Written: April 1970
Distributed: July 1970

LA-4453-MS
UC-37, INSTRUMENTS
TID-4500

LOS ALAMOS SCIENTIFIC LABORATORY
of the
University of California
LOS ALAMOS • NEW MEXICO

Design and Fabrication of a Thermal Scanner

by

Karl L. Meier

LEGAL NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Carl

DESIGN AND FABRICATION OF A THERMAL SCANNER

by

Karl L. Meier

ABSTRACT

The thermal scanner is an experimental device used to determine the size and movement of fission product gas bubbles in the bond of a sodium-bonded reactor fuel pin. A reactor fuel pin is simulated by a heater, a uranium carbide (UC) cylinder, and a 10-mil sodium bond, all contained in a 10-mil wall, 0.350-in. o.d. stainless steel cylinder that simulates the fuel pin cladding. A helium or argon gas bubble is created in the bond by a micrometer syringe. Thermocouples are used to measure the cladding temperature. Bubbles in the bond cause the cladding temperature to depart from normal. The thermocouple output is interpreted by a computer that produces a temperature map of the cladding surface. Movement of the bubble is determined from successive maps.

Status of the experiment, which has been terminated because of the Atomic Energy Commission cancellation of the Los Alamos Scientific Laboratory program in which the work was conducted, is described. Information that may be helpful if the experiment is to be reactivated is also given.

1. INTRODUCTION

The purpose of the thermal scanner experiment is to determine the size and movement of fission product gas bubbles in the bond of a sodium-bonded reactor fuel pin. The fuel pin simulator is shown schematically in Fig. 1. The position of the bubbles in the bond can be determined by thermocouples that measure the fuel pin cladding temperature. Because the bubble acts as an insulator, the cladding temperature over a bubble is lower than the temperature over an unperturbed sodium bond. The heat flow produced by the heater at the center of the fuel pin simulator is symmetrical and constant and would normally produce a uniform temperature on the outer surface of the cladding. When a bubble is present, this heat flows around the bubble and causes the cladding temperature to rise in the area around the outside of the bubble. The temperature perturbation caused by a bubble is

Fig. 1. Fuel pin simulator.

shown in Fig. 2. A heat transfer analysis¹ was used to produce Fig. 2. This analysis also indicated (for a heat flux of 10^6 Btu/h ft²) $\approx 25^\circ\text{F}$

Fig. 2. Temperature vs position.

maximum temperature rise around the periphery of a 0.100-in.-diam bubble and a drop of 35°F at the center of the bubble.

Barner's analysis¹ indicated that bubbles of a diameter less than 0.100 in. would have little or no effect on the temperature distribution in the fuel. Bubbles larger than 0.100-in. diam would cause hot spots in the fuel, which would lead to excessive swelling, cracking, and spalling. The life of fuel elements with these detrimental hot spots would be shortened.

II. DESCRIPTION OF APPARATUS

The thermal scanner shown schematically in Fig. 3 consists of a fuel pin simulator with its heater, a thermocouple rotor assembly, a bubble injection apparatus, and an outer structure.

The fuel pin simulator has a 10-mil wall, 0.350-in. o.d. stainless steel cladding, a cylinder of uranium carbide (UC), and a 10-mil sodium bond. Inside the UC cylinder is an electric heater that produces heat at about the same rate that a fuel pin would in a breeder reactor.

The cladding temperatures are measured by 40 thermocouples mounted upon a rotor that fits around the fuel pin simulator. The rotor is turned by a motor so that each thermocouple can measure temperatures at 11 azimuthal locations on the cladding. The thermocouple data are transmitted out of the rotating assembly by slip rings to an analog-to-digital converter data acquisition system.

Fig. 3. Thermal scanner schematic.

A helium or argon gas bubble is created in the bond by a micrometer syringe through an 8-mil o.d. tube leading into the bond. After injection of a measured amount of gas, this tube is pulled downward away from the bubble to eliminate any holding effect of the tube on the bubble.

The outer structure is the structural containment for the scanner. The fuel pin simulator, heater, rotor, slip rings, and heat transfer sodium are contained within it. The heat transfer sodium leaks through the thermocouple holes and bearings in the rotor. The sodium leaks into the lower casing of the outer structure that is filled with helium cover gas. Leakage of sodium proceeds until the cover gas is compressed to a pressure equal to the inlet sodium pressure and then stops.

The cover gas volume is sealed at the moving rotor by O-rings in a relatively cool portion of the scanner. This area is kept cool by flowing nitrogen gas.

The outer structure is fabricated to reduce thermal stresses caused by the temperature difference between the sodium (1000°F maximum) and room temperature.

The assembly and details of the thermal scanner are shown on Los Alamos Scientific Laboratory (LASL) drawings 37Y-61183-E1 through D17. A drawing of the scanner on its stand, attached to the sodium system, is shown in LASL drawing 37Y-61190-E1.

The thermal scanner is divided into several subsystems. A more detailed description of these subsystems and other systems required for operation is given below.

1. Sodium loop,
2. Power source,
3. Controls,
4. Data acquisition,
5. Bubble injection,
6. Thermocouples and rotor,
7. Gas seals,
8. Outer structure,
9. Slip ring assembly,
10. Top plate-sodium tube,
11. Drive train,
12. Transition section,
13. Heater,
14. Fuel pin simulator, and
15. Gas distribution.

1. Sodium Loop

The sodium loop system is shown schematically on drawings 37Y-61127-D1 and 37Y-61135-D1. The loop has a 25-gal/min, 30-psig pump, a 500-gal reservoir, and a cold trap. It supplies the heat transfer sodium to the thermal scanner. An electromagnetic flowmeter measures the sodium flow to the thermal scanner. Valves for flow control, shutoff, or bypass are included. An extensive network of electrical heaters is required to keep the sodium molten and of constant temperature throughout the system. When the scanner heater is turned on, an additional 11 kW of heat is put into the system. Eleven kW of system heaters should be turned off so that the system temperature remains constant.

2. Power Source

The power system is shown schematically in Fig. 4. Power for the scanner heater is obtained from a 45-kVA, single-phase, 1500-A maximum output transformer. The transformer input voltage is controlled by a motor-driven powerstat. A 440-V, single-phase, welding outlet services the trans-

former. Overload protection is accomplished by a series of 10-A fuses on the powerstat. They restrict the output to 500 A.

Fig. 4. Power control system schematic.

Power is transmitted to the scanner heater through copper welding cables. The high-voltage cable clamps to the heater conductor rod near the top. The ground cable clamps to the sodium inlet line at the bottom of the scanner.

3. Controls

Control of the transformer is accomplished by a bidirectional motor on the powerstat as shown in Fig. 4. A three-way switch on the control panel allows current to turn the motor to raise, lower, or hold output power.

A manual switch to turn the sodium pump on and off is mounted on the control panel, and the pump can be shut down by any of five circuits in the shutdown chain. Switches to bypass the shutdown chain are mounted on the control panel. Shutdown occurs if (a) the upper sodium level probe in the scanner is shorted by a high sodium level, (b) if the casing temperature gets too high, (c) if the G-ring seal temperature is too high, (d) if the current draw of the heater is too high, or (e) if the manual pump shutdown button is actuated.

pulled out slightly to lift the inner seal and to allow charging gas to enter the syringe. The outer seal prevents air from entering the syringe at this time. The charging port pressure should be the same as the cover gas pressure to prevent premature bubble formation in the bond. After charging, the locknut is tightened and a bubble can be created at the end of the 8-mil tube by turning the micrometer device on the syringe clockwise. A lavite insulation tube prevents overheating of the syringe by the hot sodium in the shell. The fuel pin simulator is brought down over the 8-mil tube and rests in the simulator assembly support. The carbon steel plunger rests on a spring and is connected to the 8-mil tube. After a bubble has been created in the sodium bond, a solenoid pulls the plunger downward; this in turn retracts the 8-mil tube downward and the bubble is freed from the end of the tube. Cooling of the annulus between solenoid and plunger is critical. The solenoid temperature must be less than 200°F, but the sodium must remain liquid so that the plunger will move. A computer program HTSOLEN was developed to determine the GN_2 coolant flow rate required to obtain the proper temperature distribution. The solution to this problem is incomplete.

6. Thermocouples and Rotor

As shown on drawing 37Y-61183-D11, the thermocouple rotor holds the thermocouple mounts that hold the 40 thermocouples for measuring cladding temperatures. Each mount rigidly holds two thermocouples by means of swaged collars. Good contact with the cladding is necessary for accurate temperature measurement of the cladding. A spring allows radial movement of the mount and thermocouple assembly, and keeps the thermocouples pressed against the cladding. The rotor has a Stoddy No. 6 alloy bearing in its base, which rests on another Stoddy No. 6 bearing on the base plate. The top of the rotor bears on the inner and outer O-ring seals and the sodium tube.

Sodium flows through the inside of the rotor and leaks out through the bearing at the bottom and through the lower thermocouple holes into the casing. The sodium pressure drops as it flows upward through the rotor. In the upper half of the rotor, sodium flows from the casing inward through the thermocouple holes and the upper bearing at the sodium

tube. This leakage inward and outward results in a varying sodium flow over the cladding inside the rotor. Leakage should be kept to a minimum by maintaining close clearance in the thermocouple holes and at the bearings.

The 40 thermocouples are Chromel-Alumel with a 20-mil o.d. stainless steel sheath and are grounded at the tip for fast response. The time constant is 20 msec.² When inserting or removing the fuel pin simulator, the thermocouple mounts must be pulled outward to lift the thermocouples from the cladding. This can be done through the access port in the lower casing. A small block is placed between each mount and the rotor to keep the thermocouples in an outward position until the fuel pin simulator is replaced.

The 40 thermocouples pass through the rotating seal cylinder portion of the rotor at the top. A leaktight solder seal should be made over all gaps in this area. The silastic seal shown in the drawing was inadequate, but a solder seal would be more effective. Leaktightness is important in this area and at the O-rings to prevent helium cover gas leakage. The O-rings must be lightly lubricated with silicone grease to reduce friction. A leak check should be performed on the solder seal and each O-ring. It was necessary to custom-make the first outer O-ring 9 mil oversize in section diameter and 18 mil oversize on the o.d. to correct for a machining error on the outer seal cylinder.

7. Gas Seals

At the time the scanner was designed, no dynamic seal was available to prevent sodium leakage from the rotor at 1000°F. The system was therefore designed to allow sodium to leak out of the rotor and to fill the lower casing to a point where the sodium pressure equaled that of the helium cover gas. The helium cover gas can be sealed dynamically in a cooler area by neoprene O-rings that seal against the rotating seal cylinder portion of the rotor. Nitrogen cooling gas flows downward along the inside of the inner seal cylinder to cool the inner O-rings. Cooling is similarly accomplished for the outer seal cylinder containing the outer O-rings. A baffling arrangement is needed to direct the GN_2 coolant flow. A heat transfer analysis was made on the area of the seals, cylinders, baffles, and outer casing. The analysis

consists of 31 simultaneous equations of heat conduction and convection. The computer solution is called HTSHELL and it gives GN_2 and structural temperatures at about 20 points in the system. The results show that with 1000°F sodium in the sodium tube and 800°F sodium in the lower casing, the O-ring temperature is about 210°F. A GN_2 flow rate of 0.0142 lbs/sec in each coolant passage is required to achieve this temperature. The maximum recommended temperature of the O-rings is 300°F. Thus, a lower GN_2 flow rate could be used; perhaps a factor of 2 reduction is possible. HTSHELL will predict the O-ring temperature and 20 other system temperatures for any flow rate.

8. Outer Structure

The outer structure consists of the 8-in. diam upper and lower casings, base plate, outer seal cylinder, and two GN_2 coolant distribution manifolds. The casing, top plate, and base plate complete the structural continuity of the sodium tube that was interrupted by the rotor. The level of the sodium that partially fills the lower casing is measured by upper and lower level probes. The lower casing has a helium cover gas inlet. The access port of the lower casing has an Advanced Products Company Lo-Load metal ring seal to prevent sodium leakage. This seal has not yet been tested in sodium at design temperature.

The gas distribution manifolds are designed to take gas from an inlet at one side of the casing and to distribute it equally around an annulus. The inlet pressure to the manifolds must be 30 psig to achieve 0.0142 lbs/sec GN_2 flow. The gas flow is sonic at the outlet holes to give a more even annular flow distribution. If the inlet pressure is lowered to reduce the coolant flow rate, sonic flow should still be maintained at the outlet holes. The slip ring assembly is aligned on the upper casing by means of three screws.

9. Slip Ring Assembly

The slip ring assembly transports the millivolt signals from the 42 moving thermocouples to the stationary Amphenol 348-23H18-85P connector plug. (Forty thermocouples are from the rotor and two are from the O-ring seal area.) The Amphenol connector must be disconnected from the top plate if it is necessary to remove the top plate.

Connections for the thermocouples and the slip ring wires are made at screwed connections on the connector plate. Preliminary tests indicated no need for soldering these junctions. The slip ring assembly is an Airflyte Electronic Company DAY-402. This assembly must have an O-ring seal between it and the upper casing to prevent GN_2 coolant bypass. A copper adapter is connected to the top of the slip ring assembly to hold the follower gear, but the adapter cannot be installed until subassembly 300 is inside the assembly.

The pressure of the sodium in the lower casing is greater than atmospheric. The weight of the rotor, slip ring assembly, and adapter is greater than the force of the overpressure on the rotating seal cylinder. The weight keeps the rotor on the base plate bearing if the sodium pressure is less than 7 psig. Flow control and throttling of sodium should therefore be done at a valve upstream of the scanner and all downstream valves should be kept full open.

10. Top Plate and Sodium Tube

The top plate is part of the structural continuity of the sodium tube that was interrupted by the rotor. The sodium tube carries sodium through the slip ring assembly. The sodium temperature can reach 1000°F, but the slip ring assembly should be kept below 250°F. A cylinder of insulation (Jonns Manville Min-K) was therefore placed around the sodium tube to protect the slip ring assembly. The insulation was wrapped with aluminum foil for protection from erosion by the high velocity GN_2 . GN_2 coolant from the inner seal cylinder flows between the insulation and the slip ring assembly to remove heat flowing from the sodium. This same GN_2 also cools the stress cylinder at the top of the sodium tube. The stress cylinder relieves the thermal stresses that would be present in the relatively cold top plate if it were in direct contact with the 1000°F sodium flowing through the sodium tube.

11. Drive Train

The drive train is powered by a 400-oz in. slo-syn motor with a 4-1/3 to 1 planetary gear reducer. A drive shaft is connected to the motor and a 26-tooth driver gear is keyed to the shaft. The driver gear transmits power to the 99-tooth follower gear connected to the slip ring assembly.

Three-hundred steps of the slo-syn motor turn the thermocouple rotor 1/11 of a revolution. (0.100 in. on the 1.100-in. cladding circumference.)

The motor rests on two vertical mounts that are high enough to keep the motor above the transition section and the lead heater weight. The vertical mounts are attached to the motor mount plate bolted to the top plate. The stainless steel drive shaft bears upon a bronze journal on the motor mount plate. The purpose of the motor mount plate is to simplify the seals in the area of the vertical mount screws. The journal and gears must be lightly greased with silicone grease to reduce friction.

12. Transition Section

The transition section accommodates the temperature difference between the hot sodium and the atmosphere. It has two nesting bellows that allow for expansion of the heater tube and the cladding tube. The bellows are Metal Bellows Corporation 60130-3 and 60150-3. The maximum allowable internal pressure is 4 psig and the maximum external pressure is 85 psig. The vent screw in the outer bellows assembly should be removed at the time of insertion into the scanner so that the bond sodium pressure can equalize with the coolant sodium pressure. At assembly there must be provision for 1/2 in. of compression to take place in each bellows upon reaching heater operating temperature.

The system can be evacuated or pressurized with helium through the valve on the outside container of the transition section. The outside container is sealed to its top by an Advanced Products Company Lo-Load metal ring seal. The heater can be similarly evacuated or pressurized through the valve on the heater flange. The bellows outer container should be electrically heated and insulated, but the tube leading to the heater flange and the flange itself should not be heated and insulated. There is a 500°F maximum temperature Teflon O-ring in the flange that will be cool enough if left open to the atmosphere.

13. Heater

The heater creates a heat flux of 10^6 Btu/h ft² at the cladding outer surface to simulate breeder reactor conditions. The 11 kW heater is composed of a graphite rod in which heat is generated by 400 A of ac current. It is similar to a heater designed

by Atomics International.³ A boron nitride insulator prevents the current from short circuiting around the graphite rod to ground. A 10-mil stainless steel sheath over the boron nitride insulator prevents sodium from entering the heater and causing a short circuit. During operation, the heater should be pressurized with helium through the heater flange to allow maximum heat transfer. The helium pressure should be equal to the sodium pressure in the scanner to minimize heater sheath stresses. The sheath, insulator, and graphite rod are a tight fit when cold, which is necessary to keep the gaps between them small at operating temperature, thereby achieving good heat transfer. A platinum disk is placed at the bottom of the graphite rod and a tungsten disk at the top. The disks extend heater life by reducing graphite diffusion. Current is brought to the graphite rod through a copper rod with a molybdenum tip. A lead weight is placed at the top of the copper rod to make better electrical contact between the parts of the heater. (A high resistance spot will cause overheating and heater failure.) Cleanliness of heater components is essential at assembly. Boron nitride dust must be kept off of the conducting surfaces. A helium atmosphere should be kept in the heater at all times to prevent atmospheric corrosion of heater parts.

14. Fuel Pin Simulator

A breeder reactor fuel pin is simulated by a 30-mil wall cylinder of UC, surrounded by a 10-mil sodium bond, and encapsulated by a 10-mil wall, 0.350 o.d. stainless steel cladding as shown in Fig. 1. The cylinder is composed of three pieces fitted together axially and on the same centerline to provide a smooth, step-free surface. Future tests should be performed with steps machined into the cylinder pieces to misalign them and thereby simulate actual fuel pellet stacks. Additional cylinders can be made from a UC billet stored at LASL Group CMB-6.

At assembly, the heater alignment pin at the bottom of the heater should be placed in its mating hole in the bottom of the fuel pin simulator. The 8-mil bubble tube should be placed in the simulator, and the simulator inserted into the simulator assembly support in the bubble injection apparatus. The conoseal joint should be made last. The UC cylinder

must be protected at all times by a dry, inert atmosphere.

15. Gas Distribution

Gas distribution to the various parts of the scanner is accomplished at the distribution manifold. A schematic of this system is shown in Fig. 7. GN_2 is supplied by a trailer. A regulator reduces the pressure to 150 psi at the manifold. Helium is supplied by a K-size bottle and vacuum by a pump. GN_2 O-ring coolant flow is measured by orifices according to the following equation.

$$\dot{m}(\text{lb/sec}) = 0.0127 \sqrt{\Delta P(\text{psid})} \quad (1)$$

Rotometers measure GN_2 coolant flow to the bubble injection tube solenoid and the flow of helium cover gas. The latter should be zero for proper operation of the scanner.

III. TEST RESULTS

A test was made of the heater in the sodium system with the 45 kVA power supply. The test was conducted for 30 min at 11 kW power output. The heat flux at the heater surface was 1.48×10^6 Btu/h, which would produce a heat flux of 1.01×10^6 Btu/h ft^2 at the cladding surface.

The heater test was conducted long enough to determine if there were any material, structural, or assembly defects to cause failure of the heater by short circuit or open circuit. Previous experience³ in heater testing showed that if a heater did not fail in the first few minutes of full-power operation, the heater would usually last for hundreds of hours, and failure then would be by open circuit caused by graphite diffusion.

A test was performed on the power supply and its primary transformer and circuit protection devices. Results of the tests were satisfactory.

Tests were performed on the bubble injection apparatus in a glass-walled, bond mockup by using low temperature sodium and the UC fuel cylinder. Bubbles of sizes varying from 0.050 to 0.500 in. in diameter were formed in a 10-mil sodium annulus at 200°F. A bubble can be constructed and reduced in size by the micrometer syringe, but the number of divisions on the micrometer is highly variable for the same size bubble. A varying amount of over-pressure in the syringe is necessary to start bubble formation. The scanner thermocouples can be used to tell the size of the bubble. The syringe can be

adjusted to give the size desired. The bubbles do not necessarily form at the top of the 8-mil tube, but may form slightly below the tip or to the side. Bubbles as large as 0.500 in. diam did not move in 30 min of tests in the glass bond mockup. Vibration caused the bubbles to change shape, but not to move up appreciably.

Fig. 7. Gas distribution system.

A flawless sodium bond could be made in the test apparatus by pumping a good, cold-trapped vacuum on the bond annulus and by pouring sodium into and above the bond area. Pressurization of the bond annulus from the top with helium collapsed all the voids. Bond integrity can be checked with the scanner thermocouples before bubble construction. The fuel pin simulator bond should be made in this manner.

A test of the heater inside the fuel pin simulator should be conducted before using it in the scanner. The scanner should be brought as near

to design temperature as possible with electric heaters to test the GN_2 coolant performance.

A study of bubble movement in thin annuli was made at Westinghouse Electric Corporation.⁴ Experiments were performed using glass, water, and brass pellets. It was determined that bubbles tended to grow large enough to cause fuel hot spots and tended to remain stationary even after vibration.

IV. STATUS OF FABRICATION

All parts of the thermal scanner have been fabricated. A safety shell should be built over the outside to afford personnel protection in the event of sodium leakage. The gas distribution manifold has been fabricated although the lines connecting it, the supply sources, and the scanner have not been completed. The power system is completed and operable. The data system is nearly complete except for the shutdown chain. All recorders and the A-to-D data system are operable. The computer data program is complete and has been tested. The control panel is complete except for shutdown chain controls.

Assembly of scanner parts is complete except for the heater and fuel pin simulator. These parts should be assembled in the transition section and test sodium tube, as shown on drawing 37Y-61183-D6. A test of the heater inside the fuel pin simulator should be performed in that configuration before inserting it into the scanner. This test would cause the heater parts to reach a higher temperature than that of the previous heater test. After this test has been completed, the transition section, along with the heater and fuel pin simulator, should be removed from the test sodium tube and be placed on the sodium tube of the thermal scanner in the final configuration as shown on drawing 37Y-61183-E1.

REFERENCES

1. J. O. Barner, "Quarterly Status Report of Advanced Plutonium Fuels Program, October 1 to December 31, 1967," Los Alamos Scientific Laboratory, LA-3880-MS, (Feb. 20, 1968).
2. P. G. Bentley and R. Rowley, "Comparison of the Frequency Responses and Time Constants of Mineral-Insulated Thermocouples in Sodium and Water," Reactor Engineering Laboratory, Risley, England, TRG Report 1259 (R) (May 24, 1967).
3. E. L. Babbe, J. H. Shively, and M. W. Mahoney, "High Heat Flux Heater Development," Atomica International, AI-AEC-128i3 (July 15, 1969).
4. H. O. Schad and A. A. Bishop, "Stationary Gas Bubbles in Narrow Liquid Filled Gaps," Westinghouse Electric Corp., Nucl. Appl. Tech., 8, p 261, (March 1970).