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WHOLE-PIN FURNACE SYSTEM: AN EXPERIMENTAL FACILITY FOR STUDYING IRRADIATED FUEL PIN BEHAVIOR UNDER POTENTIAL REACTOR ACCIDENT CONDITIONS*

Y. Y. Liu, H. C. Tsai, D. A. Donahue, D. O. Pushis, and F. E. Savoie[(1)]

J. W. Holland and A. E. Wright[(2)]

C. August and J. L. Bailey[(3)]

D. R. Patterson[(4)]

ARGONNE NATIONAL LABORATORY

Argonne, IL 60439-4838

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(1)Materials and Components Technology Division, (2)Reactor Analysis and Safety Division, (3)Engineering Physics Division, and (4)Electronics-Support Services Division.

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ABSTRACT

The whole-pin furnace system is a new in-cell experimental facility constructed to investigate how irradiated fuel pins may fail under potential reactor accident conditions. Extensive checkouts have demonstrated excellent performance in remote operation, temperature control, pin breach detection, and fission gas handling. The system is currently being used in testing of EBR-II-irradiated Integral Fast Reactor (IFR) metal fuel pins; future testing will include EBR-II-irradiated mixed-oxide fuel pins.

INTRODUCTION

Ex-reactor heating tests provide effective and economical means to study the behavior of irradiated materials, particularly under potential reactor accident conditions during which transient high temperatures tend to overwhelm neutron irradiation effects. Two excellent examples are the postirradiation heating tests conducted in the Fuel Cladding Transient Tester (FCTT) on oxide fuel cladding,[1] and in the Fuel Behavior Test Apparatus (FBTA) on metal fuels.[2] Whereas the FCTT tests generated data on the stress rupture behavior of irradiated cladding tubes, the FBTA tests generated data on the penetration of cladding due to fuel/cladding chemical interactions. Both are separate-effects studies, however, because only parts of the larger fuel pin system are tested and for only one specific purpose at a time: mechanical properties in the FCTT and, e.g., fuel/cladding compatibility in the FBTA. In neither system are the synergistic effects in an integral fuel pin evaluated.

In order to understand the synergistic roles of fission-gas pressure and fuel/cladding chemical interactions, a new experimental facility, the Whole-Pin Furnace (WPF) system, was constructed and installed in the Alpha Gamma Hot Cell Facility (AGHCF) at Argonne National Laboratory in Illinois. This system was designed and is currently being used to study the "integral" behavior of EBR-II-irradiated, Integral Fast Reactor (IFR) fuel pins under simulated, relatively long-term (minutes to days) loss-of-flow (LOF) and/or loss-of-heat-sink (LOHS) types of reactor accident conditions. Future testing will also include EBR-II-irradiated mixed-oxide fuel pins. The primary objectives of the WPF tests are: (1) to identify cladding breaching modes, mechanisms, and thresholds for metallic and mixed-oxide fuel pins; and (2) to provide data to enable further development and validation of fuel pin failure models.[3,4] Fulfilling these objectives will enhance our understanding on how irradiated fuel pins may fail under LOF/LOHS conditions, and bridge the gap between the short-term (seconds) transient overpower (TOP) experiments in TREAT[5] and the relatively low- temperature, inherent safety demonstration experiments in EBR-II.[6]

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SYSTEM DESCRIPTION

The major components of the WPF system (Fig. 1) are an in-cell furnace rig, a furnace control system, and a fission-gas measurement system (not shown). Ancillary components of the WPF system include a glycol/water heat exchanger for cooling the furnace body, and nitrogen and helium gas supplies for lamp cooling and environment control.

In-Cell Furnace Rig

The in-cell furnace rig consists of a test section and a furnace mounted on a self-propelled, remotely operated cart. The test section, containing the irradiated fuel pin, is a 122-cm-long stainless steel tube assembly normally evacuated and sealed during a test. Two pressure transducers, located at the top of the test section, provide the means for pin breach detection by measuring the pressure rise due to fission-gas release into the sealed system. Temperature along the length of the pin is measured by six Type-K thermocouples located at different elevations in the annulus between the irradiated fuel pin and the stainless steel tube. A Type-S thermocouple, welded on the outside of the stainless steel tube, serves as the control thermocouple for maintaining the desired test temperatures. Outside the stainless steel tube is a quartz tube that provides a channel for helium cover gas flow, which provides an inert atmosphere for the test section during the test.

The furnace is a 65-cm-long radiant heating chamber powered by four longitudinal infrared–filament lamps. Elliptically-shaped and highly reflective surfaces behind the filaments focus the radiant energy onto the centerline of the furnace where the test fuel pin is placed. The furnace is capable of continuous high-temperature (~1,100°C) operation over extended periods, with a short-term capability up to ~1,650°C. Low-mass lamp filaments and efficient energy focusing permit a rapid specimen temperature rise, up to ~30°C/s depending on the specimen size. Motorized lift and manual slide mechanisms on the cart are used to support, align, and adjust the position of the test section and fuel pin within the furnace.

Furnace Control System

Control of the furnace, based on feedback of the control thermocouple temperature, is administered by a microcomputer using commercially available software. In the closed-loop feedback algorithm, the control thermocouple temperature is compared, at a regular time interval, with the desired temperature profile, which could be a flattop, a ramp, or a specific profile that simulates a given reactor transient event. Using the conventional proportionality- integral-differential (P-I-D) method,[7] the software determines the desired amount of power to be delivered to the furnace by minimizing the deviation between the actual and the target temperatures. The coefficients of the P-I-D terms are preselected to achieve optimum temperature control, characterized by stable temperature tracking, minimum time lag, and modest temperature overshoot.

To permit unattended WPF operation for up to several days, furnace trips governed by hardware and software mechanisms, some of which are redundant, are provided. Trip initiators under normal conditions include high test-section pressure (i.e., cladding breaching) and expiration of the desired test duration. Trip initiators under abnormal conditions include high/low control thermocouple temperatures, high furnace power, high coolant temperature, and low coolant flow rates. Protection of the hot cell and the system are the primary functions of the latter trip initiators.

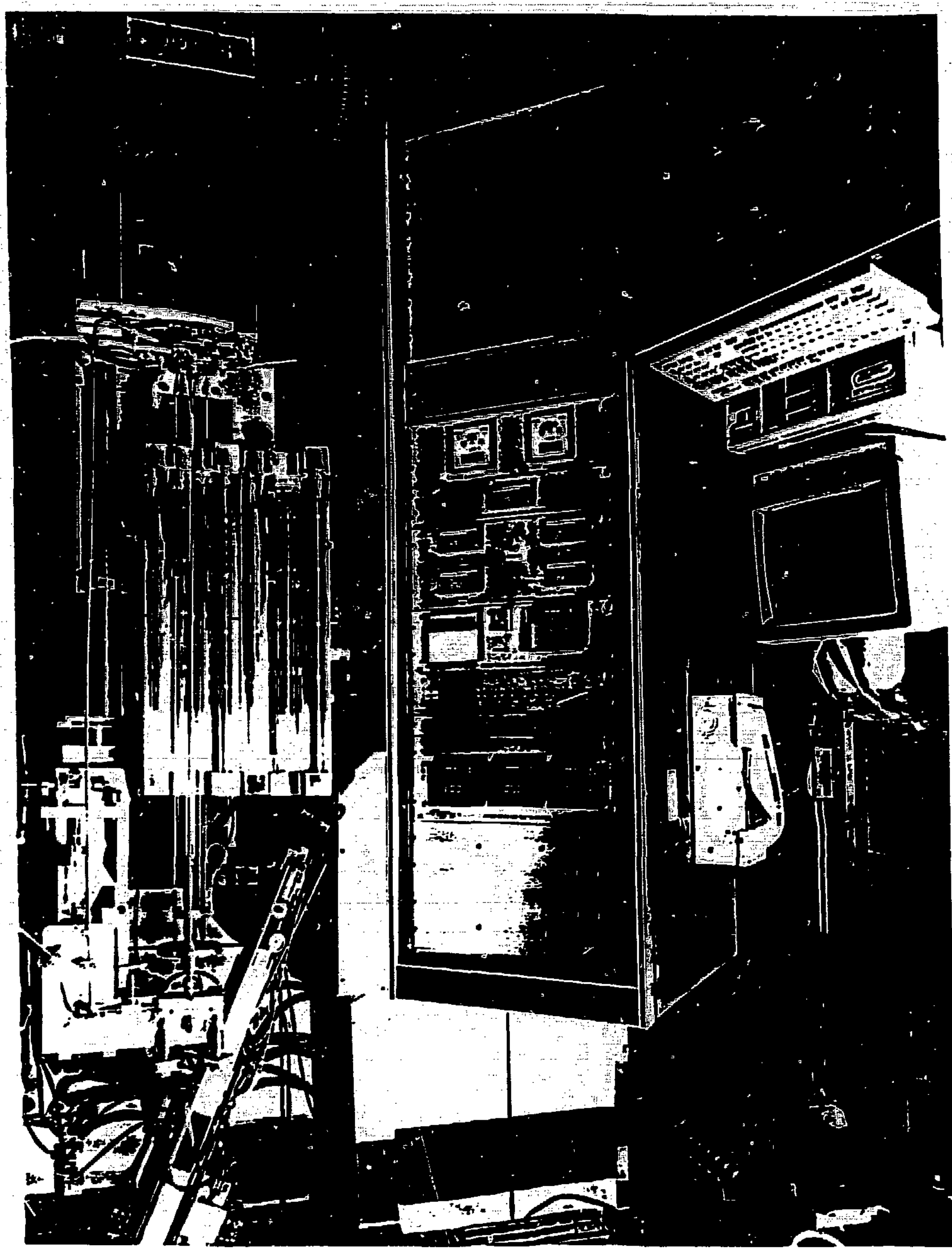

Fig. 1. The Whole–pin Furnace system before the furnace (open and at the right) was placed in–cell.

The microcomputer also performs the functions of data acquisition and storage. Key test parameters are displayed on a monitor to exhibit test progression on a real time basis. A manual scram ability is provided for operator intervention, if necessary.

Fission-Gas Measurement System

The major functions of the fission-gas measurement system are to collect the released fission gases for measurement, analysis, and a controlled disposal. The system consists of two subsystems. The gas retention subsystem, located in-cell, initially collects the non-condensible fission gases released into the test section from the breached pin. The gas sampling subsystem, located out-of-cell, measures the gas pressure and allows extraction of fission-gas samples for mass spectrometric analysis. The vacuum pump, pressure measuring devices and system gas-purging apparatus are located out-of-cell in conjunction with the gas-sampling subsystem. The manifold volumes of the in-cell and out-of-cell subsystems were designed such that only a small quantity of fission gas is brought out of the cell during measurement and sampling, while the bulk of the fission gas remains in-cell in two expansion chambers.

PERFORMANCE CHARACTERISTICS

Every phase of the WPF operation was thoroughly checked during out-of-cell acceptance testing before the furnace rig was installed in-cell. Detailed procedures were developed for the necessary tasks of pin loading into the test section, assembly and disassembly of the test section onto the cart, etc. and for contingency tasks such as replacement of the furnace lamps or the furnace itself. The fission-gas measurement system underwent leak and pressure tests, manifold volume calibration, and gas collection and measurement trials, all using helium and argon as substitutes for fission gas. After the furnace rig was introduced into the cell, a series of in-cell acceptance tests was conducted to verify system leak tightness, remote operation, and sensor functions. As a result of the thorough out-of-cell checkout, only minor procedural modifications were found necessary to perfect the in-cell operations.

The thermal performance of the furnace and the pin breach detection system were two crucial areas that were checked in-depth. Results obtained from the characterization of these areas are summarized below.

Thermal Performance

The thermal performance of the WPF system has been characterized in over sixty out-of-cell and in-cell checkout runs, most of which used an evacuated test section containing a dummy fuel pin identical in nominal dimensions to an irradiated IFR fuel pin. Early tests had established that heat transfer to the pin would not be significantly degraded if the test section was evacuated rather than containing a heat-conducting gas. For operational considerations of pressure transducer sensitivity and later when the released fission gases would be collected and sampled for quantitative analysis, it was decided that the normal mode of operation would be with an evacuated test section.

The major purpose of the thermal performance checkout runs was to determine the P-I-D parameters to be used in the closed-loop feedback algorithm for temperature control. Criteria for the desirable thermal performance were a ramp rate of 5 to 10°C/s; a stable tracking within ±5°C of the target temperatures (as indicated by the control thermocouple) in the range of 600 to 925°C (similar to those of the FBTA tests); and an overshoot of the target temperature of only 15°C or less. The results of the checkout runs indicated that the first two criteria were easily met , i.e., ramp rates between 4.5 to 7.3°C/s and target temperature tracking within ± 2°C were achieved. The third criterion was also satisfied in all but two runs, which had overshoots of ~18°C that lasted no more than 150 s before returning to a stable target temperature. A typical example of the temperature control is shown in Fig. 2 for a target temperature of 800°C.

The steady-state furnace temperature profile for a 900°C target temperature, shown in Fig. 3, indicated an ~160°C difference between the temperatures at the midheight of the furnace and at 3 cm above the bottom of the furnace heating zone. This temperature difference reduced to ~120°C at a target temperature of 800°C. In an actual test, the relative position of the fuel pin within the furnace can be adjusted (by raising or lowering the test section support platform on the cart) to match the anticipated axial temperature profile for a given portion of a fuel pin in a given reactor transient event. If this adjustment alone is not sufficient, the helium flow rate through the test section quartz tube can be altered to provide additional temperature shaping capability.

Pin Breach Detection

The sensitivity and response time of the WPF system to detect pin breaching in an evacuated test section was demonstrated by heating pre-defected pressurized capsules having fusible seals. The capsules had a 0.8-mm-diameter, pre-drilled hole (i.e., a simulated defect) soldered closed with a Ag-Cu-Zn-Sn soldering material that melts at 618°C and flows at 652°C. The lengths of the capsules were sized such that the contained argon gas pressure would approximate that of fission gas in irradiated IFR fuel pins when the capsules were at temperature. The distance between the defects in the capsules and the pressure transducers at the top of the test section was ~100 cm, roughly the same as that anticipated for the breach of a real fuel pin under test.

The pressure transducer responses in the pressurized capsule runs were qualitatively similar, and Fig. 4 shows the response for the capsule containing the least amount of argon gas. The pressure inside the evacuated test section remained low (<1 kPa) during slow heatup (~1°C/s) from 300°C, indicating that the test section was sealed tight during the temperature rise. The pressure increased abruptly at 345 s when the control thermocouple temperature reached 619°C, one degree above the solidus of the Ag solder. This pressure rise caused a furnace trip at a trip pressure of 8.2 kPa less than two seconds after melting of the Ag-soldering material. Considering the distance (~100 cm) between the defect and the pressure transducers, the sensitivity and response time of the system were excellent in detecting pin breach in an evacuated test section. Lowering the trip setpoint of the pressure transducers will further reduce the time between pin breach and detection, at a sensitivity level essentially limited by the electronic noise (~1 kPA) of the transducers.

After each of the two sensitivity runs, the argon gas was collected to test the accuracy of the gas collection and measurement system. The volumes of gas collected for the two runs were 50.6 and 146.6 cc (STP). These values are in excellent agreement with calculated contained volumes of 50.4 and 147 cc, respectively, before the tests, thus demonstrating the capability of the system to quantitatively measure released fission gases.

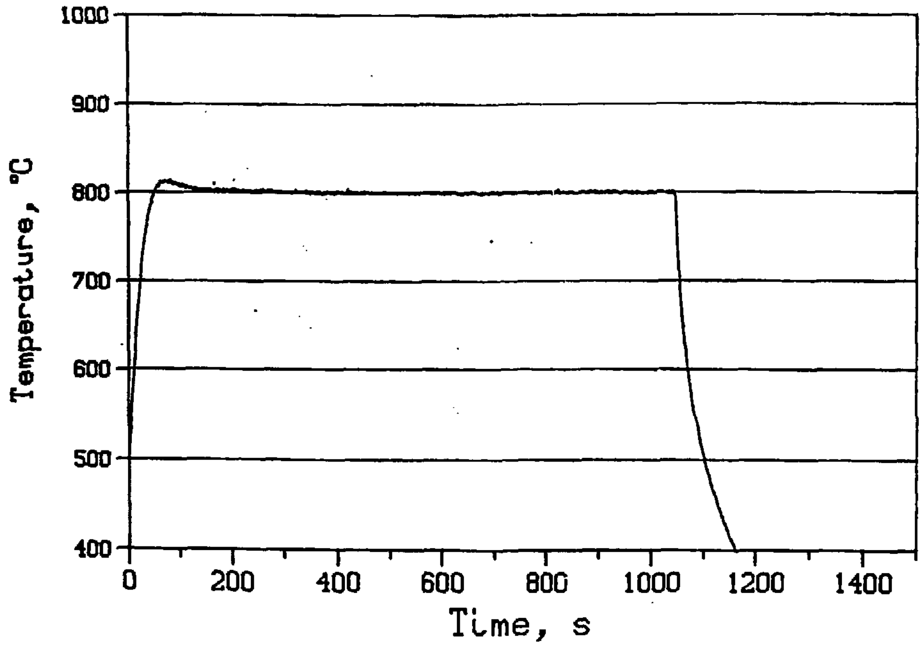

Fig. 2. Typical time–temperature history of the computer-controlled WPF system.

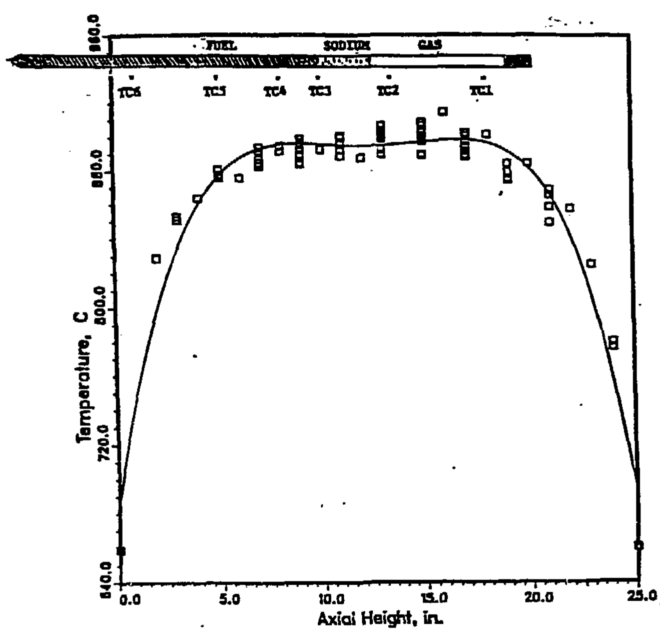

Fig. 3. Characterization of the axial temperature profile for a 900°C target temperature.

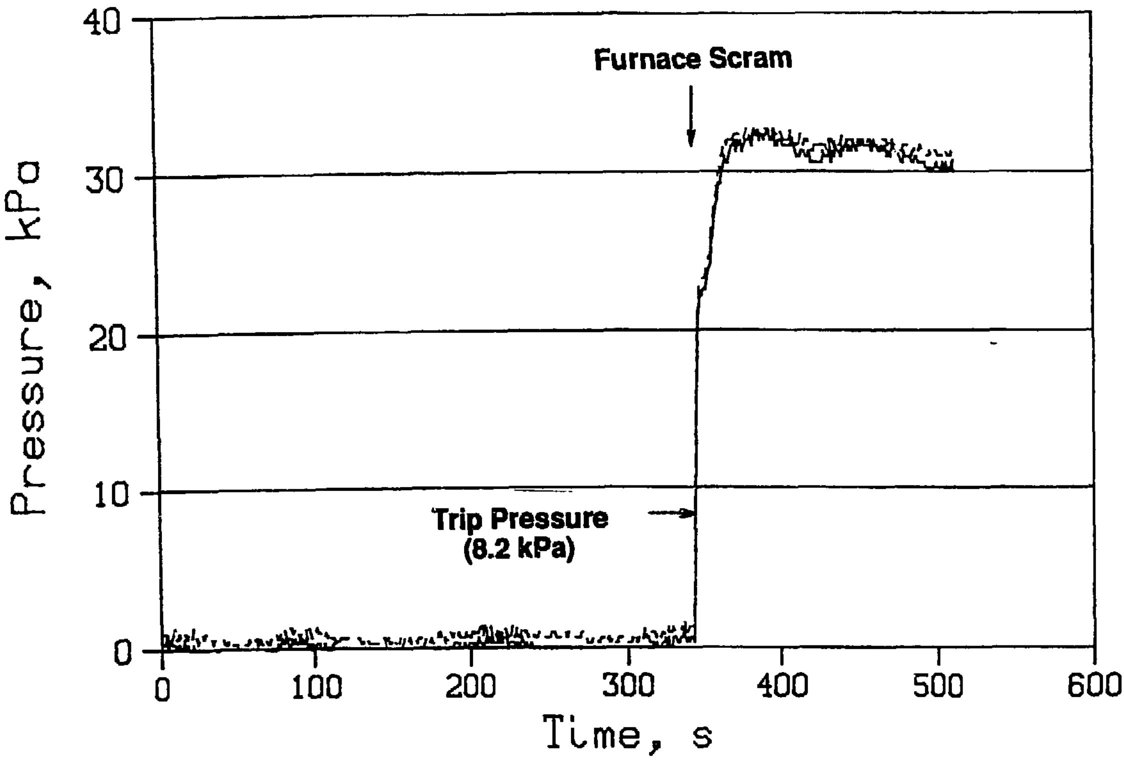

Fig. 4. Pressure transducer responses in a pressurized capsule test with a fusible seal.

CONCLUSIONS

Extensive checkout and acceptance testing of the WPF have demonstrated excellent capabilities in remote operation, thermal performance, pin breach detection, and fission gas handling. The ability to sensitively detect pin breach under closely simulated accident temperature conditions, coupled with a variety of the pre- and posttest examination techniques (e.g., pin profilometry, gamma scan, electron beam instruments), will provide a capability to better understand the modes and mechanisms of pin breach, for establishing the margins to pin breach for present and future fuel–pin designs, and for generating data to be used in the development and validation of fuel pin failure models. The first WPF in-cell test on an irradiated fuel pin has already been successfully conducted; more tests will follow in the near future.

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