeout operations. Safety interlocks, power supply interrupts, check valves, and pressure relief valves will guard against system failures, unsound operations, and operator error. Finally, structural components will support and align the furnace and its subsystems.

3.3 COLD FINGER ASSEMBLY

The cold finger assembly provides a cooled surface within the furnace and near the fuel specimen on which condensable fission products released from the fuel can deposit. The fission products of interest for collection by this assembly are the radioactive isotopes of I, Cs, Sr, Ag, and Te. The cold finger assembly can be periodically withdrawn from the furnace, the deposition surface replaced, and the assembly reinserted into the furnace. A series of samples taken throughout the experiment duration can provide an approximate release history.

The cold finger assembly consists of a water-cooled support cylinder, a thermocouple, a motorized screw drive, and a deposition cup. See Fig. 5 for a cross-sectional view of the assembly. The assembly is aligned vertically along the furnace axis and is lowered into and withdrawn from the furnace by a special remotely controlled elevator and slide assembly. A

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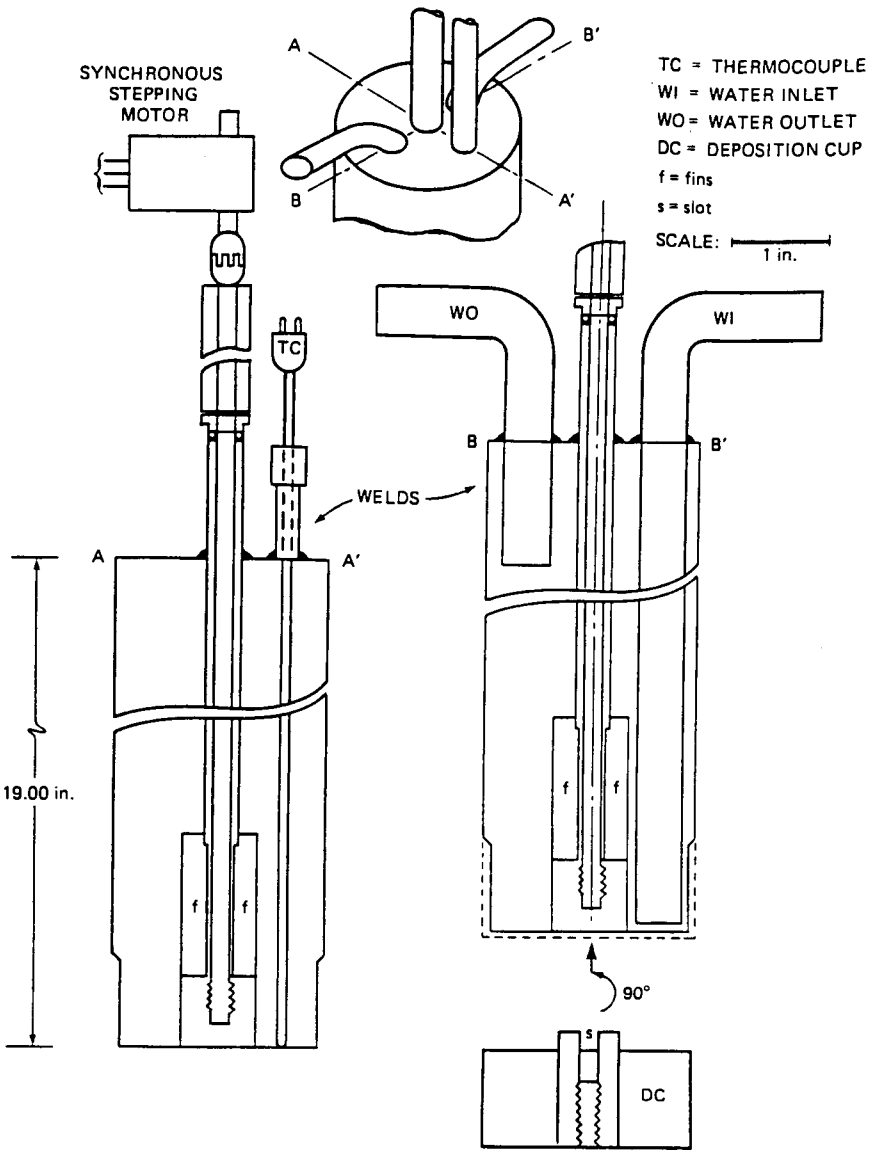

Fig. 5. Cold finger assembly.

A water-cooled gate valve, gas evacuation lines, and a series of "O" ring seals that engage the support cylinder ensure furnace isolation during the operation of the cold finger assembly. The motorized screw drive mechanism extends through the support cylinder and provides a way to attach and remove the deposition cup. The deposition cup is internally threaded to receive the screw drive shaft. Driving the motor in one direction engages the threads of the deposition

cup and draws it firmly onto the support cylinder; driving the motor in the opposite direction releases the cup from the support cylinder. For installation, the deposition cup will be held in a jig by the hot cell manipulators; for removal, the cup will be dropped off into a special container.

The support cylinder is hollow and will have chilled water flowing through it during operation. Its temperature, approximately 15°C, will be constantly monitored by a type K thermocouple and the reading logged in the data base. Heat transfer from the deposition cup to the support cylinder will be through the contact surfaces. The temperature of the surface of the deposition cup is determined by both the temperature of the furnace and the axial distance of the surface of the cup from the horizontal centerline of the furnace. Previous measurements of the cup surface temperature versus furnace peak temperature and axial distance will allow the determination of the proper cup axial location for a specified temperature. The temperature of the cup will most likely be held at approximately 350°C; the actual temperature will be a compromise between the amount of material collected by the cup and the amount that remains attached to the wall of the muffle tube and other furnace components. The deposition cup will be copper plated to aid in the analytic leaching process; the reflective copper surface also aids in minimizing the radiative heat loads.

3.4 SPECIMEN SUPPORT ASSEMBLY

The fuel specimen is located within the muffle tube, near the geometric center of the tube. A region approximately 10 cm in length and 7 cm in diameter, located near the geometric center of the muffle tube, forms the central heating region. The temperature variation over this region is small, approximately $0.013*T_{peak}$, so an essentially isothermal region is available for the heating experiments.

The irradiated fuel specimen will be supported by an assembly that extends from the furnace bottom, up into the central heating zone. This assembly will consist of three parts: a lower support, a thermocouple, and a fuel holder. The first part is the lower support. This component is, for the most part, a hollow graphite rod through which the sweep gas can flow and the thermocouple routed. The thermocouple is a tantalum-sheathed type C, which will be located as near to the fuel sample as is practical, and will provide the basis of the sample temperature measurement. The fuel holder is attached to the lower support and holds the fuel

specimen in the central hot zone of the furnace. It may also be designed to direct the flow of the sweep gas near the fuel sample as well. The fuel holder is a custom component that is likely to be different for each fuel specimen.

For the initial tests with irradiated HEU UCO TRISO particles, the holder will be a graphite disk with blind end holes to hold individual particles. Subsequent tests with fuel compacts will provide for holding single or multiple samples.

As with the muffle tube, the sorption of condensable fission products impacts the selection of materials for the fuel holder. An additional concern is possible chemical reactions between the fuel sample and the fuel holder. A significant chemical reaction could damage the fuel particle's coatings and result in spurious fission product releases. Thus, the two primary issues for design are fuel specimen/fuel holder chemical reactions and condensable fission product adsorption. The present reference design is a graphite holder because of the chemical compatibility issue, even though the graphite is known to adsorb many condensable fission products. The adsorption is mitigated to some extent by the fact that the holder is in the hottest part of the furnace; this location may aid in the driving off of the fission products. Other designs have been and are being considered. A summary of them is listed below:

1. One can easily make an all-graphite specimen holder and lower support. The advantage of this approach is that we will have no problems with metal-carbon chemical reactions or structural strength. The disadvantage is that the metallic fission products can diffuse into and be retained by the graphite holder. This design is the reference case.
2. A refractory metal specimen holder and lower support helps to avoid the problem of fission product diffusion into the holder and support. This design would remove a possibly large fission product sink from the system. It suffers from the problems of metal/carbon reactions and the generation of carbides with the graphite-coated fuel specimen and loss of strength and creep at high temperatures.
3. A hybrid specimen holder, composed of a refractory metal holder with a graphite foil lining supported by a refractory metal lower support, can avoid the carbide reactions and reduce some of the fission product retention. However, the effect may be unimportant unless the exposed graphite surface area is very small.
4. Vitreous carbon may be useful for the construction of the holder elements. Its low porosity may greatly reduce the adsorption of the metallic fission products, and carbon

poses no threat to the fuel compacts or particles. At the present time, little is known about this option.

5. A ceramic fuel holder and support may be necessary for use in chemically active environments. Candidate materials are silicon carbide and zirconium oxide. Silicon carbide is known to be compatible with the fuel and forms an excellent barrier to the diffusion of fission products but, at this time, is not expected to be usable at temperatures above about 1200 to 1300°C for long periods of time.

Because of these issues, the optimization of the design of the fuel holder and its material will progress on an experiment-by-experiment basis. It is important to avoid any chemical reactions that could lead to fuel damage problems and corrupt data. Graphite and silicon carbide are best understood in this regard.

3.5 FISSION GAS TRAPPING

The gaseous effluent from the furnace passes through a cryogenic trapping system to permit the removal of the inert fission gases and the measurement of their radioactivity. The gases of interest for this facility are the radioactive isotopes of krypton and xenon. After exit from the furnace, the sweep gas will be routed through a filter to remove the particulates and any elemental iodine. Next, the gas will be routed to the cold trap assembly. The cold trap assembly will consist of two separate charcoal trap systems with associated cooling, detectors, and electronics. The first trap is designed to do the bulk of the collection, and the second trap will be used to estimate the collection efficiency of the trap system and to act as a backup in the case of failure of the first trap. The trap system can also be reconfigured so that the first trap operates at a higher temperature than the second trap. This configuration would allow the differential collection of xenon and krypton, with xenon captured in the warmer trap and krypton captured in the cooler trap. Xenon has the disadvantage that its isotopes are short lived and may not be available in sufficient quantities in the fuel specimens to be used in the testing.

In addition to the measurement of the radioactive xenon, it may be possible to measure the stable xenon releases, as well, by the use of a mass spectrometer. This may be of use in the estimation of iodine releases because xenon is a daughter product. If so, reactivation of the fuel sample may not be necessary for the study of the short, half-lived iodine isotope. These possibilities are currently under study.

Each cold trap consists of a cylindrical charcoal bed retained in position by wire-mesh screens at each end. The charcoal bed is cooled with liquid nitrogen, and the temperature is monitored by an embedded thermocouple. Beneath the trap assembly is a sodium iodide detector that monitors the gamma activity of the collected gas. See Fig. 6 for a cross-sectional view of the trap. In operation, the fission gas is continuously trapped, and the detector signal

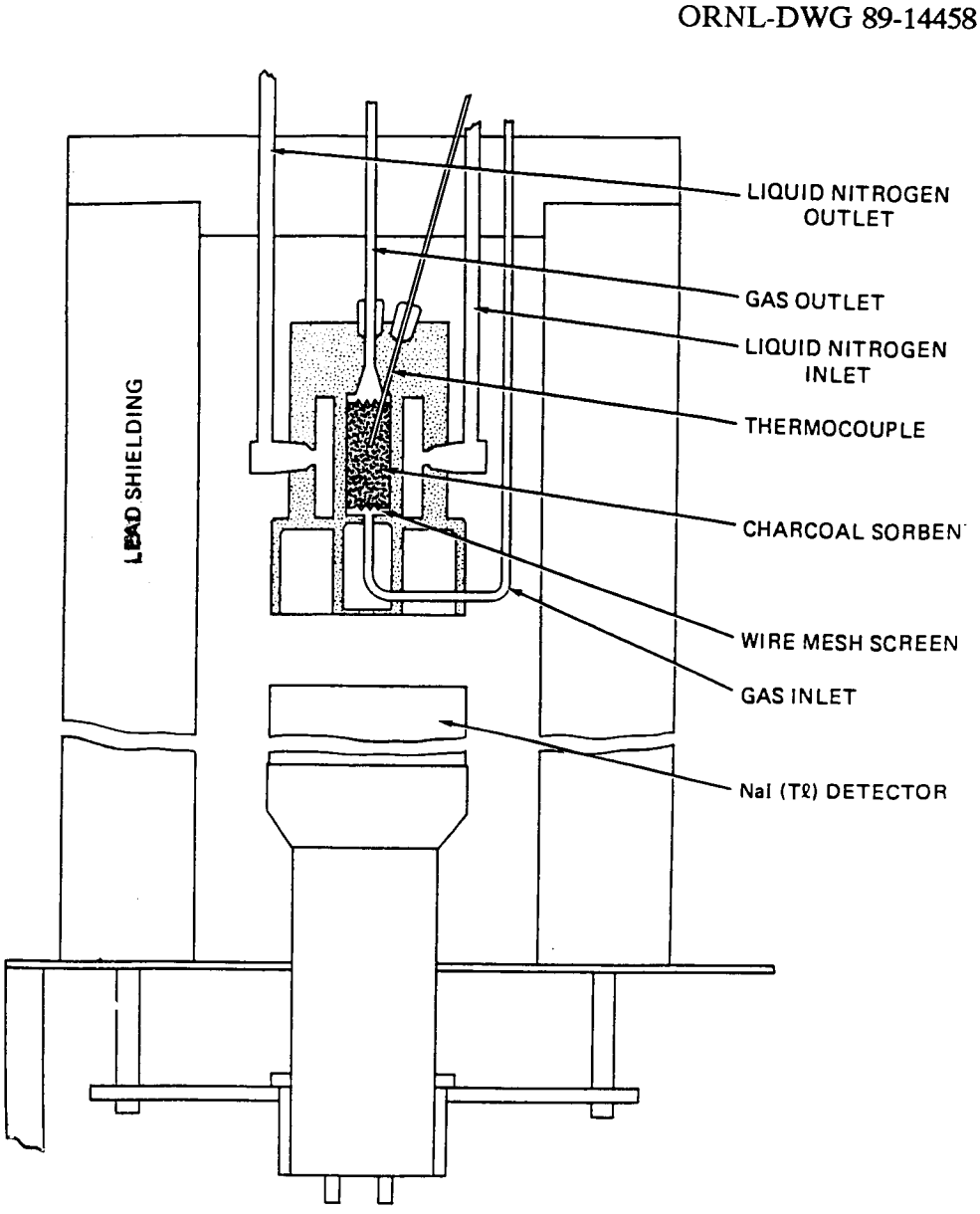

Fig. 6. Cold trap cross section.

yields a time profile of the cumulative release of the fission gas from the test specimen. The detector signal will be monitored by a dedicated computer that will also provide the necessary computational effort required to decompose the energy spectrum. A strip chart recorder will continuously record the detected trap activity and will function as a backup system. Together, these components will form the heart of a multichannel analyzer that will provide details of the observed spectrum. At the end of an experiment, a heating jacket surrounding the trap body will be used to drive off the trapped gas in preparation for the subsequent experiment.

Because the expected levels of fission gas release are small, care must be taken in the location of the traps. The CCCTF has the trap system located just outside the hot cell in which the furnace is located. Both traps are located in individual lead pigs to provide a measure of shielding from local background radiation.

3.6 DATA COLLECTION

This facility has been developed to provide real-time monitoring of the furnace temperatures and both programming and monitoring of the desired temperature ramp up, ramp down, and hold points. The data collection interval is programmable and can be tailored to the needs of the current experiment. A real-time display will show the current status of the furnace, its gas flow valves, and the temperatures of the various measuring devices. This information will be constantly collected and stored in a hard disk data base. At the termination of the experiment, this data base can be transferred to a floppy disk for use by another program participant and for storage. Portions of this information can be printed out by the system computer, as desired, or the entire data base can be entered into commonly used spreadsheet software for more detailed manipulation. The system is flexible, and additional calculations, sensors, and alarms can be added as the CCCTF matures.

Monitoring of the cold traps will be by a separate, dedicated, multichannel analyzer computer system with a commercial gamma activity analysis software package. The quantitative determination of the specimen fission product gas releases will be by gamma ray spectrometry. This computer system will store its information on a hard disk for later retrieval; a visual display will also be provided for real-time monitoring. A continuous strip chart recorder will also monitor the detector output and will provide a redundant record of the trap activity.

Monitoring of the furnace atmosphere will be by periodic mass spectrometric determination of impurities in the helium purge gas supplies and periodic mass spectrometric

determination of output carrier gas composition by the residual gas analyzer. This function is not automated at the present time; the data record will consist of a series of log book entries.

Monitoring specimen condensable fission product releases will be by collection of metallic fission products on a cold finger deposition cup within the furnace as described previously. The collected material on the cup will be gamma counted and leached off to determine if other non-gamma emitting fission products are present. Laboratory supporting services, under CCCTF guidance, will provide analysis of the fission products collected by the cold finger and deposited within the furnace on the interior components.

Routine facility operations, start-up and shut-down times, fuel specimen characteristics, etc., will be recorded in the facility operations log book by the operator in charge. Other information such as furnace component materials, quality tests, calibration results, etc., will be stored in accordance with quality control needs, and easy access will be provided to the CCCTF personnel.

The CCCTF is designed to have a fully programmable control and data collection system for hands-off, continuous operation within user-specified limits. Continuous data retrieval and recording and subsequent digital or hardcopy output are capabilities of this facility.

3.7 EMBEDDED SAFETY FEATURES OF THE CCCTF

The CCCTF is protected by several safety systems independent of its experimental program. The furnace power supply will shut down automatically if the furnace body cooling water supply is interrupted or if an overpressure condition occurs in the furnace. Following an automatic shutdown, the system can only be reset manually. An overcurrent limit will prevent excess furnace power supply current from flowing, should a fault occur. The upper gate valve is interlocked to prevent its opening without the cold finger in the proper position. The furnace specimen elevator cannot be operated with the locking jack in position. Check valves and shutoff valves will be in the source gas and water lines to prevent backflows. The furnace can be quickly and safety shut down by the interruption of the main power supply or by a computer command.

In addition to these "hard" limits, other monitoring and checks on furnace operation are possible and desirable. The furnace temperature is monitored by three separate sensors providing independent indications of furnace temperature. The gas flow to both the furnace interior and exterior is monitored, along with the manifold pressure, to provide an indication

of overall gas flow performance. The furnace off-gases will be examined on a periodic basis by a mass spectrometer RGA to determine purge gas composition and to monitor possible furnace degradation. Finally, the system software is capable of safety alarms and any special system shutdown needs as well. This function can be tailored to the needs of a specific experiment as necessary.

4. FURNACE CHARACTERIZATION

The facility has been characterized by measuring furnace temperature profiles, deposition cup temperatures, fission product distributions in the furnace, and fission product collection efficiencies. The former measurements will define the range of the approximately isothermal region, peak temperature, the furnace temperature profile, and the cold finger temperature behavior. The latter measurements will establish suitable locations for the cold finger, the components on which the fission products are distributed, system fission product collection efficiency, and the measurements necessary to achieve a mass accounting.

4.1 TEMPERATURE PROFILES

Initial characterization tests using the aluminum oxide muffle tube were conducted in which the axial temperature profiles in the furnace along the centerline were measured at furnace peak temperatures of 1200, 1400, 1500, and 1920° C. There was an approximately isothermal zone of 8 cm slightly offset from the furnace center. At 1550° C, the zone is symmetric about the midpoint but is shifted slightly downward at lower temperatures; the cause of this shift is unknown, but it is minor and does not present any problems. Within this approximately isothermal zone, the variation in temperature is approximately $0.013*T_{max}$. Beyond this zone, the temperature declines symmetrically about the midplane. A typical axial temperature profile is shown in Fig. 7. Insertion of the cold finger to within 140 mm of the furnace midplane did not alter the temperature profile within 100 mm of the furnace center. However, at this depth of insertion, the deposition cup may be at too high a temperature for good metallic fission product collection. Measurements with a sheathed thermocouple, touching the surface of a deposition cup modified to permit this measurement, yielded the temperature of the deposition cup as a function of furnace peak temperature and height above furnace midplane. These measurements are shown in Fig. 8.

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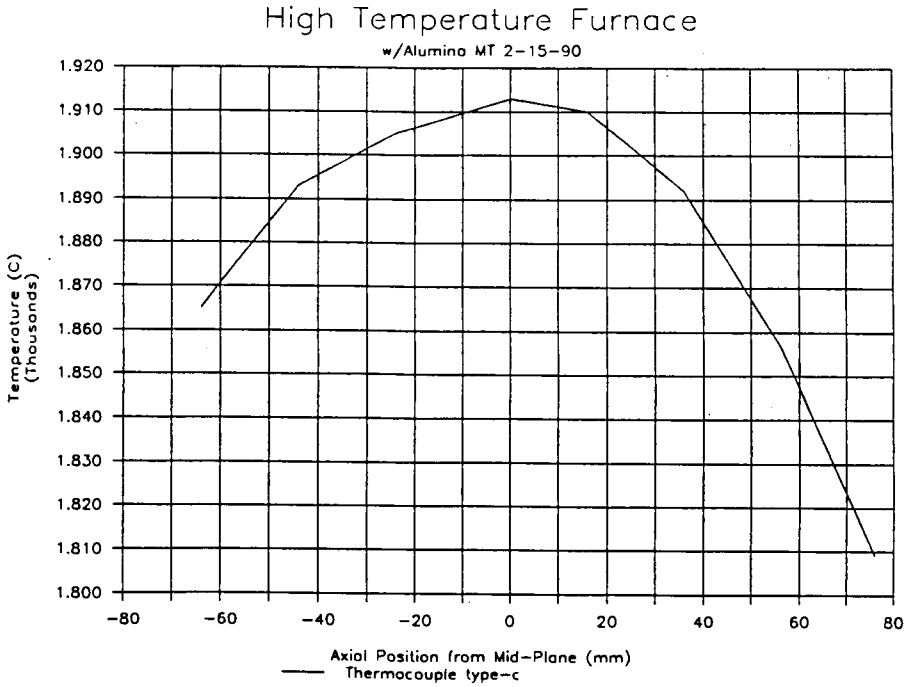

Fig. 7. Aluminum oxide muffle tube axial temperature profile at 1915°C.

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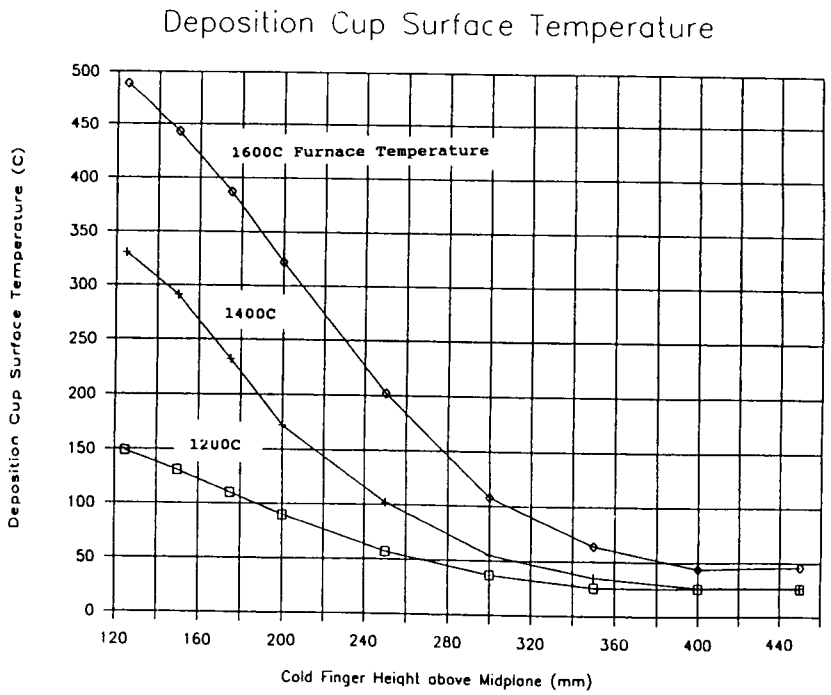

Fig. 8. Deposition cup surface temperature versus furnace temperature and height above midplane.

The temperature uniformity of the graphite outer muffle tube with the tantalum liner has not been examined to the degree that the alumina muffle tube has. The primary emphasis has been on high-temperature material problems. More detailed temperature profiles will be measured in the near future; no major differences are expected.

Because of mechanical difficulties, it is not possible to measure the surface temperature of the deposition cup during an experiment; the surface temperature must be inferred from the characterization measurements. This issue will be readdressed in the future to ensure that the deposition cup collection efficiency is maximized and does not degrade with time. As experience is gained with the facility, the cup may be redesigned to take advantage of this experience.

One final point is the stability of the thermocouples and the pyrometer. In general, the pyrometer has exhibited stable behavior. The type C thermocouple has also exhibited stable behavior, as well, but in-operation failure has occurred for thermocouples cycled many times. The cause of this failure is not clear, but a new thermocouple will be used for each experiment. Finally, the BGT does exhibit some drift during the first 10 to 25 h of operation. The temperature drift has been estimated to be as much as 8%. This device will have to be calibrated before an experimental run.

4.2 FISSION PRODUCT PROFILES

The metallic fission product deposition profile and fission gas collection efficiency are under study at the present time. A radioactive tracer test will be used to determine the metallic fission product deposition profiles and the cold finger collection efficiency. This test is currently in its planning stage; current plans are to use the high-temperature decomposition of a compound containing a measured amount of ^{137}Cs as the source term. The injection of ^{85}Kr into the furnace sweep gas will be used to determine the collection efficiency of the trap system. These tests will be run soon after the furnace has been installed, checked out in the hot cell, and all required safety and operational documentation completed. The plans for examining the deposition of the other metallic fission products are not currently well developed, and later work will be required to examine or estimate the deposition patterns of iodine and strontium.

The cold traps have been tested by passing helium (containing small amounts of stable krypton) through them while cooling the traps with liquid nitrogen and monitoring the trap

exhaust with a residual gas analyzer. As the trap temperature was lowered below about -100°C, the krypton was observed to be trapped. The flow rate was 0.4 L/min of helium. Baking the traps quickly removed the krypton as expected.

4.3 FURNACE OFF-GASES

In addition to the temperature measurements, the furnace off-gases have been examined and will be examined during the course of the planned experiments for their chemical composition. An RGA will be used to monitor the gases to determine if any chemical reactions or thermal decompositions are taking place within the furnace. The RGA will not be able to determine all reaction possibilities within the furnace, but it will provide information about a variety of gaseous reaction products and will provide warnings about an air or water ingress. It will also provide assurances about the quality of the furnace sweep gas.

4.4 ACTIVITY MEASUREMENTS

One of the more difficult operational problems of this facility will be the gamma/beta counting of the furnace components to determine the fission product releases. Three factors add to the difficulty. The first is the very low expected release. Because of the low releases, a determination of the loss in fuel activity is not possible by a before and after measurement of the fuel specimen. Thus, it will not be possible to compare the fuel specimen losses with the collected fission products to perform a mass balance. Second, it is possible that the metallic fission products could be spread over a large area, reducing the activity per unit area if the deposition cup collection efficiency is low. Finally, the size and geometry of the parts to be measured may make their handling awkward. The difficulties and seriousness of these problems is under consideration; operational experience will be necessary to solve these problems in detail. While challenging, these problems are not expected to result in program stumbling blocks.

Several possible concepts for counting the parts are currently being examined. It is likely that a combination of techniques will be necessary. Possible avenues of attack are:

1. Develop special detector systems and fixtures to hold and count the parts. Use calibrated tests and modeling to relate the measured counts to absolute activity.

2. Leach and/or dissolve the parts. Use a well detector to count the liquid. Perform a relative before and after count on the parts to measure the efficiency of the leaching.
3. Cut the parts into small pieces that can be more easily handled and measured.

Each of these methods have their strong and weak points. Details of the methods are being drawn up and evaluated. In addition to the development of experimental techniques, some mathematical models are being examined to see if they can be used to predict the distribution of fission products within the furnace. If such an attempt proves successful, then computer-aided design techniques may allow the optimal design of experiments for best fission product collection efficiency. This could lessen the experimental difficulties considerably and result in more accurate and useful data.

5. CURRENT STATUS AND ISSUES

At the present time, one furnace is under construction, and the other has been installed in the hot cell and made operational. The hot cell has received the piping and wiring necessary for the installation of the furnace, and the furnace has been placed into the hot cell. Testing of the installation is expected to begin immediately after the final connections are made. Furnace characterization tests and simulated fuel heat-up tests are being devised and will be run as the facility becomes operational. The early goal of demonstrating reliable and safe operation has been accomplished. The next major goal is to enter the experimental program and perform the specified heating programs using irradiated fuel.

Operating procedures and safety analysis reports have been written, reviewed, and approved. The test plans for the first series of fuel heating experiments using the unbonded HEU UCO TRISO particles from HRB-17/18 have been developed. The fuel specimen(s) will be carefully examined in the IMGA facility before and after its heating cycle. Because of the varying levels of fuel activity and the associated handling regulations, additional facility coordination issues with other groups will arise, and they will be examined on a case-by-case basis with emphasis on the development of a routine procedure. Programs that require highly radioactive specimen handling by several facilities are not expected to present major problems other than bookkeeping issues.

Two material issues are currently under consideration. The first is the muffle tube and its ability to effectively isolate the furnace sections. The second issue is the sorption of the

metallic fission products by the furnace components. Future issues will include chemical attack and erosion of the muffle tube and furnace components by a chemically active sweep gas such as air or steam. The issues surrounding both the muffle tube and the specimen holder/support are not completely resolved for all cases at the present time, but workable options are available, and they will be used for the first phases of the experimental program, as was previously discussed in the components sections. Future investigations, tests, and operational experience with the CCCTF may identify other, more flexible options. Tests will be conducted to determine the cold finger collection efficiency and to determine if carbide reactions are important for the time scales of interest. Finally, it is not clear if the furnace temperature gradients will remain the same with the different muffle tube types or with the fuel specimen and its supporting structure in the furnace. Since the introduction of the cold finger into the furnace made little difference in the hot zone area temperature profiles, this point is likely to be minor. Detailed measurements of the furnace hot zone are probably not possible under all experimental conditions; however, the three temperature measuring sensors, one very close to the test specimen, will provide a good picture of furnace operation.

Also under consideration is a computer model of the furnace system that would allow prediction of the temperature profiles and an estimation of the metallic fission product deposition. The computer model may also provide insight as to the time delay between the fission product release from the fuel specimen and its deposition on the cold finger.

6. CCCTF OPERATION

The following sections provide a brief overview of the planned operation of the CCCTF facility. Their purpose is to outline the operations of the facility, their limitations, and their complexity to the reader. This information should help the experimenter, who will be planning experiments for this facility, to grasp some of the detailed limitations and possibilities of the CCCTF. For a more detailed description of the CCCTF, the reader should consult the current CCCTF standard operating procedures and the specific procedures for the task of interest. All furnace operations will be performed in a hot cell using manipulators and remotely controlled equipment.

6.1 PREPARATION FOR OPERATION

The CCCTF will be operated in two different modes. The first and preparatory mode is the bakeout mode. This operation will consist of purging and baking the furnace to remove any adsorbed gases. It also provides an opportunity to notice any abnormal behavior with the furnace, its material, or the control system. The other mode of operation is the run mode. This mode is used to conduct the experiments.

Preparing the furnace for operation would entail the following operations:

1. Remove all furnace internal components and install those components that can withstand the bakeout temperature, such as the furnace heating elements, insulation, and depending on their material, the muffle tube and fuel specimen holder. The BGT port should be sealed with the manufacturer-supplied plug.
2. Evacuate and purge the furnace by using the computer-driven purge/evacuate control routines.
3. Bake out the furnace in manual mode at 2300°C for 4 h periodically monitoring furnace off-gas composition and pressure. The pyrometer will be used for temperature control.
4. When the furnace has cooled sufficiently for handling, backfill with purified helium to slightly over atmospheric pressure.
5. Install the remaining furnace components.

The furnace will now be ready for insertion of the fuel specimen and the beginning of the experimental program.

One should be aware of the need to bake out furnace components at a somewhat higher temperature than the expected operational temperature of the furnace. This is necessary to ensure that impurities such as air and moisture do not constantly outgas during operation. It is possible to bake out components in another furnace and transfer them to the CCCTF furnace, but one must be careful about picking up impurities along the way. The bakeout needs may limit the complexity of the furnace internal hardware.

6.2 FUEL SPECIMEN LOADING

Loading the fuel specimen is the final operation before the furnace is sealed up and brought into operation. This operation must be done remotely using the hot cell manipulators and the furnace elevator because of the radiation hazard. These requirements may place

restrictions on the complexity and shape of the furnace internal components such as the fuel holder. During the fuel loading sequence, helium will be flowing to prevent the introduction of air into the baked-out and purged furnace. The expected sequence of events is:

1. Establish purified helium flow to the furnace.
2. Release and move the bottom door locking jack to the back of the furnace. Lower the bottom door/specimen holder using the specimen elevator, and unlock the horizontal slide. Using the horizontal slide on the specimen elevator, position the bottom door/specimen holder for easy access by the hot cell manipulators, and load fuel specimen into holder.
3. Horizontally position the specimen elevator under the furnace bottom entrance and lock in place. Insert the fuel specimen into the furnace by operation of the specimen elevator.
4. Secure bottom door in place by moving the jack assembly forward and securing the locking screw. Verify that the purified helium flow is continuing.

The furnace and fuel sample are now ready for experimental operation. The operator should verify that sufficient quantities of helium are available for the intended run time, all equipment is functioning normally, and the hot cell personnel are aware of the activities and their expected duration. Note that any further visual examination of the fuel sample will require the interruption of the furnace heating cycle and the opening of the furnace.

The major concern during this phase of operation is the fuel handling. The fuel, in a transport cask, will be introduced into the hot cell through an access port in the ceiling. The fuel will be remotely removed from the cask and placed into the specimen holder by use of the manipulators. Problems would include items such as dropping the fuel, damaging the fuel, or damaging the apparatus. Since this operation is done remotely in a hot cell, only simple operations are possible in a reasonable period of time. This fact places limitations on the complexity of the fuel holding and handling apparatus. Also, if the fuel specimen is dropped or damaged the hot cell can be contaminated by debris and a delay could be introduced into the program by the clean up requirements.

6.3 EXPERIMENTAL RUN

Programmed control of CCCTF operation is via the computer-controlled system. Most operations will be entered via the display screen menu, and important system parameters will be displayed on this screen as well. Provisions will be made for both automatic and manual

operation, but manual operation is expected to be used in special cases only. Tracking of process variables (optical pyrometer, type-C thermocouple, etc.) will be done by the computer system and recorded on a timely basis in the data base.

A typical run would proceed as follows:

1. Enter the temperature ramp profile and control parameters into the computer system using the menu-driven screen options.
2. Verify that the current system parameters are within acceptable limits, gas and cooling water flows are active, the temperature control inputs are as desired, and the water chiller is operational. The power limit potentiometer should be set for maximum furnace element current.
3. Activate the automatic data logger, and enter the relevant information into the system log book.
4. Activate the computer start-up and heating programs. Initially monitor the system variables to ensure the startup has been performed correctly.

At this point the furnace interior temperature will be ramping up in a controlled fashion, and the experiment will be under way.

During the course of long experiments, it is likely that the helium supply will need replacement. The helium cylinder changeover procedure will require the operation of manifold and purge control valves to ensure that no air is introduced into the system. Helium cylinder replacement is expected to be necessary every day or two.

Concerns at this stage of operation are mainly malfunctions and include items such as furnace overheating, air or water ingress, and line breaks. The likelihood of these faults is expected to be remote because of the safety interlocks and the system design, but prudence dictates that such issues be addressed.

It is during this part of the operation of the CCCTF that the computer system is most valuable. The programming ability allows complicated heat-up and cool-down profiles to be automatically followed with no operator attention. Furnace and cold trap data collection are also automatic. The only operator direct action requirement is the changing of the deposition cup. This part of the operation allows the most freedom for the experiment designer.

6.4 DEPOSITION CUP INSERTION/REMOVAL

The deposition cup is located at the lower end of the cold finger assembly. The purpose of the cup is to collect the metallic fission products; the cup will be removed and replaced at various time intervals during the experiment. The analysis of the set of deposition cups will provide an approximate time history of the metallic fission product release for the specimen.

The process for the installation of the deposition cup on the cold finger assembly is as follows:

1. Record the deposition cup number and experimental details on the cup log sheet. Using the cold finger drive system, place the cold finger assembly in its upper, horizontally extended position for cup installation.
2. Using the hot cell manipulators, position the deposition cup on the bottom of the cold finger assembly using the alignment boss to the locate cup. Activate the cold finger lead screw until the cup "bottoms" on cold finger assembly.
3. Horizontally move the cold finger to its position over the furnace gate valve. Turn on the chilled water supply, and verify operation and cold finger temperature.
4. Vertically lower the cold finger into the furnace gate valve. The cold finger will stop at the first interlock position. Verify that the chilled water is flowing and the cold finger assembly is cooling down.
5. Evacuate the upper gate valve region and purge with helium. Open gate valve and insert the cold finger assembly through the gate valve to its interlock position inside the furnace.

After the insertion of the cold finger, the experiment will continue under computer control. The operator will verify and log that the system is operating normally. The removal of the deposition cup is essentially the reverse of the above procedure. The removed cup is to be placed into a special carrying container to minimize contamination problems and to provide for removal from the hot cell. The entire removal and replacement cycle of the deposition cup can be done in less than 20 min.

The time intervals between cup changes will depend on the experimental needs of the program under study and is limited to an interval of no less than 20 min because of the operations that have to be performed. Also, the operation of the cold finger apparatus could

lead to malfunctions that terminate the experiment because of the possible failure of the interlocks and valves; one should limit the use of the cold finger to only collecting significant data.

7. CCCTF FURNACE FAILURES AND DATA INTEGRITY

Three major failure categories are of interest for the CCCTF. The first is programmatic in nature and involves the failure of the experiment to run to its full duration. The second type challenges data integrity by the loss of control of the experimental environment. The third type involves unplanned, major damage to the fuel specimen and a release of a significant fraction of its inventory.

7.1 DURATION FAILURE

The first type of failure would occur when a major component fails during a run. This fault would affect the data after the time of failure but not the data obtained before the failure. For example, if the furnace elements were to burn out 80 h into a 100-h run, the first 80 h of data would be usable; the remaining 20 h of data would not be obtained. The data logger would clearly show this type of event.

7.2 DATA INTEGRITY

The second type of failure can challenge the data integrity and involves uncontrolled temperature variations in the furnace or fission product traps, improperly prepared specimens, a design fault that makes collection of fission products uncertain (such as unreliable furnace internal components), or unplanned chemical attack of the fuel specimen. The CCCTF guards against these uncertainties in many ways. The constant monitoring of the furnace internal temperatures provides a run history of the experiment. Multiple-temperature sensors of different types provide redundant measurements to the data logger and avoid overdependence on one type of sensor. The preparation of the specimen will be dependent on outside sources to a large degree, but the specimen and its irradiation history will be examined at ORNL to ensure that no gross problems are evident. Collection uncertainty will be handled by the post-experiment examination of the furnace internal components, cold finger, and traps. Constant monitoring will allow problems to be addressed on a case-by-case basis if they arise. Chemical

attack of the fuel specimen could conceivably result from impurities in the purge gas, furnace internal components, or the use of improper materials. Control of the composition of these components and periodic monitoring of the exhaust gases will be required to ensure that the furnace atmosphere is acceptable.

The critical components of the CCCTF are those components which, if contaminated, flawed, or failed, can lead to corrupt data. Of most concern are problems that escape detection by the data logger or furnace gas analyzer. The redundant temperature logging provides an indication of the temperature history from several different sources; thus, it is very likely that a temperature control problem will be evident. Of greater concern is the furnace atmosphere. Contaminated furnace components or purge gas could lead to fuel damage if the contamination is severe. Since analysis of the furnace exhaust gases is not a guarantee of a benign furnace atmosphere, strict control of the material in the furnace is necessary to prevent contamination of the specimen by surface contact or by the diffusion of contaminants from the furnace components.

Because of the possibility of chemical attack and the difficulty of online determination of this phenomena, all components that form the furnace environment must be considered critical components, and care must be exercised to ensure that these components do not result in chemical interactions or introduce foreign materials to the system. Impurities in most components can be controlled by quality control of the materials and by baking the components before use in the furnace.

The cold traps have several elements that could contribute to a single-point failure leading to data collection problems. These elements are the connecting lines, the liquid nitrogen supply, and the common data collection system. These elements are not difficult to monitor to detect failures. Outside of these elements, multiple failures of the cold trap system would be required to result in the loss of the fission gas collection capability because of the two series-connected traps. Failure of the cold finger is a single-point failure mechanism that could result in the failure to collect a large fraction of the metallic fission products. The temperatures of the cold finger and cold trap system are monitored, and it is likely that these faults would be recorded in the data logger.

A major failure of the computer would result in the controller going into its fail-safe mode, which is currently set to the last good command. The operator can determine the best course of action when this happens by review of the current system status display. A momentary

power failure results in the shutdown of the furnace power supply; the controller will be powered by an uninterruptible power supply and will remain operational. An automatic restart can occur when the power is restored. A loss of purge gas flow could result in a small air ingress if the system has developed any leaks over the course of the experimental run. Air could damage furnace internal components and perhaps the specimen. It is unlikely that this event would escape detection because the lack of purge gas flow could be easily seen on the flow meters. Since the most likely cause of sweep gas flow failure is empty gas cylinders, periodic monitoring of the helium manifold and gas cylinder pressures is required. A daily checklist in the operations log will guard against oversight of empty gas cylinders.

Serious internal furnace damage can be determined by inspection of the furnace after the experimental run. Since major furnace components are to be replaced and examined for fission products after each run, a visual inspection is easily performed. Clearly, damage will indicate some sort of furnace dysfunction even if the data logger indicates no problems.

7.3 SPECIMEN FAILURE

The third type of failure is the most serious and involves the release of a significant quantity of the fuel specimen radionuclide inventory. This type of failure would require multiple failures of the quality control and furnace control systems. The probability of this type of accident is considered to be remote. This section will consider several worst-case scenarios that could result in the release of radioactive material. Since the focus will be on the worst case, no solid physical mechanisms leading to these cases will be examined; the accidents will simply be assumed to have happened.

The release from the specimen will be initially within the furnace but may spread outside the furnace if the isolation boundary were to fail or be responsible for the accident. The fuel release can be caused by uncontrolled furnace temperature increases, by massive chemical attack, or by a defective fuel specimen. In these cases, the furnace internal components will become contaminated. For the purposes of this document, two categories need to be considered.

The first category is the failure of the fuel specimen with the furnace isolation boundary remaining intact. Radioactive materials will contaminate the furnace interior, the cold finger assembly, and the outlet gas lines. The condensable fission products would be expected to contaminate the furnace and a short portion of the gas exhaust lines. Only the gases, aerosols,

and very volatile fission products would be expected to travel to the filters leading to the cold traps. The filters will pass only the gases to the cold traps. Accident effect mitigation is possible because a large amount of the furnace contamination can be dealt with by removing the deposition cup in the normal fashion and by remote removal of the furnace muffle tube liner and the fuel holder and fuel specimen. A multistage filter in the furnace exit gas line will prevent large quantities of radioactive particulate from entering the cold traps. The gases that do enter the cold trap can be driven off and routed back into the hot cell by heating the traps in the normal fashion. Other furnace external components can be removed remotely, with difficulty, if necessary. If massive failure of the furnace internal components also takes place and a large amount of contamination occurs, the furnace teardown and decontamination will be lengthy because a complete disassembly by remote techniques will be very difficult. Because of the small quantity of fuel involved in many experiments and the expected low probability of simultaneous fuel and furnace failure, the long downtime for this case is considered acceptable.

If the furnace isolation boundary were to be breached, radioactive materials could be introduced into the hot cell or fission gases could be released outside the hot cell if the cold traps or their lines fail.

The inventory of radioactive material will vary from experiment to experiment, but the near-term fuel specimens will consist of several hundred fuel particles, either loose or bonded together into fuel compacts. The total inventory of fission products can vary considerably, but it is expected to be of the order of 1 mCi per particle for the older fuel to be used in the first part of the experimental program, for a total of 1 Ci per 1000 particles. Thus, the fission product inventory for the first part of the experimental program is very modest and poses minimal hazard.

Later experiments using freshly irradiated fuel composed of thousands of particles could contain several hundred curies of activity and may require modification to the facility and its operation. The important radionuclides and their activity for an experiment involving 1000 unbonded fuel particles 180 d old are listed in Table 1.

7.4 CRITICAL COMPONENTS

Several internal components can have a direct influence on the furnace performance and its atmosphere. These components can adversely effect furnace behavior either by their structural failure or by the release of contamination to the furnace atmosphere. The major

Table 1. Inventories of principal radionuclides in 1000 irradiated MHTGR fuel particles after 180-d decay

Radionuclide	Half life (y)	Specimen inventory (mCi)		
		Specimen LEU[a]	Inventory HEU[a]	ThO_2
^{85}Kr	10.72	16.2	11.9	10.6
^{90}Sr	29	116	93.2	57.3
^{106}Ru	1.01	844	97.5	41.9
^{125}Sb	2.77	13.1	4.37	8.18
^{129}I	1.59E7	4.3E-5	2.0E-5	2.4E-5
^{137}Cs	30.2	160	96.1	55.5
^{144}Ce	0.778	3130	2115	979
Total fission products		4280	2420	1150
^{232}Th	1.40E10	0	0	5.8E-5
^{233}U	1.59E5	0	0	0.0644
^{235}U	7.04E8	1.3E-6	1.1E-6	1.8E-6
^{238}U	4.47E9	8.7E-5	1.5E-6	1E-9
^{238}Pu	87.7	2.33	2.12	0.0159
^{239}Pu	2.41E4	0.127	0.0043	1.3E-5
^{241}Pu	14.7	70.1	1.87	2.4E-3
Total actinides		72.8	4.00	2.96

[a]LEU = low-enriched UCO particle, 20% ^{235}U; HEW = high-enriched UCO particle, 93% ^{235}U.

requirement on these components is that they perform their function and not release material that could result in furnace damage, trap plugging, or chemical reactions with the test specimen. This goal can be achieved by using materials of known composition and by baking as many components as possible just before the experiment begins. The level of impurities in the components does not have to be extremely low; rather, they must not be substances that

can diffuse out and cause damage during furnace experimental operation. At the present time, the following components are considered critical:

1. Graphite heating element — the graphite resistance heating element is the source of heat for the furnace, and it is necessary that it last the duration of the experiment. The element must also not introduce any significant quantity of materials into the furnace atmosphere that may result in damage to the other furnace components or the fuel specimen. The source of this component is the furnace manufacturer. This component will be tested during the furnace bakeout cycle; the furnace off-gas will be analyzed and the voltage/current delivered to the furnace will be monitored.
2. Graphite insulation and heat shield — the graphite insulation and heat shield provide insulation for the furnace. The major issue is that they last for the duration of the experiment and not introduce any significant contamination into the furnace atmosphere. The source of this component is the furnace manufacturer. This component will be tested during the furnace bake-out cycle by monitoring the furnace off-gases and furnace performance.
3. Boron graphite thermocouple — this thermocouple is one of three temperature sensors that can be used for control of the furnace temperature. This device has two other back-up sensors so that its failure will not result in termination of the experiment or loss of temperature control. Since it is inside the furnace, introduction of contamination is a concern. For data and control purposes, the drift should be as small as possible and its operation predictable. This part will be supplied by the manufacturer.
4. Outer muffle tube — this graphite part will form the first barrier between the heating and testing regions of the furnace. It will also provide support to the muffle tube liner. Strength is not an issue because common grades of graphite have sufficient strength, neither is porosity for the inert atmosphere tests because the inner muffle tube will function as the important barrier between furnace regions, at least for the early experiments. The primary concern is that this component introduce no significant contamination into the furnace atmosphere that would damage any components. Low porosity would be a plus, if possible, for the general case. The material for this part will be obtained from quality-controlled stock.
5. Fuel holder — support for the fuel specimen during the heating cycle will be provided by this component. At the present time, its composition is graphite, but the material is likely

to be test sensitive. It is important that this part not react with the fuel specimen or release any contamination to the furnace atmosphere. In addition, strong absorption of the fission products is to be avoided, but the present design is not optimal in this respect. The material for this part will be obtained from quality-controlled stock. Again, machinability and purity are the most important properties as strength is a minor issue.

6. Fuel Holder Support — this part will support the fuel holder in the center of the furnace. At present, it is a hollow graphite rod extending from the bottom furnace flange. It may have one or more tantalum heat shields attached to it. As usual, the primary concern is that this part not release any materials that could cause damage to the furnace or fuel specimen. Minimal absorption of fission products would also be useful. Minimal strength is required from this component. The material for this part will be obtained from quality-controlled stock.

7. Muffle tube liner — the liner will see the interior of the furnace and forms the primary barrier to the diffusion of the metallic fission products. The present design material is tantalum. Minimal absorption of or reaction with fission products is desirable, and no significant contaminants should be released to the furnace. Most of the mechanical support for this part will be provided by the outer muffle tube. The material for this part will be obtained from quality-controlled stock.

8. Tantalum-sheathed thermocouple — this sensor will function as part of the furnace temperature control and data collection system. It is one of three different temperature sensors, and its failure will not, in general, terminate the experiment. It is constructed of a type C thermocouple junction/wire enclosed in a sealed tantalum tube. Primary concerns are dependable operation, the possible introduction of impurities, and loss of accuracy by component drift. It will be purchased from the manufacturer.

9. Helium Purifier — this subsystem will ensure that the helium furnace purge gas is free from significant amounts of oxygen. This device has a self-contained oxygen gauge to monitor its operation. In addition, the furnace output gas will be periodically checked by the residual gas analyzer to check/monitor the operation of this unit. The primary concern is malfunction. This component will be purchased from the manufacturer as a unit.

10. Helium sweep gas — helium will be constantly flowing through the furnace during normal operation and could be the largest source of contamination if not properly controlled.

The helium will be inspected by the residual gas analyzer before its introduction to the system, and it will then be run through the purifier before its introduction into the furnace.

11. Deposition cup — the deposition cup will be within the furnace during its collection cycle. The present design is a copper-coated stainless steel cup. The primary concern is that the cup introduce no contaminants into the furnace. Contamination is less of a concern with this component because it will see much lower temperatures, and it is located downstream of the gas flow. A primary concern is that it fit snugly to the cold finger support cylinder to ensure good heat transfer.

12. Fuel specimen — while this item is not a furnace component, it must be carefully examined before its introduction into the furnace to guard against unplanned large releases.

The list of critical material is evolving both on an experiment-by-experiment basis and on an experience basis. Essentially, three issues are important: minimal degradation during the experiment, no significant release of contamination, and minimal uptake of released fission products.

7.5 FURNACE SYSTEM LEAKS

A small leak in the furnace system within the hot cell is not of major concern for safety reasons because the furnace system is held at a positive pressure, and the hot cell ventilation system can easily handle the gas volume. Thus, it is not likely that an air ingress will occur. If a leak occurs in the portion of the piping outside the hot cell or in the cold traps, it is possible that fission gases will be allowed to enter an occupied area. The maximum possible exposure for this accident will depend on the quantity of gases and their dilution factor. In addition, the occupied area has its own ventilation system. As was stated above, the maximum quantity of fission gas available for release is small, approximately 1 mCi for 100 particles, in the first series of experiments. This concern may have to be readdressed if much larger radionuclide inventories are contained in the specimen than in the initial tests.

An air ingress into the furnace could occur if multiple lines break or the cold finger apparatus malfunctions. The inrush of air can result in damage to the fuel and furnace; however, the chemical reaction rates are modest, and rapid catastrophic burning is not credible. This event can release fission products from defective fuel particles. In any case, the release, if any, will be contained by the hot cell.

The above accident scenarios can result in furnace damage, isolation boundary breaches, and fission product releases, but they are not associated with any energetic reactions that would result in large, or rapid hot cell pressure increases.

The only cases that could result in a significant pressure surge would be the flashing of water into steam and the accompanying water-gas reaction that generates hydrogen and carbon monoxide. Two cases are of interest. The first is a steady-state leak and the production of steam; the second is a large and sudden water leak, which is flashed into steam. The cases are:

1. In the steady-state case, the power input is approximately 10 kW. The greatest volume of steam would occur if water at 100°C is converted to steam at 100°C and atmospheric pressure and then exhausted to the hot cell with no cooling taking place. While clearly unphysical, this estimate can be used to bracket the worst case. At constant pressure (atmospheric) about 2.16×10^6 J/kg of water are required for this transformation leading to the generation of about 4.6 g of steam per second. This steam will occupy a volume expanding at about 0.45 m^3/min. The hot cell has a volume of approximately 20 m^3, and the ventilation system exhausts ~ 34 m^3/min. The steam will result in a flow change of less than 2%, which will have a negligible effect on hot cell pressure.
2. In the sudden leak case, one assumes that all the stored energy of the furnace is available for converting water to steam on a short time scale. Again, we will assume a conversion of water to steam at 100°C, immediate escape from the furnace to the hot cell, and no steam condensation within the hot cell. The furnace contains approximately 4.5 kg of graphite with a heat capacity of 700 J/kg (°C). If one assumes that the average temperature of the graphite is half the maximum temperature of the heating zone, one computes a stored energy of about 3.0×10^6 J. Transforming the water to steam in the same fashion as case 1 leads to the generation of 1.4 kg of steam. At 1.64 m^3/kg of steam, a total volume of about 2.3 m^3 of steam is generated. Since the cooling system of the furnace is composed of small-diameter tubes on the outside of the furnace body, only the cold finger assembly is in a position to rapidly dump water into the furnace. It is not clear how a massive rupture could occur, but for bounding conditions, one could assume that the event takes place over a 1-min period. The steam source, 2.3 m^3/min, represents an effective reduction in the hot cell ventilation rate of about 7%. With the cell negative pressure drop proportional to the cell inlet flow rate, a similar reduction in the hot cell pressure differential would occur. The change in pressure differential would be noticeable,

but tolerable, even for higher steam production rates. Only the instantaneous flashing of water into steam would cause a cell overpressure condition. This event is not credible for this furnace design.

Because of the modest steam generation rates, the modest hydrogen generation rate by the water-gas reaction, and the high rate of cell ventilation, hydrogen accumulation and explosive mixture generation is not considered to be a problem. None of the postulated accidents challenge the hot cell by large overpressure events or explosions. Future experiments will be assessed for this possibility, but at the present time, it appears to be remote.

Another possibility for the breach of the hot cell containment appears to be the rupture of the lines leading to the cold traps or the rupture of the cold traps themselves. In this case, the major concern is the fission gases. The danger posed by this threat is determined by the magnitude of the gas inventory and by the presence of mitigating systems such as room ventilation or a ventilation hood over the trap assembly. The maximum fission gas inventory available for release is expected to be on the order of millicuries, even in the worst cases for the first experimental series, and there is no mechanism for a sudden release of a large fraction of this inventory.

Massive furnace failure, such as the destruction of the furnace by overheating, melting, and burning due to loss of cooling, will not radically change the above accident scenarios because they assumed a major fission product release, and the destruction of the furnace will not result in a major pressure surge that will challenge the hot cell containment. Several other faults that are independent of the furnace may also occur. A failure of the chilled or process water hoses may result in the spilling of many gallons of water on the hot cell floor. A remote shutoff switch will allow the manual turnoff of the water pumps. The constant flow of the furnace sweep gas will prevent the accumulation of hydrogen should a small water leak occur in the furnace.

7.6 FAULT SUMMARY

In summary, most serious faults will be apparent by the temperature record, system lock or shutdown, furnace system damage, furnace exhaust gas analysis, or loss of purge gas flow. Chemical attack of the fuel specimen may be difficult to determine because sampling the exhaust gas may not be sufficient to determine if in situ damage has occurred. Also, the

physical appearance of the fuel specimen may not show the damage. The best way to handle this problem is to ensure that only known and understood materials are present in the furnace during the experiment.

Serious accidents such as overheating, air ingress, and steam generation are not expected to challenge the hot cell containment ability. Line breaks do not challenge containment as long as they do not occur in the lines outside the hot cell that connect the furnace to the cold traps. If the gas lines outside the hot cell break, it is possible for fission gases to enter an occupied area. The seriousness of this event will depend on the release rate and the inventory of the fission gases and on the availability of mitigating factors such as room ventilation.

7.7 CCCTF FAILURE MODES

The CCCTF is not expected to present an injury hazard to personnel should it fail. During operation it will be located in a well-shielded hot cell, and it will be guarded by safety shut-off devices. Failures will primarily threaten the furnace, the specimen, and the experimental program. Broadly speaking, failures fall into two modes. The first mode is a failure from which recovery is possible if mitigating actions are quickly taken. The second failure mode results in the termination of the experiment. At the present time, not all accidents will result in automatic shutoff; manual operation of shut-down controls may be necessary.
The types of accidents capable of recovery are:

1. Short-term loss of cooling water — loss of cooling water results in the automatic shutoff of the power supply. If the cooling water supply can be restored in a short period of time, the system can be restored to active status with only a small furnace temperature drop. Longer times will result in a major furnace temperature decrease and less chance for a recovery without data impact. At the present time, temperature drops of greater than 50° C would be considered serious.
2. Short-term loss of building electric power — loss of power will result in controller shutdown; the controller can automatically reset. If the power can be restored and the computer system restarted in a short period of time, the temperature impact will be small. The use of an uninterruptible power supply for the computer system may help mitigate this problem. Longer times may result in significant cooling.
3. Short-term loss of helium purge gas supply — if the helium flow can be quickly restored, no problems are expected. If it cannot, the system must be shut down because of the loss

of flow to the cold traps. Because of the expected small releases and low flow rates, tens of minutes should be available for supply restoration.

4. Loss of the control thermocouple — if the control thermocouple fails, the operator can switch to the other thermocouple or the optical pyrometer. If no action is taken by the operator, the control system may be able to automatically switch to the "best" thermocouple. This design feature is not yet complete, and details are not available. If all system thermocouples fail, the system must be shut down. At the present time, this must be done manually. An automatic shutdown is under consideration.
5. Loss of the computer and/or RTP control — the most likely response to a computer and/or RTP control failure is to attempt a restart. If this cannot be done, manual operation may be possible, but the most likely course of action is system shutdown.
6. Loss of cold finger water supply — if the chilled water supply cannot be restarted quickly, the cold finger must be withdrawn from the furnace and the system shut down. The water in the cold finger must be kept below the boiling point.

Emergency furnace shutdown poses no safety problems. Power off at high temperatures initiates immediate cooling of the furnace. All valves are positioned to provide normal mode open or closed to vent system. Should water or air ingress into the furnace occur, the subsequent combustion products and/or steam can be vented through the point of ingress, the furnace body rupture disc (1.7 atm), the furnace body relief valve (0.68 atm), or through the normal exit lines. The exhaust path for the rupture disc and relief valve will be into the hot cell. The relaxation time for the furnace temperature to drop from normal operating temperature to ambient is approximately 2 h under normal conditions. At any time, emergency shutdown of the furnace may be undertaken by manual operation of the main power switch or by a software command.

After an emergency shutdown of the furnace, an assessment should be made as to the status of the support systems such as the process water, chilled water, and helium purge gas. If no hazards exist, these systems should remain on as they will aid in the cooling of the furnace and the maintenance of the proper internal atmosphere.

The computer control system can be used to program other nonemergency shutdowns for other abnormal conditions. These situations will be dependent on the specific experimental conditions.

7.8 BUILDING FIRE ALARM/EMERGENCY EVACUATION

Should a building evacuation be required, the operators can immediately leave the area when the CCCTF is in its automatic mode of operation. It will continue to operate normally if cooling water and power are available, and it will shut down when these supplies are disrupted. If necessary, the system can be shut down by emergency personnel by pushing one button.

The only operation that would require attention is to ensure that the upper gate valve is closed if the emergency takes place during the changing of the deposition cup.

8. SUMMARY

The CCCTF is a unique facility for conducting high-temperature MHTGR irradiated fuel release experiments. It is a flexible computer-controlled system that requires minimal operator interaction during operation yet is capable of complex experimental configurations and data collection. Safety hazards are expected to be minimal due to the small test specimens, furnace automatic shutdowns, remote operations, and the use of a hot cell. A high degree of monitoring and data logging will provide comprehensive information on the state of the furnace and auxiliary controls. The strict control of the material used in the furnace will ensure that the experiments are carried out in the proper atmosphere with minimal likelihood of adverse chemical reactions, and the computer control system will provide the required level of temperature control.

The facility has completed the final phases of installation of the first furnace system. The testing and shakedown runs are essentially complete pending final calibration for the experimental runs. Some materials and operational issues need to be optimized, but these issues are not expected to impact the near-term inert gas atmosphere tests. Many of the problems of operation in chemically active atmospheres are under study, and materials having the required properties are under consideration for future designs and testing.

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