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INSTRUMENTATION AND CONTROL ACTIVITIES AT ARGONNE.
Annual Report for Period Ending June 30, 1971

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FOREWORD

The first annual report describes the accomplishments and/or status of LMFBR Program-oriented instrumentation and control research and development activities at Argonne during fiscal year 1971. These activities are directly or indirectly funded by the Division of Reactor Development and Technology, USAEC, and can be divided into three categories: (1) those in support of near-term program objectives, i.e., operation of the Fast Flux Test Facility (FFTF); (2) those in support of long-term program objectives, i.e., operation of demonstration and commercial LMFBR plants, and (3) those in support of other programs, i.e., operation of critical reactor facilities. In addition to laboratory development and fabrication of prototype instruments in support of these programs, Argonne has a commitment to prepare standards or specifications for commercial procurement of materials, components, and assembled instruments, with emphasis on development of competitive industrial sources of supply.

To orient the reader, each activity is prefaced with a brief description of the nature of the work, the objectives, and prior progress, if any. This is followed by a summary of the accomplishments and/or status of the activity during fiscal year 1971, with a minimal description of how the work was done. References to more comprehensive coverage are given where available; if not, interested readers desiring more information may call or write the investigators identified with each activity.

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INSTRUMENTATION AND CONTROL ACTIVITIES AT ARGONNE

Annual Report for Period Ending June 30, 1971

ABSTRACT

This annual report, the first of its kind from ANL, describes the status of instrumentation and control activities in the LMFBR program during fiscal year 1971. Activities supporting near-term objective (e.g., operation of the FFTF) to long-term objective (e.g., commercial LMFBR plants) are described. Reactor monitoring techniques, plant control, FEDAL systems, nondestructive testing, and instrument test facilities are described, as well as the systems for measuring reactor-system parameters.

I. SODIUM FLOW INSTRUMENTATION

A. Flow Probes for Fuel Assemblies

The ability to reliably and accurately measure sodium coolant flow through individual LMFBR fuel assemblies would permit reduction of "hot-channel factors" in reactor core design calculations. Also, during reactor operation, these measurements would provide the earliest indication of flow blockage in an assembly, thereby initiating reactor shutdown before significant damage to the fuel could result.

Accordingly, prototype flowsensors are being designed, developed, constructed, tested, and evaluated to meet stringent criteria and requirements specified by the FFTF Project, and, simultaneously, to satisfy the associated LMFBR Program Plan Task. Continuous monitoring of sodium flow at the outlet of each FFTF fuel assembly is a specific requirement of the development. In addition, the flowsensor must be replaceable, small in size, and give a significant output signal. Specifications are prepared for commercial procurement of materials, components, and assembled flowsensors, with emphasis on development of competitive sources of supply. Currently, these flowsensors include eddy-current, permanent-magnet, and magnetometer probe-type devices.

1. Permanent-magnet Flow Probes--F. Verber

The stringent space requirements of the FFTF fuel assembly necessitated development of a new concept in permanent-magnet flowmeter design. This design uses a solid, cylindrical permanent magnet enclosed in

a tightly fitting sheath and aligned axially in the sodium stream. With the direction of magnetization perpendicular to the stream, an electrical potential difference is developed in the sodium around the sheath. The maximum potential exists on a line perpendicular to the direction of magnetization. When two electrodes or leads are affixed to the inner wall of the sheath on this line, an electrical potential is produced which is proportional to the velocity of the flowing sodium and the magnetic flux density. A typical permanent-magnet flowsensor design is shown in Fig. I-1. The sodium duct is not integral with the flowsensor, and in the FFTF is represented by the outlet duct of each fuel assembly.

Fig. I-1. Permanent-magnet Probe-type Flowsensor. ANL Neg. No. 113-3901.

Early work in this program established the suitability of Alnico magnets for service in a neutron fluence typical of the FFTF. Examination of magnet samples irradiated in EBR-II revealed that the magnets, particularly Alnico VIII, probably will survive a dose of 10^{22} nvt at 1000°F while maintaining 5% stability of magnetic moment.

Feasibility of the probe-type design was demonstrated in a series of tests in sodium at 300 and 400°F ; ample signal sensitivity was obtained [>0.5 mV/(ft/sec)]. The relationship of magnet width to sensitivity

and the need for electrical insulation of the magnet also were studied. Optimum design was established after a series of short-term tests in sodium at 900 and 1000°F. A procurement specification was prepared, and several commercially built flowsensors were purchased.

Concurrently, an ANL-built flowsensor was tested for 5000 hr in the Core Component Test Loop (CCTL) in sodium at 1100°F and 16.4 ft/sec. Although the flowsensor generated a continuous output signal and no structural failures occurred throughout the test, the magnet strength degraded, indicating the need for a better understanding of the high-temperature characteristics of Alnico magnets.

Consequently, a long-term high-temperature test was initiated to temperatures from 700 to 1200°F. It involves simultaneous exposure of Alnico V and VIII magnet samples in a multisection controlled-heat oven, with periodic removal of samples for magnetic measurements at room temperature. These magnets are from the same lot procured for the irradiation tests performed earlier in EBR-II, and before the loss of magnet strength at high temperature was observed in the CCTL test. Therefore they are not typical, geometrically or magnetically, of those to be used in the probe-type flowsensors, but will yield results in direct support of the radiation data. Testing to date has revealed an unexpected recovery effect in magnets at 1000°F, and other unstable characteristics at high temperatures.

Shorter-term high temperature tests will be initiated in early FY 1972, using Alnico VIII magnets in the exact geometry of the permanent-magnet probe-type flowsensor. A method has been developed which will allow continuous magnetic measurements to be made at temperature. These tests are planned to be comparative only, not absolute, and will relate directly to the output signal that would be generated in an actual flowsensor.

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- F. Verber, R. A. Jaross, and T. P. Mulcahey, Development of an In-Core Permanent-Magnet Probe-Type Flowsensor for Operation in the Fast Flux Test Facility (FFTF), IEEE Trans. Nucl. Sci. NS-18(1), Pt. 1, 366-371 (Feb 1971).
- G. A. Forster, Irradiation of Alnico Magnets in EBR-II, ANL-ETD-71-03 (Jan 1971) (limited distribution).
- Reactor Development Program Progress Reports: July 1970, ANL-7726, p. 29; August 1970, ANL-7737, p. 40; September 1970, ANL-7742, p. 23; October 1970, ANL-7753, p. 39; November 1970, ANL-7758, p. 27; December 1970, ANL-7765, p. 24; January 1971, ANL-7776, p. 14; February 1971, ANL-7783, p. 21; March 1971, ANL-7798, p. 47; April-May 1971, ANL-7825, p. 3.2; and June 1971, ANL-7833, p. 3.1.

2. Eddy-current Flow Probes--J. Brewer

As with the permanent-magnet flow probe development, limited space, environmental conditions, sensitivity, reproducibility, and durability are the design criteria for the eddy-current flowsensor. Development of flowsensor design has received major effort over that of the signal-treatment instrumentation. Feasibility of flowsensor capability to detect gas bubbles in sodium was demonstrated to show a possible use of this flowsensor for failed element detection and location (FEDAL) systems in the FFTF.

In simple form, the flowsensor consists of three closely spaced coaxial coils. The center coil is the primary or excitation coil. The two end secondary coils are connected together, series opposing, as in a differential transformer arrangement. With these coils positioned in an axially flowing fluid stream, the ac flux developed by the primary is forced downstream as a result of the reaction between it and the fluid eddy-current flux. This creates an unbalanced condition in the secondaries and produces a net differential voltage that is nearly proportional to flow velocity. A typical eddy-current flowsensor, within a sodium duct, is illustrated in Fig. I-2.

Fig. I-2. Typical Eddy-current Probe-type Flow-sensor within a Subassembly Duct

After a series of oven tests from 300 to 1400°F, and sodium loop tests from 300 to 1200°F, a prototype design was established, including probe geometry, coil geometry, and materials for the housing, coil bobbin, coil wire, potting, and cable. A probe consisting of shallow-depth coils wet-wound with fine-grain ceramic cement and small wire, and an Inconel 625 coil bobbin has produced the best results. The coil is wound with 0.015-in.-dia ceramic-coated gold wire. The size was chosen for durability although a smaller-diameter wire may be adequate and certainly more efficient. Other wire materials were considered, but the gold appeared most promising. Oven tests on probes containing five coils revealed that stability with temperature was poor; therefore, three coils were selected for the prototype. These tests also revealed that more extensive thermal curing is required with hermetically sealed probes than with nonsealed units.

Good reproducibility has been demonstrated in sodium test loops to 1100°F. More than adequate sensitivity has been obtained: approximately 0.7 mV rms/(ft/sec) in sodium at 1100°F and 8 ft/sec, and with 500 mA rms at 1000 Hz excitation current. One flowsensor was operated continuously for 1100 hr in sodium at 1100°F and an average velocity of 16 ft/sec, with no indications of degradation.

A limited number of argon gas-bubble detection tests have been performed. These bubbles have been detected with an upstream gas injection rate as low as 2.5 cc/sec.

A commercial eddy-current flowsensor, built to ANL design data, is currently being tested. Results thus far indicate insufficient thermal curing, and sensitivity is about 20% less than ANL-built units. The latter is attributed to a physical difference in the vendor's design. The vendor's instrumentation also has been tested for frequency stability and intercoupling; after minor repairs it performed well.

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Reactor Development Program Progress Reports: July 1970, ANL-7726, p. 30; August 1970, ANL-7737, p. 40; September 1970, ANL-7742, p. 25; October 1970, ANL-7753, p. 40; December 1970, ANL-7765, p. 25; January 1971, ANL-7776, p. 14; February 1971, ANL-7783, p. 22; March 1971, ANL-7798, p. 47; April-May 1971, ANL-7825, p. 3.2; and June 1971, ANL-7833, p. 3.3.

John Brewer, Robert A. Jaross, and R. L. Brown, Eddy-Current Probe-Type Sodium Flowsensor for FFTF Reactor Fuel Channel Flow Monitoring, IEEE Trans. Nucl. Sci. NS-18(1), Pt. 1, 372 (Feb 1971).

3. Magnetometer Flow Probes--D. E. Wiegand

With reference to Fig. I-3, the two basic elements of the magnetometer flowsensor are: (1) a dc magnetic field source, which may consist of a system of permanent magnets or electromagnets; and (2) a magnetometer device. As sodium (or other liquid metal) flows through the magnetic field, electric currents are induced in the sodium. The magnetometer measures the distortion or anomaly produced in the magnetic field by the induced current, and thus provides a measurement of the sodium velocity.

The magnetometer device (fluxgate sensor) consists of primary and secondary coils coupled to a ferromagnetic core. Simplicity in the signal processing equipment results if the coils form a balanced system (zero coupling with no applied field). The sensor design tested meets the balance requirement and lends itself to miniaturization. The primary winding

consists of a solenoid with equal numbers of opposing turns divided along the length of a single core member at the coil axis. The secondary winding is a simple solenoid coaxial with the core and primary. The resulting single-cylinder envelope of the sensor affords a significant reduction of overall size, particularly in the projected diameter, compared to conventional constructions which employ a pair of core and coils mounted side by side. Flowsensors can be built for encapsulation in 0.375-in.-OD, 8.5-in.-long cases; this includes the magnets, fluxgate, and space for cable terminations and connections.

Fig. I-3. Magnetometer Flowsensor Used in Feasibility Test. ANL Neg. No. 103-Q5174.

Feasibility of the magnetometer flowsensor was demonstrated first by dry tests, in which an aluminum tube was oscillated lengthwise relative to the flowsensor mounted inside, and later by tests in a sodium loop. The latter test results agreed, within the accuracy of measurement, with computer-predicted values of sensitivity as a function of electromagnetic parameters. Therefore, the results of future dry tests can be, with confidence, converted to equivalent velocity errors. In addition to the convenience, compared to an extended test in a sodium loop, the dry tests will give more information, since the effects of balance drift, changes in magnet strength, and fluxgate variations will be definitely separated.

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Reactor Development Progress Reports: October 1970, ANL-7753, p. 41; November 1970, ANL-7758, p. 30; December 1970, ANL-7765, p. 27; January 1971, ANL-7776, p. 16; February 1971, ANL-7783, p. 24; March 1971, ANL-7798, p. 48; and April-May 1971, ANL-7825, p. 3.4.

B. Transit-time Analysis of Thermal Disturbances--A. E. Knox

If two thermocouples are placed serially in a flowing stream that exhibits temperature fluctuations, and the time it takes for a given fluctuation to traverse the known distance between the thermocouples is measured, the average velocity of the stream can be calculated.

Temperature-fluctuation data from inlet and outlet thermocouples have been recorded on magnetic tape during operation of Tests XX01 and XX02 of the EBR-II Instrumented Subassembly Facility (ISA). Data from ISA Test XX01 were analyzed for the frequency spectrum of inlet and outlet coolant temperature variations. The normally occurring variations were found to be large enough for measurement of ISA flow by two-thermocouple cross-correlation. Deduction of flow information from data of Test XX01 has been scheduled for FY 1972. Thermocouples with measured time response have been supplied to the EBR-II Project for use in the ISA Test XX04.

C. Flowmeters for Instrumented Fuel Assemblies--G. A. Forster

The objectives of this program are to develop commercial sources of supply and to calibrate permanent-magnet, in-core, flow-through sodium flowmeters for use in the EBR-II Instrumented Subassembly Facility (ISA). The initial development encompassed design and test of a suitable instrument, followed by development of specifications and quality-assurance procedures for procurement from commercial vendors.

The design of the first model to be flow-tested was based on developments of the FARET reactor program. This model demonstrated the feasibility of the design concept. An advanced design, the Mark-II, was installed in the first fueled EBR-II ISA Test (XX01). This ISA was installed a few inches below the fuel in the EBR-II core, where it was exposed for about three months to the 700°F inlet sodium and maximum neutron and gamma radiation of the reactor. During this exposure, the flowmeter output approximated the expected flow and the unit was fully operational at the end of the test.

The Mark-III design (see Fig. I-4) was developed to provide a flowmeter that could be calibrated in sodium prior to use in a reactor. An ANL-built unit was calibrated in sodium and then installed in ISA Test XX02, where it performed satisfactorily for the full test run of 11 months. At the end of the run, the flowmeter sensitivity, as inferred by magnetic measurement, was within 2% of the initial value.

In FY 1970, procurement was initiated for six Mark-III flowmeters from two manufacturers. The procurement, including in-plant inspections, material certification, and quality-assurance reports, was successfully

concluded early in FY 1971. One of these flowmeters was calibrated in sodium and installed in ISA Test XX04. The remaining units will be calibrated, and flowmeter designs with the same or other dimensions or pressure-flow characteristics will be procured and calibrated, as needed by users of the ISA Facility.

Fig. 1-4. Schematic and Typical Operational Characteristics of Mark-III Flowmeter

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- G. F. Popper and M. C. Glass, The Design and Performance of a 1200°F Magnetic Flowmeter for In-Core Application in Sodium-Cooled Reactors, Trans. IEEE NS-14(1), 342-347 (Feb 1967).
- M. C. Glass and G. F. Popper, The Calibration and Stability of a 1200°F Permanent Magnet In-Core Sodium Flowmeter, Trans. IEEE NS-15(1), 37-40 (Feb 1968).
- G. F. Popper, D. E. Wiegand, and M. C. Glass, Summary Review of Flowmeters Suitable for Measuring Sodium Flow at Temperatures up to 1200°F in the Fast Flux Test Facility (FFTF), ANL-7340 (Dec 1967).

G. A. Forster, Performance of Permanent Magnet Flow-Through-Type Sodium Flowmeters in EBR-II Instrumented Subassemblies, Trans. IEEE NS-18(1), 363-365 (Feb 1971).

G. F. Popper and A. E. Knox, FARET In-core Instrument Development, ANL-7161 (July 1966).

D. Fluidic Flow Monitors--T. P. Mulcahey

A study was completed under contract by Bendix Research Laboratories on the use of flow-sensitive fluidic oscillators as flowmeters in fuel assemblies. The acoustic output of these oscillators would eliminate the need for electric leads required for conventional flowmeters.

The study indicated that a rather small band of frequencies (<15 channels) was available, compared to the number of oscillators required in a reactor, and a quite narrow range of flow sensitivity for a given oscillator. Therefore, further effort on this concept has been deferred in favor of higher-priority tasks.

E. Ultrasonic-pulse-propagation Techniques--H. W. Buschman

The anticipated high cost and large mass of electromagnetic flowmeters or velocity-head meters has prompted an investigation of alternate methods of determining sodium flow rates in large-diameter (>24 in.) piping systems. One such method, reported here, has been used on aqueous systems. A proof test on a hot sodium piping system was desired.

The test was conducted on a 12-in. pipe in the EBR-II secondary-sodium system to demonstrate the feasibility of measuring the flow rate of liquid sodium by the ultrasonic-pulse-propagation technique. Personnel from Idaho Nuclear Corporation who have had experience with this technique were contracted to provide the test equipment and run the test. The results of the tests are encouraging.

The ultrasonic test device was installed, checked out, and later removed without affecting normal plant operation. During the test, the sodium pipe on which it was installed was hot (>800°F), and the temperature of the secondary sodium at the existing electromagnetic flowmeters was ~580°F.

The purpose of the test was to demonstrate the feasibility of the technique; no attempt was made to optimize the system for accuracy. However, before the test, it was predicted that the accuracy would be within 10% of the actual maximum flow through the system. As evidenced by Fig. I-5, this accuracy was achieved. The accuracy primarily depends on: (1) resolution time of the instrumentation; (2) how well the geometry of the installation is known; and (3) the error associated with not knowing the exact velocity profile in the pipe.

Fig. I-5. Results of Feasibility Test of Ultrasonic Measurement of Sodium Flow Rate.
ANL Neg. No. 113-3902.

For practical reasons, the ultrasonic technique probably should be limited, at present, to piping larger than 4 in. in diameter. With piping 1 ft in diameter and larger, and with reasonably high flow rates, the technique appears capable of measuring flow rates with acceptable accuracy. In addition to savings in mass and cost in larger pipe sizes, the technique does not require penetration of the pipe wall, no head loss penalty is exacted, and most important, precalibration may not be required.

REFERENCE

Reactor Development Program Progress Report: August 1970, ANL-7737,
p. 59.

II. PRESSURE INSTRUMENTATION

The development of LMFBR fuels requires experimental irradiation in a prototypical environment to determine operating characteristics. Most fuels experiments rely only on postirradiation examination to determine the parameters of interest; thus the determination of rates of change or other time-dependent parameters and variables requires a large number of irradiations of varying durations. To accomplish the monitoring of fuels experiments during irradiation requires specialized instrumentation. A pressure transducer has been developed to fulfill one of these needs.

A. Fuel-element Pressure by Null-balance Techniques--J. R. Folkrod

The ability to monitor pressure in experimental fuel elements can yield important information on fission-gas release and release rates. A null-balance bellows-type of pressure transducer has been developed for use in the EBR-II Instrumented Subassembly Facility (ISA).

Fig. II-1. Components of Null-balance Pressure Transducer

Four prototype transducers of the type shown in Fig. II-1 were fabricated and installed on fuel elements in ISA Test XX01. These transducers successfully measured the gas pressure contained within the fuel elements for the life of the test.

Similar prototype transducers have operated successfully in laboratory tests for eight months at 900°F, one week at 1200°F, and for an additional six weeks at 1300°F, all at a maximum pressure of 350 psig, at which time they failed. These transducers were designed for 350 psig at 900°F.

The prototype design was revised, specifications were prepared, and improved pressure transducers are currently on order from two commercial sources of supply. These transducers are designed for 1000 psig at 1200°F.

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A. Smaardyk et al., The EBR-II Instrumented Subassembly System: Tests 1 and 2, ANL-7757 (July 1971).

J. R. Folkrod, Design and Test of Null-Balance Fission Gas Pressure Transducer and Controller, Nucl. Appl. Technol. 8(5), 432-436 (May 1970).

III. TEMPERATURE INSTRUMENTATION

The instruments described in this section are being developed for use in the EBR-II Instrumented Subassembly Facility (ISA).

A. Coolant and Spacer-wire Thermocouples--A. E. Knox

Prototype fuel elements for an LMFBR are typically tubular and wrapped with a spiral wire that acts as a spacer. If sheathed thermocouples of proper diameter and length were substituted for the spacer wires, axial temperature profiles could be obtained during experimental irradiations.

Coolant and spacer-wire thermocouples were specified, purchased, and successfully tested in- and out-of-reactor. The thermocouples that were specified were Type K (Chromel-Alumel), alumina-insulated, stainless steel sheathed assemblies of different designs and configurations. The configuration of the thermocouples procured consisted of (1) uniform-diameter-sheathed 62.5-mil thermocouples; (2) dual-diameter-sheathed 62.5-mil thermocouples, with the lower portion of the sheath consisting of either a 0.5-in.-long, 40-mil tip or 40-mil tips of varying lengths and solid 40-mil wire attached so they could be used as fuel spacer wires; and (3) dual-diameter-sheathed 62.5-mil thermocouples, with the 40-mil tip prespiraled for use as fuel spacer wires. These thermocouples were used in the ISA Test XX01 for monitoring assembly inlet and outlet coolant temperatures, and coolant temperature along the elements within the assembly. Thermocouples also were provided for EBR-II ISA Tests XX02, XX03, and XX04.

During irradiation, these thermocouples were exposed to temperatures from 700 to 830°F, a gamma flux of approximately 10^9 R/hr, and a fast-neutron flux of approximately 2×10^{15} nv.

The thermocouples developed have provided reliable sources of temperature measurement for reactor experiments in the EBR-II ISA. In addition, ANL specifications used for the procurement of thermocouples for this program have served as the basis of writing several RDT Standards. ANL is currently supplying thermocouples for use by the FFTF Project and their fuels development program tests in the EBR-II ISA Facility.

REFERENCES

- A. E. Knox and G. F. Popper, "Some Design Aspects of the Proposed EBR-II Instrumented Subassembly System," Proceedings of the Symposium on Liquid Metal Instrumentation and Control, Idaho Falls, Idaho, March 1-2, 1967, ANL-7380, pp. 174-179.
- A. Smaardyk et al., The EBR-II Instrumented Subassembly System: Tests 1 and 2, ANL-7757 (July 1971).

A. E. Knox and G. F. Popper, "ANL Participation in the FFTF Instrument Development Effort," Proceedings of the Symposium on Liquid Metal Instrumentation and Control, Idaho Falls, Idaho, March 1-2, 1967, ANL-7380, pp. 9-14.

B. Fuel Thermocouples--A. E. Knox

Measurement of fuel centerline temperatures during irradiation can provide information of great value to experimenters. In the oxide fuels of interest to the LMFBR Program, these temperatures can be as high as 2800°C, well above the melting point of common thermocouple materials. However, since tungsten-rhenium alloys have been used as thermocouple elements in this temperature range, a design was developed (see Fig. III-1) and a group of thermocouples were assembled at ANL from commercially available components. These were W-3% Re versus W-25% Re as the thermoelements, thorium oxide as the insulator material, and tantalum as the protection tube.

Fig. III-1. Cross Section of Fuel Thermocouple Used in EBR-II ISA Test XX01

After successful laboratory tests, seven of these thermocouples were incorporated into fuel elements containing uranium oxide fuel and into ISA Test XX01. Although none of the thermocouples exhibited a gross

failure during the test, there was some anomalous behavior. These thermocouples are currently undergoing postirradiation examination.

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IV. REACTOR SURVEILLANCE AND MONITORING TECHNIQUES

Instruments and techniques are and will continue to be needed in LMFBR plants to monitor reactor parameters and components, and to detect and locate incipient failures which may affect plant safety, reliability, and, consequently, availability of operation. In-core and piping instruments are being developed to monitor reactor performance and detect and diagnose abnormalities. Basic phenomena are investigated, and components and systems are developed, tested, and specified. Although the long-range goals are instruments for surveillance of large LMFBR power plants, the requirements of EBR-II, FFTF, and the Demonstration Plant are being used for near-term developmental guidance. It is planned to use prototypes in EBR-II and FFTF.

A. Acoustic Surveillance--T. T. Anderson

Detectors and techniques are being developed for monitoring and interpreting the in-core acoustic frequency spectrum of an LMFBR. The current principal objective is to reliably detect coolant boiling in an LMFBR core. Since acoustic signals, including the sounds of boiling, are distorted and masked by the coolant and core components before they reach the reactor exterior, they must be sensed as closely as possible to the source, and then transmitted in as distortion-free a manner as possible to the exterior of the reactor vessel.

Two techniques for monitoring the in-core acoustic signals that minimize signal distortion are being investigated: (1) use of acoustic sensors immersed in the coolant at the core outlet; and (2) use of waveguides to transmit the core noise to acoustic or vibration sensors outside the core region. The acoustic spectrum information contained in the signals from these techniques will be used to reliably detect off-normal conditions, so that corrective action can be taken.

The corresponding research and development activities in this acoustic surveillance program include: (1) construction and evaluation of sodium-immersible high-temperature radiation-resistant piezoelectric transducers in a prototypical environment, and integration of signal information and processing equipment into a complete operational boiling detection system; and (2) waveguides capable of transmitting desired in-core acoustic information to distant detection and processing equipment. Also under investigation is the acoustic noise spectrum of typical liquid-metal systems as detected by each technique, and its relation to the noise generated in reactor systems.

1. Immersible Piezoelectric Sensors--A. P. Gavin and T. T. Anderson

A high-temperature sodium-immersible acoustic sensor is being developed to be capable of producing the required signal for at least

one year while exposed to sodium coolant at 1200°F and neutron and gamma radiation in a typical operating LMFBR core. Recent improvements in

methods and materials of construction have resulted in sensors (see Fig. IV-1) which have operated continuously in an air furnace for 1½ months at 1200°F, with no degradation.

Fig. IV-1. Components of Sodium-immersible Acoustic Sensor

Lithium niobate crystalline material is also a leading candidate for high-temperature radiation-resistant piezoelectric components in accelerometers and ultrasonic detectors for the LMFBR Program. Irradiations by 2-MeV Van de Graaff

electrons to 8×10^9 R at room temperature, and ^{60}Co gamma photons to 4×10^9 R (2×10^9 R at 537°C), show that lithium niobate has exceptional radiation stability toward ionization comparable to closely packed oxides such as sapphire. However, exposure to particulate irradiation by neutrons must eventually lead to gross destruction by gas within the lithium niobate crystal structure from the nuclear reaction ${}^6\text{Li} + {}^1_0\text{n} \rightarrow {}^4\text{He} + {}^3\text{H}$.

To anticipate the results from a lengthy neutron irradiation, the blistering from gas injection is also being studied. Specimens of lithium niobate have been subjected to neutron irradiation (to 10^{19} nvt thermal) in the CP-5 reactor, and to ion bombardment at 140 keV (proton, deuteron, and helium) in a Cockroft-Walton machine. The ion bombardments were performed by the Solid State Science Division at Argonne to determine the effects of injecting gas into the lithium niobate, thereby simulating the effects of gas generated by fissioning of lithium. The five major effects observed were

- (1) All bombarded areas became elevated relative to surrounding unbombarded areas.
- (2) Gas trapped in a thin surface region within the crystal eventually caused destruction at 2×10^{21} injected atoms/cm³.
- (3) Surface destruction occurred by crazing in a triangular pattern, parallel Z and perpendicular Y, followed by exfoliation.
- (4) Bombarded areas, and particularly crazed areas, possessed altered surface characteristics causing droplets of water to condense on the surface, especially in a humid atmosphere.
- (5) Specimens bombarded with protons or deuterons (but not those bombarded with helium ions) developed progressively intense coloration with dose.

These effects are being explored further to establish dose, temperature, and orientation dependences.

2. Waveguides--T. T. Anderson

Acoustic waveguides are being developed as a second method of remotely sensing pressure-sound disturbances in the LMFBR coolant. Initial tests of a Type 304 stainless steel tube, 6 m long by 3.2 cm in diameter, demonstrated the presence of multiple echos in the tube, amplitude resonances associated with radial motion of the tube, and the propagation of waves along the tube at longitudinal and shear velocities. Design goals are to improve acoustic response over that complicated by multiple echos and resonances to achieve a usable reproduction of the sound pressure field in the reactor core region.

3. High-temperature Accelerometers--A. E. Knox

Accelerometers or low-frequency-sound transducers are being developed to measure fuel motion, core structural vibration, control-element flutter, and acoustic vibrations from sources that might disturb overall reactor stability or warn of impending mechanical failure. To the extent of availability, commercial accelerometers advertised as meeting the temperature and environmental requirements of the LMFBR Program Plan are procured from vendors willing to modify their units for sodium immersion and testing. Based on the experimental findings, new specifications including vendor testing and quality-assurance requirements are then developed to meet near-core applicational needs, and new units are procured and tested. Out-of-pile tests are performed to determine temperature effects and operability in sodium; these are followed by radiation facility tests to determine sensor performance during irradiation. Sensors are environmental- and life-tested under conditions that will contribute to other programs such as vibration monitoring of the FFTF Mark-II fuel assembly during flow-testing in the Core Component Test Loop (CCTL).

A survey made in 1968 of commercial accelerometers showed that none fully met the requirements of the LMFBR Program, but that considerable development was underway in the field of piezoelectric transducers. At that time, two manufacturers claimed a developmental accelerometer rated at 1150 and 1200°F, respectively. Three 1150°F accelerometers were ordered with attached triaxial, stainless steel-sheathed cables. The accelerometers were calibrated at temperature by the vendor and then given further testing at ANL. Although these accelerometers showed marked decreases in response, the decision was made to install one of them on the FFTF Mark-II fuel assembly during its long-term flowtesting in the CCTL. The objectives were to monitor the fuel assembly for vibration as well as to test the accelerometers in a sodium environment at operating temperatures. The accelerometers failed (shorted) during the initial startup at approximately 850°C; however, they were not removed from the loop until 6300 hr of flowtesting were performed on the fuel assembly.

After removal of the fuel assembly from the CCTL, the accelerometer was disassembled and X-rayed to determine the cause of failure. The results indicated the likely cause of the shorting was excess lead length inside the case, which allowed the leads to touch the case. X-rays of the other two units also indicated excess lead length inside the case, indicative of a faulty assembly technique. (The actual cause of the low resistance was not discovered at this time.) This diagnosis was forwarded to the manufacturer for appropriate action.

During the CCTL run, accelerometers also were attached externally to critical components: the pump outer ring, the pump base, and pump discharge line, and a lower vessel support. Typical vibrations were recorded at various pump speeds for the purpose of obtaining reference recordings for a system known to be operating satisfactorily; thus any change in frequency or power density spectrum could help in diagnosing faulty operation. One case of suspected pump rotor rubbing was investigated, but the trouble did not recur.

Revised procurement specifications were written for high-temperature accelerometers, with emphasis on quality assurance; these included functional vendor tests and ANL observation of tests. The specified performance requirements were within advertised commercial capabilities. The functional tests included four temperature cycles between room temperature and maximum temperature rating of the accelerometer. These accelerometers are designated for use during flowtesting of the FFTF Mark-IIA fuel assembly in the CCTL as well as out-of-sodium testing. Three accelerometers are currently on order from each of two vendors.

4. Evaluation of High-temperature Sensors

Facilities are being developed and used to evaluate and calibrate acoustic and vibration sensors in air, water, and sodium at high temperatures. An acoustically excited (200-500 Hz) air furnace is used routinely to test acoustic sensors at 1200°F for periods ranging from days to months.

A Waveguide Evaluation Facility has been constructed for determining sensing and transmission characteristics of waveguides up to 20 ft long. The waveguides are suspended over a 5½-ft-dia tank, with the sensing portion, immersed in water, detecting the sound pressure produced by U.S. Navy standard projectors (hydrophones).

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B. Neutron Noise Analysis--L. J. Habegger

A literature survey of liquid-metal boiling detection in LMFBR's, using neutronic noise techniques, led to the conclusion that additional information must be obtained to demonstrate the feasibility of this technique. As part of the program for meeting this need, an in-core boiling experiment in the EBR-II is being planned. In-core boiling (or simulated boiling voids) for the experiment is to be produced within the EBR-II INCOT facility. It has been estimated that to meet the experimental objectives, the minimum average void volume in the INCOT assembly should be 8 cm³. Existing neutronic instrumentation at the EBR-II site has been evaluated and determined to be adequate for data collection in initial experiments.

As a corollary to these experiments, a theoretical determination was made of the possible advantages of locating neutron detectors in positions other than in the reflector of an LMFBR. The use of various detector absorber materials also was considered. The plant design used for this study was that of an LMFBR Demonstration Plant perturbed by a 10% step decrease in sodium density in the central subassembly.

The computed transients were used to determine the relative reaction rates for ²³⁵U, ²³⁸U, and ²³⁹Pu fission detectors at various locations. By locating the detectors at the reactor centerline where the voiding occurs, an approximately 5% larger change in reaction rate is obtained with ²³⁵U and ²³⁹Pu detectors compared to similar detectors placed in the reflector. With a ²³⁸U detector, a 10% increase is obtained by placement at the reactor centerline instead of in the reflector. For the detection of changes in flux, the

small advantage of placing detectors in the area where the boiling is occurring is more than offset by the larger permissible size of detectors located in the reflector.

The feasibility of boiling detection in an LMFBR by analysis of neutron noise is strongly dependent on the level of background noise superimposed on the noise induced by boiling. Experimental measurements of background noise power spectral density $[PSD(f)]$ levels for the EBR-II have been obtained at various reactor power levels. In the frequency range 4-100 Hz, the ratio of the background neutron noise power spectral density to squared mean neutron density $[PSD(f)/\bar{n}^2]$ was found to vary from a maximum of $2 \times 10^{-6} \text{ Hz}^{-1}$ to a minimum of 10^{-8} Hz^{-1} . (A much higher peak in the power spectrum occurred at 12 Hz, but this peak is considered to be a unique characteristic of the EBR-II and was not included in the feasibility analysis.) This ratio remained independent of reactor power in the 4- to 100-Hz range, indicating the source of noise to be reactivity perturbations from thermohydraulic or structural fluctuations. This type of background noise cannot be readily reduced by redesign of the detection system, and is thus a fixed level above which boiling-induced noise must be detected.

In the frequency range of 100-1000 Hz, the ratio $PSD(f)/\bar{n}^2$ was inversely proportional to the mean density $\bar{n}$ and independent of frequency f . This type of dependency is characteristic of noise resulting from either the statistics of the detection process or inherent neutron-density fluctuations, and the relative level of this noise can be reduced by increasing detector efficiency or increasing reactor power. Thus, in this frequency range, the $PSD(f)/\bar{n}^2$ value of 10^{-8} Hz^{-1} , obtained at the highest power level of 50 MWt, is a maximum value for the background noise.

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C. Detection of Entrained Gas in Sodium--R. A. Jaross

Gas entrained in the sodium coolant pumped into an LMFBR core could lead to reactivity perturbations and interfere with heat transfer. An FFTF requirement calls for the detection of gas voids in amounts of 3% (by volume) of sodium prior to their entrance into the reactor core.

Preliminary tests were performed to show the feasibility of detecting voids in flowing sodium by their effect on the ability to produce an electromagnetic force in the sodium. The functioning of electromagnetic pumps is very sensitive to gas voids entering the pumping region. Under certain conditions of gas void fraction and flow rate, the gas will quickly accumulate at the point in the pump where electrical conduction through the liquid metal is taking place and where the pressure is lowest. When this occurs, pumping will decrease.

A detection system was tested, using a small bypass sampling stream in conjunction with an electromagnetic (em) pump and flowmeter.

Fig. IV-2. Simplified Schematic Diagram of System for Detecting Entrained Gas in Sodium

With reference to the simplified schematic diagram in Fig. IV-2, the system functioned as follows: A sample of sodium was taken from the centerline of a pipe of flowing sodium and directed through an em flowmeter into the inlet of an em pump. The sampling loop was arranged so that a large head loss occurred in the inlet pipe. As a result, entrained gas in the sample accumulated in the pump and the sample flow decreased, reflecting a large decrease in flowmeter signal. In these tests, argon gas injected into flowing sodium, in the volumetric ratio of 100 ppm, resulted in a reduction in flowmeter signal from 0.92 to 0.70 mV within 25 sec from start of gas injection. This flow reduction occurred in the em pump-sample stream. Other tests with various injection ratios, rates, and sodium flow rates yielded similar results.

D. Reactivity Monitoring--J. R. Karvinen and C. C. Price

Techniques for monitoring reactivity are being developed, since knowledge of the reactivity along with information on burnup, control-rod position, and temperature can be used to detect any anomalies and thus provide early warning of potentially dangerous conditions within the reactor. As a first step, a prototype analog reactivity meter has been developed for EBR-II.

In operation, this meter accepts an amplified signal that is proportional to reactor power, and then uses integrated circuitry to manipulate the signal according to point-kinetic reactor theory to produce a direct readout of reactivity in inhours (lh). The meter obtains the first derivative

of the neutron flux, using a filtered differentiator, and incorporates six delayed-neutron groups, using closed-loop dynamics. The meter has a frequency response from dc to 40 Hz, and can measure reactivity changes with an accuracy of 0.1 Δk (0.03%).

Since becoming operational in July 1969, the meter has been used to monitor reactivity for all EBR-II operations. Endurance and stability of the meter have been excellent. Some resistor values have been changed to decrease noise. No integrated circuit component has failed. To date, the only malfunction has been a mechanical failure in the autoranging section of the instrument.

Although the delayed-neutron fraction is slightly sensitive to loading changes, the meter still uses the original values since becoming operational. The resultant error has not been significant. The instrument has proved to be accurate and reliable; with improvement of the autoranging and a more modular design, it can be considered for routine use.

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E. In-core Neutron Monitoring--C. C. Price

In the large cores projected for future LMFBR's, monitoring the reactivity and stability will be enhanced if in-core neutron flux can be measured directly. High temperatures and size requirements prohibit the use of conventional neutron detectors directly in the core. However, a type of detector known as a self-powered ion chamber has characteristics that enable it to function in the high-flux high-temperature environment of an LMFBR core.

Self-powered ion chambers have been used successfully in thermal reactors. However, a recently published survey on in-core flux detectors for power reactors shows that experience with self-powered detectors in an LMFBR is limited to detectors irradiated in EBR-II ISA Tests XX01, XX03, and XX04. These ISA's were located in an axially symmetric position about the core centerplane in Row No. 5.

Chambers employing three types of emitter materials (rhodium, cobalt, platinum) have been tested to date. Briefly, the results show that:

(1) The rhodium neutron flux detector has an output signal that is proportional to reactor power; it has a nominal current of 0.2 μA at 62.5 MWt for a 7.9-in. detector. The detector has excellent steady-state characteristics; however, the relatively long-lived activation product ^{104}Rh (42 sec, 4.4 min) interferes with the signal during rapid transients. Capture gamma rays cause an 8% prompt response.

(2) The cobalt detector is sensitive to both neutrons and gamma flux; it has a signal that is slightly nonlinear with respect to reactor power. Nominal detector current output is $\sim 0.01 \mu\text{A}$ at 62.5 MWt for a 13.8-in. detector. This detector has prompt response characteristics.

(3) The platinum detector is essentially sensitive to gamma flux. For the case of cold-clean fuel, the detector signal is proportional to fission rate and reactor power during the initial rise to power. Nominal current is $0.5 \mu\text{A}$ at 62.5 MWt for a 13.8-in. detector. After reaching steady-state power, the detector current continues to increase as a function of fission-product gamma rays.

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V. NEUTRON-DETECTION CHANNELS

A. Wide-range Neutron-flux Monitor Systems--T. P. Mulcahey

Current practice in monitoring reactor neutron flux is to provide separate channels and chambers to cover the source, intermediate, and power ranges. The chambers and cables used are either located in a low-temperature environment or, when located in a high-temperature region, are gas-cooled. Present and future LMFBR applications may preclude location of chambers and cables in a low-temperature environment; and incorporation of cooling systems into channels used in safety systems may require (as for EBR-II) additional protective action capability with its high initial cost, maintenance cost, and potential adverse effects on plant availability. The availability of wide-range systems (10 decades of power) with high-temperature neutron detection chambers and cables will reduce the number of chambers, eliminate the need for cooling and monitoring the temperature as part of the reactor protection system, thus simplifying construction and maintenance, lowering capital and maintenance costs, and possibly improving plant availability. An additional advantage of statistical noise techniques inherent in the use of wide-range systems is the greater neutron-gamma discrimination, which may be necessary for operation of the LMFBR.

The objectives of the Neutron Detection Channel Development Program at ANL are to: (1) ensure that complete channels (detectors, cables, and electronic systems) for detecting neutrons over the intermediate- and wide-flux range are available on a timely basis to the FFTF, EBR-II, and Demonstration Plants; (2) develop, to the maximum extent possible, an industrial capability to supply these systems and components; (3) generate standards and specifications so that reliable systems and components can be procured and tested; and (4) to report the findings to the LMFBR community. Neutron detectors and cables that are to operate in thimbles at temperatures initially up to 700°F, and ultimately up to 1200°F, are to be developed. The EBR-II NITF O-1 and J-2 thimbles and other facilities will be used to test the developed detectors and cables.

B. Neutron Detectors--G. F. Popper

An industrial capability is being developed to supply, adequately test, evaluate failures, and generally assure operability of their own products when manufactured to rigid standards. Standards for detectors and testing procedures are being generated as needed.

High-temperature fission chambers obtained from the Los Alamos Scientific Laboratory (LASL) are being modified by the original vendors for testing in the EBR-II NITF. The LASL fission chambers modified by Westinghouse and Reuter-Stokes were vendor- or ANL-tested at temperatures up to their ratings; successful units are being tested in the EBR-II NITF.

Specifications for new high-temperature fission counters and compensated ionization chambers have been developed, contracts let, and vendor testing programs monitored. Specifications for British fission counters were generated, and a commercial procurement contract was executed. Failure-mode analysis of detectors has been performed with the cooperation of the manufacturers. Performance of detectors is established by appropriate measurement of collection time and other important parameters.

C. Electronics--G. F. Popper

This activity includes specification, procurement, and experimental evaluation of commercial intermediate- and wide-range neutron-flux monitoring channels and components. Long-term successful performance of commercial Mean Square Voltage (MSV) channels operating with detectors initially at 700°F, and ultimately at 1200°F, in the EBR-II NITF is a prime consideration. Standards are generated when needed as a part of this activity.

A Gulf General Atomic Ten Decade Neutron Flux Monitoring System and a Milletron Wide Range Neutron Flux Monitoring System have been procured and installed at the EBR-II for experimental evaluation. The Gulf system has been under test since 1968 and the Milletron system since 1969; both systems have operated satisfactorily. Concurrent short-term tests performed in TREAT demonstrated that this equipment could follow reactor periods as fast as 30 msec; the same tests indicated that the period trip circuits had design defects which had to be corrected. Monitoring of the EBR-II testing of these units is continuing.

Specifications for a second-generation Logarithmic Mean Square Voltage (MSV) Intermediate Range Neutron Flux Monitoring System have been developed, procurement initiated, and bids received and evaluated. These specifications are being rewritten in the form of an RDT Standard (C15-6), which will be used to procure intermediate-range channels for the FFTF.

The following Standards also are being prepared for use in procurement of neutron-detection channels for the FFTF:

RDT C15-8: Direct Current Power Range Channel

RDT C15-9: MSV Power Range Channel

RDT C15-10: Logarithmic Count Rate Source Range Channel

D. Cables--A. Hirsch

Because of the very high impedance characteristic of neutron detecting chambers and their relatively high operating voltage, the requirements for cable assemblies used with the detectors are unusually severe.

Although satisfactory cable assemblies are available for modest temperatures, the mineral-insulated cable assemblies required for high-temperature operation cannot be procured with any assurance of acceptable quality. The lack of suitable cable assemblies has severely hampered the testing of high-temperature neutron-detecting chambers, and has prevented testing of advanced circuitry with cables and chambers at elevated temperature.

After laboratory tests on commercial assemblies at ANL and other organizations indicated the severity of the problem, another problem arose: nonuniformity of test procedures between organizations. Therefore, an RDT Standard F3-39, Testing of High Temperature Cable for Nuclear Detectors, was written, subjected to a broad review by non-ANL organizations, revised accordingly, and submitted to RDT for approval. This Standard will provide standardized tests that characterize cables, so that results from the various cable testing organizations can be compared. The Standard does not contain acceptance or failure criteria. However, testing in accordance with the Standard along with suitable criteria will be used as the basis for specifying the quality of cable assemblies. Cable assemblies from two vendors have been tested to 850°F in accordance with this Standard and the results reported.

Three types of cable assemblies are necessary for the neutron channel program. These are broadly described as ac signal, dc signal, and dc excitation. Preliminary specifications for these assemblies have been developed.

E. NITF Test Program--V. J. Elsbergas

Promising neutron detectors and cable assemblies are being tested in the EBR-II Nuclear Instrument Test Facility (NITF) in simulated LMFBR thimble environments up to 1200°F.

Testing at up to 700°F was initiated in EBR-II O-1 thimble in November 1968, using a Westinghouse WX 4036 detector. However, the cable attached to this detector failed after 30 days, and since a replacement has been unobtainable, the testing of this detector has not resumed.

In late FY 1971, the RSN-286 S/N M402 and WX-31384 S/N 703901 fission chambers were installed in the EBR-II O-1 NITF and are currently undergoing tests.

EBR-II experimental procedures for use of both the O-1 and J-2 thimble NITF have been written, and approval-in-principle has been received from RDT for testing of all detectors on hand or on order.

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VI. REACTOR AND PLANT CONTROL

Development in base technology is needed to solve control design problems arising in a large LMFBR plant and to satisfy the need for improved plant performance. Development is of subsystems used in design, rather than of the overall design. These subsystems consist of improved control models of the reactor, simulations to investigate control of reactor and plant, development of control theory, and the solution of control problems in reactor and plant operation.

It is evident that computers will be necessary to acquire the required data, process it, and, ultimately, perform the control function.

A. Plant Dynamics and Control Analyses--L. J. Habegger

The objectives of this program are to (1) study the control systems that have been proposed for the large LMFBR plant designs in conjunction with the 1000-MWe LMFBR plant-design studies; (2) determine the adequacy of these systems to meet the overall control and performance goals; (3) identify current and potential LMFBR control problems; (4) identify systems where further control-system optimization would improve the economic and operational aspects of an LMFBR; and (5) identify development required in the area of LMFBR reactor and plant control.

To facilitate this study, a simplified complete-plant model for a 1000-MWe LMFBR was developed and is being programmed on the ANL hybrid computer. This hybrid program will be used initially to simulate mild LMFBR transients resulting from normal or slightly off-normal conditions, with provision for future extension to severe transients resulting from emergency or faulted conditions.

The major components in the plant simulation include the reactor, reactor thermohydraulics, reheater, intermediate heat exchanger, and once-through steam generator. Except for the steam generator, these component models are based on well-known forms using a continuous-time representation with one or two spatial nodes.

A more elaborate model is used for the initial simulation of the steam generator, since this component is potentially a main source of instability and undesirable transients. This model is based on mass and energy balances in three regions of varying length: single-phase water, boiling, and superheat steam. These regions correspond to regions with major differences in heat-transfer coefficients between the tube wall and secondary fluid (H_2O).

Included in the simplified plant model are pure time delays for the coolant temperatures introduced by transport lags through the piping connecting the major plant components. These time delays are being simulated

digitally on the hybrid computer, and necessary programs have been written. For constant flow velocities, the variables are sampled and stored in the computer and become output after a fixed number of time delays. However, for variable flow velocities, the time delay becomes a variable, dependent on the flow-velocity history. The procedure being used to simulate variable time delay is to sample both temperature and flow velocity, and store values for temperature variables which are averaged over fixed mass increments flowing in the piping. This is opposed to averaging over fixed time increments, as is the procedure for fixed velocity. The temperature stored in the computer becomes output after an additional number of mass increments, fixed at a constant value by the total pipe volume, have been sampled.

Development of simulations for the sensors, controllers, and control actuators in the LMFBR plant is in progress.

As part of this activity, consultation has been provided to RDT on the evaluation of proposals for Demonstration Plants.

B. TREAT Auto-power Control System--J. F. Boland

An increasing number of TREAT experimenters desire shaped-power pulses lasting several seconds to simulate mild overpower, loss-of-flow, and decay-heat conditions of relevance to power-reactor safety programs. Since the original reactivity-control system did not provide for closed-loop control, shaped-power pulses were often a poor approximation of what was desired. Recently, a control system, consisting of a digital computer, two servohydraulic control-rod drives, reactor-power and period measuring instruments, and associated interface equipment, has been assembled to provide closed-loop control of shaped transients.

Conceptual design of the TREAT automatic control system was started in FY 1968, system design was completed during FY 1969, and equipment was then ordered. The computer was delivered early in FY 1970, but the servohydraulic equipment was not delivered until the first quarter of FY 1971. An addendum to the safety analysis report covering operation of the reactor under digital-computer control was submitted in September 1969, but approval to operate the reactor to test out the system was not received until January 1971. Installation and testing activities were completed during April 1971, and approval for routine operation with the automatic control system was received in May 1971.

Programs for generating transient shapes desired by the experimenters are being developed as the experimenters submit their requirements. Each new program is tested by operating the reactor without an experimental capsule to prevent programming errors from damaging an experiment. Figures VI-1 and VI-2 show the reactor power and energy data from transients conducted using the two programs that were made

operational during FY 1971. These programs have satisfied the requirements of all experiments submitted to date. We believe that this is the first successful demonstration that closed-loop digital-computer control is a practicable method for controlling a reactor under prompt-critical and superprompt-critical conditions. Of course, a reactor with a shorter neutron lifetime than TREAT (0.9 msec) would be more difficult to control under these conditions.

Fig. VI-1. Power History of TREAT
Transient No. 1394

Fig. VI-2. Power History of TREAT
Transient No. 1398

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- C. EBR-II Data Acquisition System--R. W. Hyndman

The EBR-II Data Acquisition System (DAS) consists of a Xerox Data System (XDS), Sigma-5 computer with a 32-k core, an analog-to-digital (A/D) front end, and peripheral devices for input/output (I/O) and data storage. The A/D front end provides capability for data input on 10 high-level, 512 low-level, and 10 experimenter channels. In addition, there are 208 digital lines for input directly into the computer. The analog data are multiplexed, digitized, and then presented to the computer as digital values for storage or processing.

A variety of peripheral devices provide for storage or display of data from real-time and "batch process" programs. These include:

two rapid-access disks (RAD), three magnetic-tape transports, a line printer, a card punch, four alphanumeric (A/N) CRT units, a Calcomp plotter, and an interactive graphics unit. Three of the four A/N units are for display of reactor parameters and data to operations personnel; the remaining I/O devices are available for program output.

Core and fast bulk storage (RAD) are divided into foreground and background areas. Real-time programs are assigned to foreground areas and may use background if necessary. Programs not directly associated with real-time operation are assigned or run in background areas as "batch process" jobs; these programs are restricted to background areas and execute only when no real-time programs are in operation.

The system is operated through use of systems and user-oriented software (computer programs) developed by XDS and the EBR-II Project. A number of real-time general or special application and background programs have been developed. Some of the functions performed are data logging, postincident recall, statistical analysis, curve fitting, acquisition and reduction of experimental data, reactor operations support, mathematical modeling, and display or hard-copy output.

DAS capability includes response, within microseconds, to internal or external events. This capability allows for execution of periodic functions, such as data logging, and for execution of specific programs when called for by another real-time program, a user, or when triggered by an external event.

For real-time programs, a priority structure operates so that critical programs, which have the highest priorities, can halt an executing program, execute themselves, and exit, allowing the interrupted program to continue.

Reactor operations support includes such functions as control-rod calibration, anomalous reactivity determination, system heat balance, time sequence of events and postincident recall, display of important reactor parameters and conditions on A/N scopes, audible and visual display of abnormal conditions, shift log, and reactor run data log. Programs to perform these functions are either presently operational or in an advanced stage of development. In addition, there are background programs to perform such functions as the bookkeeping associated with the reactor core loading and subassembly irradiation history, fission-product activation levels, and production of hard-copy output from data stored on a bulk storage device.

Experimental support is available on a request basis. Any area of data acquisition, data reduction and analysis, alarm limit check, and special control function can be added to the normal operational support, or special software can be developed.

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VII. SODIUM IMPURITY MEASUREMENT INSTRUMENTATION

A. National Meter Program--L. Burris

Argonne National Laboratory (ANL) has been given the responsibility of administering a National Meter Program involving major sodium technology contractors in the United States. This program for the development and application of sodium-purity monitoring stations is designed to (1) characterize the performance capabilities of present meters; (2) standardize the design and operational procedures, and establish commercial availability for these characterized meters; (3) determine the requirements for meters on a continuing basis, as LMFBR's are advanced to a commercial status; and (4) upgrade performance or develop new meters, as required, to meet long-range performance goals.

Sodium-technology contractors will participate in a coordinated test plan to determine the capabilities of existing impurity meters that have been developed for continuous monitoring of LMFBR sodium. Completion of this plan will result in the needed characterization of the meters in the shortest possible time by taking advantage of existing facilities. Impurity monitors in this program include oxygen, hydrogen, and carbon meters, and steam-generator leak detectors.

At present, the foremost goal of the program is to meet the needs of the Fast Flux Test Facility (FFTF) for commercially available oxygen and carbon meters by early FY 1972. An additional goal is to have commercial hydrogen meters available by that date, or shortly thereafter, although this has not been listed as an FFTF requirement.

In addition to the meters themselves, prototype meter modules are being designed for FFTF; the modules include the individual meters and equipment for controlling sodium temperature and flow. A module is also being developed for equilibrating metal specimens with sodium to obtain measurements of the chemical activities of impurities for calibration of the meters. Both the meter modules and the calibration modules will have general utility in LMFBR systems. Commercial suppliers will be sought for these modules, as well as for the meters themselves.

B. Direct Measurement of the Activities of Impurities in Sodium--

J. T. Holmes and R. J. Meyer

The objective of this work is to develop methods for calibrating impurity meters for carbon, oxygen, hydrogen, and possibly nitrogen, by independent chemical determinations of the impurity activities. Application of such methods in on-line meter-calibration devices is sought. The methods under development generally involve equilibration of thin wires of a suitable metal in sodium. The equilibrium concentration of the impurity being

determined is a measure of its chemical activity in the sodium. These methods are being developed in a cooperative program between the Chemical Engineering and Materials Science Divisions.

Laboratory development of a method for determining oxygen activity in sodium with vanadium wires is essentially complete. Measurements of the distribution coefficients for oxygen in V-O-Na system temperatures between 500 and 750°C, in 50° intervals, have been reported. Chemical activities of oxygen in sodium of up to 0.1 ppm at 500°C, and up to 16 ppm at 750°C, can be determined from measurements of the equilibrium concentration of oxygen in vanadium. The method will be used for calibration of electrochemical oxygen meters and for measurements of oxygen activities in operating sodium systems, including reactor systems.

Vanadium also is being considered as a detector metal for measuring hydrogen activity in sodium, and some distribution coefficient data have been obtained. Vanadium, iron, and iron alloys are being considered for carbon detectors. The wire-equilibration method also may be applied to nitrogen activity measurements; however, a suitable detector metal has not yet been found.

A significant effort also is being made to establish reliable, routine analytical procedures for the determination of the oxygen, carbon, nitrogen, and hydrogen in the equilibrated metal specimens.

The use of these methods for periodic on-line calibration of the various impurity meters requires that suitable equipment for specimen equilibration be designed and incorporated into a modularized package with the necessary devices for controlling sodium temperature and flow. The module must be designed for rapid access to the specimens after equilibration. For radioactive sodium systems, this can be accomplished most easily by providing for complete drainage of the radioactive sodium. The conceptual design of the module is shown in Fig. VII-1. Since the module heats sodium to temperatures up to 750°C, it will also be used as the carbon meter module (see Sec. VII.D) by replacing the wire holder with the carbon-meter membrane system.

Fig. VII-1

Module for Wire Equilibration and Carbon Meter. ANL Neg. No. 308-2382.

C. Oxygen Meter--V. M. Kolba, L. J. Marek, and R. R. Schlueter

The goal of this work is to develop and prooftest an on-line oxygen-meter module for monitoring oxygen activity in the primary and secondary sodium systems of LMFBR's. Electrochemical oxygen meters will be evaluated and improved, where necessary, to provide (1) reliable and reproducible measurement of the oxygen activity in sodium, and (2) continuous operation of the meter at temperatures from 700 to 900°F. Testing and development of the meter-module components will be carried out at the Illinois Site of ANL. Field testing of the meter will be through the national program, which will involve major LMFBR sodium-technology contractors. The module will be prooftested on the Radioactive Sodium Chemistry Loop (RSCL), which has been installed on the EBR-II primary sodium system. Operating experience gained at EBR-II and in the meter-characterization program will be useful in qualifying oxygen-meter modules for the FFTF and for general LMFBR use.

A joint program involving ANL, Brookhaven National Laboratory (BNL), WADCO Corp., and the Zirconium Company of America (ZIRCOA) has resulted in commercial availability of oxygen meters for the test program. The meter has a gas reference electrode and an improved thoria-7.5 wt % yttria solid electrolyte produced by an isostatic pressing process.

The electrolyte tubes will be of the size (1/4-in. diameter) that is currently used in the Westinghouse version of the oxygen meter.

Fig. VII-2. Oxygen-Hydrogen Meter Module.
ANL Neg. No. 303-2383.

A layout of a prototype module for FFTF containing two oxygen meters and one hydrogen meter has been completed (see Fig. VII-2). The hydrogen meter, which is being developed at ANL (see Sec. VII.E), has been included in the module with the oxygen meters, since both types of meters operate at the same conditions of sodium flow and temperature. As

a result, a considerable savings can be made by sharing accessory equipment. Designs of the heat exchanger and hydrogen-meter housing are complete. Oxygen meters for the modules have been ordered from Westinghouse. Preliminary layouts of the electrical and instrumentation packages for the modules have been made and reviewed.

A prototype module is being pretested at ANL-Illinois prior to prooftesting at EBR-II.

Work is underway to characterize oxygen-meter performance at temperatures from 700 to 900°F (370 to 480°C). An Oxygen Meter Rig (OMR) will provide for (1) calibration and testing of 12 meters installed in series, and (2) tests of the on-line calibration. Startup of the OMR is expected in early FY 1972.

D. Carbon Meter--C. Luner, D. J. Raue, and P. J. Mack

This work involves the development and proof testing of an on-line carbon-meter module for monitoring carbon activity in the primary and secondary sodium systems of LMFBR's. The meter housing and equipment for control of sodium temperature and flow are of the same design as the on-line calibration module described in Sec. VII.B. Carbon-diffusion meters of the best available design will be evaluated for the meter component of the module. Testing and development of the module components will be done at the Illinois Site of ANL. The module will be proof tested on the Radioactive Sodium Chemistry Loop (RSCL) of EBR-II. Operating experience at EBR-II will be used to provide recommendations for carbon-monitoring stations for FFTF and general LMFBR use.

A carbon meter developed by the United Nuclear Corporation (UNC) is being given prime consideration as the on-line meter component of the carbon-monitoring station. This meter is based on measuring the rate of diffusion of carbon through an iron membrane at 1200-1400°F (650-760°C). The carbon reaching the reverse side of the membrane reacts with a flowing, moist, hydrogen-argon gas mixture to form CO. The CO is catalytically converted to CH₄, and the CH₄ concentration in the gas stream is continually measured by a flame-ionization detector.

An understanding of the basic relationship of the carbon-meter response to carbon from various sources is a necessary part of the meter development. The UNC carbon-diffusion probe was immersed in sodium, and its response to the addition of various materials and carbon species was tested. All-copper equipment (except for the probe) was used because copper is inert to carbon.

Addition of trace amounts (<1 ppm) of sodium cyanide (NaCN) or sodium acetylide (Na₂C₂) to sodium at 630°C increased the carbon flux through the iron membrane. In each instance, the carbon flux reached a maximum and then remained constant for a number of hours. (Since the probe removes carbon, the carbon flux does eventually slowly decrease.) Figure VII-3 shows the relationship obtained between carbon flux and the measured concentration of NaCN in the sodium at 630°C. Initially, the carbon flux increased rapidly on the addition of 1 ppm or less carbon (as NaCN), but above 10-20 ppm carbon, the flux did not change. The addition of trace quantities of Na₂C₂ also increased the carbon flux, the initial increase being about twice that for cyanide. At the temperature of the experiment, acetylide

Fig. VII-3. Carbon-meter Response to NaCN and Na_2C_2 in Stirred Sodium at 630°C . ANL Neg. No. 308-2384.

increased. After the rod was removed, the carbon flux reached a maximum and remained constant for 12 hr. When a Type 304 stainless steel rod was inserted, the flux decreased. The UNC meter housing, in which the probe is located and the sodium is heated, is itself made of stainless steel and can act as a getter to remove carbon from the sodium. Consequently, an inert liner for the meter housing is considered a possible improvement.

The effect of the water-vapor content of the decarburizing gas on the carbon flux through the iron membrane was investigated. For these experiments 10% H_2 -90% Ar, instead of the usual 5% H_2 -95% Ar, was used as the decarburizing gas to ensure that the mixture, when combined with varying amounts of water, would prevent oxidation of the iron membrane at the temperature employed. Figure VII-4 shows the results obtained from experiments performed on a small pumped-sodium apparatus (Test and Evaluation Apparatus, TEA) using the UNC housing, a sodium temperature of 370°C , and probe temperatures of 625 and 750°C . The data indicate about a fivefold increase in the carbon flux for a change of 0.77-2.38% in the water-vapor content of the decarburizing gas. These data also indicate that there is little effect of temperature on the carbon flux over the range 625 - 750°C . Therefore, consideration is being given to decreasing the operating temperature of the

decomposes rather slowly, so that the variation of carbon flux as a function of acetylide concentration could not be readily measured. Further addition of sodium acetylide led to the formation of particulate carbon without noticeable increase in the analyzed acetylide content of the sodium (see Fig. VII-3).

The response of the carbon meter was also tested by inserting a rod (5 in. long by 1/4-in. OD) of low-carbon steel (1020) into the sodium at 630°C . A few minutes after the rod was inserted, the carbon flux in-

Fig. VII-4. Effect of Water Vapor in Decarburizing Gas on Carbon-meter Response. ANL Neg. No. 308-2385.

meter below the recommended 750°C, which was based on static pot tests performed by the developer of the meter, UNC; the decrease may be to a temperature as low as 650°C.

E. Hydrogen Meter--D. R. Vissers and L. J. Bartholme

The goals of this program are the design, development, and proof-testing of an on-line hydrogen meter for measuring the hydrogen activity in primary and secondary LMFBR sodium systems. A diffusion-type meter under development at ANL is being evaluated for the on-line hydrogen-meter component of the oxygen-hydrogen meter module to be installed at EBR-II, as discussed in Sec. VII.C. Operating experience at EBR-II will be used to provide recommendations for hydrogen monitoring for FFTF and general LMFBR use.

The hydrogen meter can be operated in two modes. The first is an equilibrium mode, in which the equilibrium hydrogen pressure above the sodium is measured directly and then related to hydrogen concentration in the sodium by Sieverts' law. The second is a dynamic mode, in which the hydrogen flux across the membrane is monitored by an ion pump. Operation of the meter in the equilibrium mode permits direct determination of the hydrogen activity of the sodium. However, during continuous operation in this mode for long periods of time, especially at low levels of hydrogen (<0.3 ppm), degassing from the high-vacuum components creates an error in the measurement. One method of avoiding this problem is to use the dynamic mode as the normal mode of operation, with the equilibrium mode being used intermittently. Operation in the equilibrium mode will provide a calibration for the dynamic mode of operation. Methods of reducing degassing are also being pursued.

Fig. VII-5

Apparent Solubility of Hydrogen in Sodium as Determined by Hydrogen-activity Meter. ANL Neg. No. 113-3093.

During recent preliminary studies on the Sodium Analytical Loop, the sensitivity of the hydrogen activity meter was tested during operation in the equilibrium mode. The sodium was first cold-trapped stepwise to 110°C, and the apparent hydrogen solubility* of the sodium measured at the various cold-trap temperatures. The results of these studies are shown in Fig. VII-5. Although the meter did not reach equilibrium values that were completely stable at the cold-trap temperatures tested, the responses are believed to be adequate at these low levels.

*The assumption is made that the solubility of hydrogen in sodium obeys Sieverts' law, even at these low hydrogen levels.

F. Detection of Leaks in Steam Generators--D. R. Vissers,
C. C. McPheeters, and L. J. Bartholme

The work involves evaluating the requirements for a leak-detection system for LMFBR steam generators, and developing and prooftesting a detection system to meet these requirements. First consideration is being given to diffusion-type hydrogen monitors for leak detection because they appear to be durable and sensitive to small changes in the hydrogen level of sodium. A signal-interpretation and alarm unit will be developed that accommodates normal hydrogen fluctuations in the sodium without giving false alarms.

1. LMEC Leak-detection System

A steam-generator leak detector is being fabricated for use on the Sodium Components Test Installation (SCTI) at the Liquid Metal Engineering Center (LMEC) during their tests of the AI-designed steam generator. Operation of the leak detector depends on diffusion of hydrogen from sodium through a nickel membrane into a dynamic vacuum system. Changes in the hydrogen concentration in the sodium are detected by changes in current in the vacuum-system ion pump. A rapid increase in this current activates an alarm system.

The vacuum-system ion pump operates with a 5000-V input, and currents of 10-100 μ A are normally drawn. The SCTI installation requires cable lengths of approximately 150 ft; therefore, the possibility that significant current leakage could occur over that length was tested. It was found that the current leakage directly attributable to the long cable length was insignificant; however, at ambient temperatures of 100-150°F, the leakage was approximately 0.7 μ A, which is significant at low hydrogen levels. Ambient temperature changes are generally slow, however, and this current leakage should not cause inadvertent alarms or other serious problems.

The requirements of the nickel membrane to be used in the leak detector are (1) that it provide sufficient surface area and be thin enough to diffuse hydrogen at a rate that matches the pumping speed of the ion pump, and (2) that it have sufficient strength to withstand the pressure of the sodium system. The membrane used in the leak detector for LMEC is a nickel tube 0.250-in. ID, 0.009-in. wall thickness, and 2 in. long. Reinforcing rings are placed inside the tube at equal intervals along the length to prevent collapse at high pressure. When this membrane configuration was hydrostatically tested, the tube collapsed in independent sections between the reinforcing rings at a different pressure for each section. The minimum collapse pressure was 650 psi at room temperature. This is equivalent to 250 psi at the operating temperature of 900°F, which is well above the operating pressure (100 psi) of the SCTI.

Fabrication of the leak detector has been completed, including machining, welding, inspection, and installation of heaters, thermocouples, wiring, and insulation. Figure VII-6 shows the leak detector completed, except for installation of the sheet-metal cover. The unit was shipped to LMEC on March 30, 1971. The document submittal requirements of LMEC were satisfied, and an operating manual was written for LMEC personnel to use in installation and operation of the unit.

Fig. VII-6. ANL Steam-generator Leak Detector To Be Installed at LMEC. ANL Neg. No. 308-2469A.

2. LMFBR Steam-generator Leak Detector

A greatly simplified steam-generator leak detector is being designed for installation on EBR-II, and as a prototype for future LMFBR's. The objectives are minimum time for sodium transfer through the detector piping to the nickel membrane, high reliability, and simplicity of design (low cost).

Design of a preliminary model has been completed, and fabrication has been started. This model will be tested on an available sodium loop. The model consists of a regenerative heat exchanger, a sodium pump, a nickel membrane, a vacuum system, and associated heaters and instrumentation. One end of the heat exchanger is attached directly to the main sodium pipe. Sodium enters the annulus of the heat exchanger at this point and flows to a flow-dividing tee, where it is diverted to a side leg in which the sodium pump is located. Flow continues from the pump, back to the flow-dividing tee, and along the annulus to the high-temperature end of the heat exchanger where the membrane is located. The sodium then flows past the membrane and returns to the main stream through the center tube of the heat exchanger.

Fabrication costs, in the ANL shops, of leak detectors suitable for installation on EBR-II have been estimated at about \$9000 per unit for 10 units. This cost includes all hardware items as well as all instrumentation and alarm systems.

An important component in this design is the sodium pump. Current plans are to use an annular linear-induction pump consisting of a linear motor with high-temperature (250°C) coils, and an iron center tube, which serves as a magnetic flux return. Sodium is pumped along the annulus between the coils and the iron tube. Motors with these high-temperature coils have been ordered for testing on a sodium system, and inquiries are being made about higher-temperature (>250°C) coils.

G. Characterization of Impurity Meters and Meter Response to Impurity Species--C. C. McPheeters

The primary goal of this work is the determination and interpretation of nonmetallic impurity levels in cold-trapped sodium as a function of cold-trapping parameters and procedures. The methods for determining the impurities (O, C, H, and N) in the sodium will be on-line impurity monitoring, and sampling and analysis. Experimental work will be performed in a pumped-sodium apparatus (Apparatus for Monitoring and Purifying Sodium, AMPS) that will provide stable, but adjustable, impurity levels in the sodium fed to the experimental cold trap.

AMPS will be equipped with on-line instrumentation, including an oxygen-hydrogen meter module and a sampling module at both the inlet and outlet of the experimental cold trap. Additional instrumentation will include a specimen-equilibration module and a sodium distillation sampler. A cold trap and a hydrogen trap (titanium or zirconium) will be used to control the oxygen and hydrogen concentrations, respectively. Changes in oxygen and hydrogen concentration across the experimental cold trap will be measured. The effect of the pressure of hydrogen at various concentrations on the activity of oxygen, as measured by the oxygen meters, and the effect of oxygen on the hydrogen activity will be studied. The interaction of these two species and their combined effect on the on-line meter operation will be determined.

The piping and equipment layout for AMPS has been completed, and stress-analysis calculations for the piping have been performed on the entire system. Detail design of the system is in progress. Work has been started on the electrical system design, and work is in progress on the component-fabrication packages. Construction of the sodium system is scheduled to start early in FY 1972.

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VIII. FEDAL SYSTEM DEVELOPMENT

Failed element detection and location (FEDAL) systems may be a requirement of future LMFBR's. Since failure of a sealed fuel element will be accompanied by the release of gaseous fission products and fill gas, flow sensors mounted at the outlet of fuel assemblies may be able to detect such gas releases and thus serve in a FEDAL system. The fission gas released will greatly affect the overall activity of the reactor cover gas. Systems to measure this activity and an understanding of the changes will be necessary in any FEDAL system.

A. Flow-probe Signal Reaction to Entrained Gas--R. A. Jaross

As an adjunct to the In-core Flowsensor Development Program (see Sec. I.A), tests were performed on both permanent-magnet and eddy-current probe-type flowsensors to determine their sensitivity to gas bubbles in sodium.

The permanent-magnet flowsensor showed a response to the gas by an increase in the relative signal-level response with gas injection. This increase was proportional to the increased velocity of sodium in mixture with injected gas. A 1% (volume) injection of inert gas into sodium resulted in an $\sim 1\%$ increase in flowsensor output signal. This low sensitivity was considered inadequate for use in an LMFBR.

Gas-injection tests were performed to establish the feasibility of using the eddy-current probe-type flowsensor in support of the FFTF Fuel Failure Location System. These tests were performed at 100% flow (16.4 ft/sec), 75% flow (12.3 ft/sec), and 50% flow (8.2 ft/sec). In each test, argon gas was injected, at a rate of 100 cc/sec for 5 sec, into the center of the sodium stream at a point 14 in. upstream of the probe.

With reference to Fig. VIII-1, the oscilloscope traces illustrate: (A) normal sodium-turbulence modulation of the output signal without gas injection; and (B) combined sodium turbulence and gas-bubble modulation with gas injection. Bubble modulation has higher frequency components than the turbulent modulation, and both the amplitude and percent modulation increase with the decreasing flow rate. By comparison, normal sodium-turbulence modulation of the signal decreases with decreasing flow rate.

A second series of tests on the eddy-current flowsensor was performed with the flow signal nulled out with the normal balance control. Most of the gas-bubble signals were recorded in the range 50-300 Hz. The test conditions were as follows:

Excitation current:	500 mA at 1000 Hz
Average sodium velocity:	16.4 ft/sec (525 gpm)

Sodium Velocity = 16.4 ft/sec

Sodium Velocity = 12.3 ft/sec

Sodium Velocity = 8.2 ft/sec

(A)

(B)

Fig. VIII-1. Oscilloscope Traces of Eddy-current Flowsensor Output (A) without Gas Injection and (B) with Gas Injection. ANL Neg. No. 113-3709.

Sodium temperature:	1100°F
Display instrument:	Storage oscilloscope
Horizontal sweep:	2 sec/cm
Scope vertical sensitivity:	1.0 V/cm

Argon gas was injected with a hand-operated syringe, and the injections were timed with a stopwatch.

The oscilloscope traces in Fig. VIII-2 show the normal sodium-turbulence modulation of the flowsensor output signal before gas injection, and typical bubble signals in response to various average gas-injection rates.

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B. Reactor Cover Gas Monitor--G. S. Brunson

The Germanium-Lithium Argon Scanning System (GLASS) at EBR-II applies a high-resolution lithium-drifted germanium crystal to the gamma spectrometry of the reactor cover gas. The purpose is to detect noble-gas fission products which are indicative of a leaking fuel element. Despite the high level of electrical noise, the system has given resolution of better than 4 keV (measured at the 1332-keV peak of ^{60}Co), which is higher by a factor of about 30 than the resolution obtained with the current Reactor Cover Gas Monitor (RCGM).

As reported in several references, the capricious behavior of ^{23}Ne has caused fluctuating indication of the count rate for the fission products of interest. A delay line was used to afford decay time for the RCGM, but this has been found unnecessary in GLASS due to higher resolution and to the development of electronic techniques for cancelling the effect.

Actually two different background-subtract circuits have been designed and built. The first, which has proved very successful, provides for pulse-by-pulse subtraction of background before the pulse train is fed to a conventional count-rate meter. The AEC has filed a patent application on this design. Experience revealed that there is a substantial dead-time problem in the amplifier channel which reduces the overall effectiveness of the first background-subtract device. A second and somewhat more complex circuit is now under test in prototype form. This device uses a sample-and-hold technique coupled with a gated clock to provide dead-time compensation.

(C) During Gas Injection: 5 cc/sec

(D) During Gas Injection: 10 cc/sec

(B) During Gas Injection: 2.5 cc/sec

(E) During Gas Injection: 50 cc/sec

(A) Before Gas Injection

Fig. VIII-2

Gas-bubble Signals Obtained with an Eddy-current
Flowsensor Using Flow-signal Suppression and Half-
wave Amplitude Detection. ANL Neg. No. 113-3762.

There is the problem of providing adequate dynamic range for GLASS. This is especially important, since a substantial fission-product release in the primary tank might overload the counting channel when it is adjusted for monitoring low-level background. To meet this need, a variable-volume gas sample chamber was designed and installed. This chamber uses a motor-driven sliding sleeve to change the volume of gas being counted by the detector. When a count-rate meter detects an overload, the volume is automatically reduced so that the count rate is scaled down by a factor of about 15.

The computer-controlled multichannel analyzer incorporated in the system is programmed for continuous operation, with periodic (at optional intervals) printout of the integrated data for peaks of interest. It has been possible simultaneously to analyze data from a second Ge-Li detector, which is being used to detect airborne radiation in the reactor building.

Provisions have been made for the computer-analyzer unit to exchange data with the Data Acquisition System (DAS) of the EBR-II; however, this function may not be realized for some time.

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Reactor Development Program Progress Reports: February 1971, ANL-7783, p. 21; and April-May 1971, ANL-7825, p. 3.2.

2

IX. NONDESTRUCTIVE TESTING

No attempt is made in this report to record the nondestructive testing activities at ANL. However, these activities have led to the development of a sensor of wide applicability to the LMFBR Program.

A. High-temperature Ultrasonic Transducers--K. J. Reiman

The hot, highly radioactive and corrosive environment of LMFBR's imposes severe requirements on transducers that may be used to monitor or evaluate their performance. Piezoelectric lithium niobate crystals show promise of being able to endure such an environment. Other investigators at the Laboratory (see Sec. IV.A.1) are developing pressure-plate-mounted transducers using this material. However, this type of construction limits the upper frequency of operation to several hundred kilohertz. To extend the operating frequency range to several megahertz, the supports must be brazed to the crystalline material.

Fig. IX-1. Brazed Ultrasonic Transducer.
ANL Neg. No. 113-3889.

A successful method for bonding the high-curie temperature lithium niobate to a metal support has been developed. Air-brazed transducer assemblies have been successfully operated at temperatures up to 600°C. Stainless steel-jacketed transducers of this type are suitable for operation immersed in liquid sodium or NaK. Figure IX.1 shows a transducer of this type before and after assembly.

Experience in monitoring acoustic emission has been gained by an extended period of transducer operation on the CCTL sodium test loop at 1100°F and a flow rate of 536 gpm. Additional information on transducer performance was obtained from acoustic emission monitoring of stainless steel tensile specimens undergoing fatigue cycling at 800°F, and a preliminary correlation between crack formation or growth was established.

As an alternate to the piezoelectric-type transducer, prototype capacitive transducers using high-temperature crystalline dielectric materials were investigated. These prototypes exhibited sensitivity instabilities due to surface phenomena. Also, the necessary corrective action, such as employment of a pulsed supply voltage, limits the area of application of such transducers.

REFERENCES

Reactor Development Program Progress Reports: June 1970, ANL-7705, p. 148; September 1970, ANL-7742, p. 111; December 1970, ANL-7765, p. 66; January 1971, ANL-7776, p. 76; and March 1971, ANL-7798, p. 74.

X. FAST-REACTOR CRITICAL-FACILITY INSTRUMENTATION AND TECHNOLOGY

A considerable amount of development effort in the LMFBR Program is devoted to instrumentation and techniques for applications in fast-reactor critical experiments. These experiments are usually made at room temperature, at low reactor power, and in a clean reactor core, and the application is often rather specialized. Although no extension of these developments to power-reactor adaptation is now funded or planned, the principles of the instrumentation or of the techniques occasionally may be directly applicable or be extended to LMFBR applications upon the base of equipment already on hand and of the experience already attained with relatively moderate additional cost.

In this sense, the following novel instruments and techniques, which have been or are being developed for special application in the ZPR-6, ZPR-9, and ZPPR critical facilities can be cited.

A. Instrumentation

1. Neutron-insensitive Gamma Counter--E. F. Bennett

This counter was developed for on-line monitoring of gamma background in a pulsed fast-reactor neutron time-of-flight facility. In operation, a number of scintillating slabs are viewed by two photomultiplier tubes, light from alternating slabs being directed to either photocathode. A coincidence requirement thus discriminates proton recoils from fast neutrons which have a range somewhat shorter than the slab thickness, as well as dark current emission from the photocathodes, but delivers pulses from Compton recoils which tend to penetrate several slabs. After intercalibration with the neutron detectors in the time-of-flight system, the gamma background can be measured concurrently with the neutron spectrum, and thereupon subtracted. The counter has been tested successfully, but is not yet in service.

2. Reactor Power Monitor Based on Cherenkov Radiation Detection--R. Gold

In a reactor, copious gamma radiation is emitted by decay processes originating from induced activities and fission products; gamma rays of somewhat higher average energy also are originated in prompt processes of capture and fission. The latter vary with reactor power level. Conventional gamma detectors cannot discriminate to a practically useful extent against the two components. However, Cherenkov light is generated by relativistic Compton recoil electrons which originate in scattering processes involving only the high-energy component of the gamma flux. Since the

Cherenkov effect has a threshold that depends on density in a gaseous medium, a threshold above, say, 2 MeV can be selected by suitable choice of gas pressure.

The detector itself, made from tubing with highly polished walls, transmits information from the reactor core region to a photomultiplier tube outside the core environment, thus avoiding the need for cable or insulators which are adversely affected by heat and radiation.

A series of preliminary proof-of-principle tests of the detection system concept has been carried out, using the LINAC and the Van de Graaff electron accelerators. Further development was not undertaken.

REFERENCES

R. Gold, K. G. Porges, and W. C. Corwin, "Gas Cherenkov Reactor Power Monitor," Reactor Physics Division Annual Report: July 1, 1968 to June 30, 1969, ANL-7610 (1970), pp. 437-440 (Jan 1970).

K. G. Porges, R. Gold, and W. C. Corwin, Reactor Power Monitor Based on Cherenkov Radiation Detection, IEEE Trans. Nucl. Sci. NS-17(1), 501 (1970).

3. Si(Li) Compton Recoil Gamma-ray Spectrometer--R. Gold

Although the Compton response of a high-resolution Si (lithium-drifted) solid-state detector is a troublesome complication in the measurement of nuclear energy-level spectra, this response can be exploited for continuous in-core and environmental gamma-ray spectroscopy. The measured electron-recoil spectrum is related to the continuous gamma-ray spectrum through the Klein-Nishina formula and can be determined by an unfolding process from the measured electron-recoil spectrum. The Compton response of this detector dominates, by one or two orders of magnitude, in the energy region from about 100 keV to a few MeV.

The detector has been used for in-core gamma-ray spectrum measurements in ANL critical facilities. It has also been used as an environmental monitor to measure the spatial gamma-ray distribution in the irradiation rooms at the JANUS reactor.

REFERENCES

R. Gold, "Compton-Recoil Gamma-Ray Spectroscopy," Nucl. Instr. Meth. 84, 173-194 (1970).

R. Gold, "In-Core Gamma-Ray Spectroscopy," Reactor Physics Division Annual Report: July 1, 1968 to June 30, 1969, ANL-7610, pp. 248-250 (Jan 1970).

R. Gold and K. E. Freese, "Gamma-Ray Spectral Measurements at JANUS," Applied Physics Division Annual Report: July 1, 1969 to June 30, 1970, ANL-7710, pp. 344-349 (Jan 1971).

4. Improved Proton-recoil Proportional Counter--E. F. Bennett

An extended study of the energy dependence of the proton energy loss per ion pair created (W) has led to an approximate evaluation of the dependence of W on ionization. An analytic determination of the response function has been developed for a proton-recoil counter that corrects measured energy-distribution data for distortions introduced by the truncation of high-energy proton-recoil tracks by walls.

During studies relating to the quality of the internal field in small proportional counters required for in-core proton-recoil spectroscopy, it was observed that certain internal redesign of the chambers would greatly reduce systematic errors and provide more precise measurement of absolute spectra in critical assemblies.

These improved chambers are being evaluated.

REFERENCES

E. F. Bennett, Low Energy Limitations on Proton-Recoil Spectroscopy Through the Energy Dependence of W , Trans. Am. Nucl. Soc. 13(1), 269 (1970).

T. J. Yule, High Energy Limitations in Neutron Spectrometry with Proton-Recoil Proportional Counters, Trans. Am. Nucl. Soc. 13(1), 269 (1970).

E. F. Bennett and T. J. Yule, Calibration of Gas Multiplication Versus Voltage for Proportional Counter Neutron Spectrometers, internal memorandum ZPR-TM-31 (1970) (limited distribution).

E. F. Bennett and T. J. Yule, Techniques and Analyses of Fast-reactor Neutron Spectroscopy with Proton-recoil Proportional Counters, ANL-7763 (Aug 1971).

5. Absolute Proportional Counter--E. F. Bennett

Proportional counters filled with enriched boron-trifluoride are among the oldest types of neutron monitors. They are used routinely and satisfactorily for relative measurements, but have seen little application for absolute ^{10}B reaction-rate determinations in fast fluxes. Recent

instrument developments, particularly those related to the improvement of proton-recoil proportional counters, make it appear feasible to use specially constructed chambers of this type for absolute measurements.

A very moderate effort, limited by current funding, is being devoted to the development of this absolute detector. The goal is an instrument capable of 1-2% accuracy in flux measurement as opposed to the previous limit of 5-10%.

REFERENCE

E. F. Bennett and T. J. Yule, Improvements in Absolute Boron Proportional Counters, Trans. Am. Nucl. Soc. 14(1), 415 (June 1971).

6. Back-to-Back Plate-type Proportional Counter--S. G. Carpenter and L. S. Beller

This counter has been developed for either of two modes of operation, depending on the method of fabrication: (1) gamma-ray discrimination while counting neutrons with a ^{10}B proportional counter in a critical assembly, and (2) measurement of neutron spectral indices during operation of a fast critical assembly. In mode 1, back-to-back mounting of a ^{10}B and a blank foil in a common chamber provides the basis of an instrument in which the count rates from a ^{10}B proportional counter can be corrected for the gamma-ray contribution by subtracting the count rate in the blank foil. For the second mode of operation, ^{10}B can be applied on one side of the chamber, and ^{235}U or ^{239}Pu on the other, to form an integral chamber for the measurement of a spectral index. Then, by calibrating the chamber in a known thermal-neutron flux, one can calculate the relative number of ^{10}B and fissile atoms, using their thermal cross sections; this calibrated chamber then can be used to measure reaction-rate ratios in neutron fluxes of high energy. Comparisons with previously used gas counters in ZPR-3 cores have demonstrated considerable improvement in ease of operation and accuracy of the counters when the gamma-to-neutron field ratio becomes large.

These instruments have been in use for about one year; approximately 14 detectors have been made. Their potential as an absolute device requires additional work to establish calibration.

REFERENCE

L. S. Beller, "Detection for $^{10}\text{B}(n,\alpha)$ -to-Fission Ratio Measurements," Applied Physics Division Annual Report: July 1, 1969, to June 30, 1970, ANL-7710, p. 288 (Jan 1971).

7. Double Fission Chamber--E. F. Bennett

Dieaway fission chambers show promise for resolving the unique and difficult problem of monitoring neutron bursts in a pulsed fast-reactor time-of-flight facility. The chambers are of double construction, and accommodate one ^{238}U and one ^{235}U foil in each detector. The cross-sectional area of each foil is 10 cm^2 . The detectors and their electronic circuits are designed to have a pulse length of about 10 nsec. The detectors, to be used in-pile, will monitor the shape of the neutron bursts and provide complementary information to a gamma background monitor (cited above) on the timing and composition of the pulsed beam radiated from the critical facility.

Chambers have been fabricated and are under evaluation.

8. Flux-plotting Spark Chamber--K. G. Porges

Designed for rapid measurement of reaction-rate distributions in a critical facility, this device consists of a single-wire stainless steel spark counter, using a resistive wire anode facing a fission foil with connections for high voltage and signal pulses at one end. Since the uniform spark-discharge current pulses tend to divide according to the resistance of the central wire, a spatial resolution of the location of the fission event within 1-2 mm can be achieved. Signals are large and require attenuation rather than amplification; they are unaffected by noise and gamma background, and alpha background and natural activity can be discriminated against. Although a relatively long time ($\sim 100\text{ }\mu\text{sec}$) is required for complete recovery, a multichannel pulse-height analyzer with a comparable processing time is required to display the output.

A 1.5-m-long, 2-cm-dia chamber has been tested. A second chamber, 20 cm long and of 38.5 mm^2 cross-sectional area, also has been developed.

9. Varactor-diode Electrometer--S. G. Carpenter

Used in connection with inverse-kinetics techniques to determine subcriticality levels, this instrument is designed to minimize inherent noise levels, to have high frequency response, and to have a linear reactor power-current output function. This sensitive, stable electrometer using varactor diodes was developed for reactor power level and period measurements. It has an input bias current of approximately 10^{-18} A , and features responses of 5 msec in the 10^{-5} -, 10^{-6} -, 10^{-7} -, and 10^{-8} -A ranges, and 80 msec in the 10^{-9} - and 10^{-10} -A ranges. To transmit the reactor power history to the reactor control room, analog outputs from the electrometer are transmitted via differential amplifiers. Gain and zero offsets for each gain range are separately adjustable from the control room.

This instrument is currently in service at the ZPPR.

REFERENCE

An article on this instrument will be included in the Applied Physics Division Annual Report, ANL-7910, to be published in June 1972.

10. Resonance-absorption Sodium-vapor Monitor--J. F. Meyer

This instrument was developed to continuously monitor circulating argon cover gas of the Variable Temperature Rodded Zone in ZPR-6 for sodium vapor to obtain early indication of a sodium leak in the facility. In operation, a sodium light source produces a monochromatic light beam of the emission-line frequency of sodium. This beam then passes through the monitored argon gas to a photomultiplier tube. If the monitored gas bears sodium atoms, the light from the 5890- and 5896-angstrom peaks will be resonantly absorbed and the beam strength attenuated. The monitor is capable of detecting as little as 0.03 ppm sodium vapor in argon gas (about 2.5×10^{-11} g/cm³).

The monitor has been fully tested and is to be incorporated into the instrumentation of the VTRZ on ZPR-6.

REFERENCE

J. F. Meyer, T. W. Johnson, and J. E. Sustman, "A Sodium-Vapor Monitor," Applied Physics Division Annual Report: July 1, 1969 to June 30, 1970, ANL-7710, pp. 359-362 (Jan 1971); also, Trans. Am. Nucl. Soc. **13**(1), 794 (1970).

B. Technology

1. Subcriticality Measurement Techniques--C. E. Cohn

A series of measurements has been carried out on ZPR-9 to compare the results of several methods of measurement of reactor subcriticality. The methods used were (1) rod drops; (2) straightforward multiplication; (3) noise analysis techniques, which included cross-power spectrum analysis of the reactor noise by a group from ORNL, and a polarity coherence method carried out by a representative from HEDL; (4) a variation of the multiplication method which assumes constant worth for particular control rods; and (5) changes in detector responses caused by an asymmetric source were analyzed. The objective is to attain at least two validated techniques that can then be applied routinely to the measurement of subcriticality.

A current difficulty lies in the area of adequately and realistically estimating the absolute accuracies to be assigned to the various subcriticality measurements. Intensive effort in this area will continue throughout FY 1972.

REFERENCES

C. E. Cohn and W. K. Lehto, Reactivity Meters for Operational LMFBR's, internal memorandum ZPR-TM-20 (1970) (limited distribution).

C. E. Cohn, Status of Subcriticality Determinations Using Inverse Kinetics Methods on Rod Drops, internal memorandum ZPR-TM-40 (1970) (limited distribution).

2. TLD Measurement of Gamma-ray Heating Effects--
S. G. Carpenter and G. G. Simons

Quantitative measurement of in-core spatial gamma-ray flux is necessary to evaluate gamma-ray heating effects. Thermoluminescent dosimeters (TLD's), using various enrichments of ^7Li in lithium-fluoride, are commercially available, as is an analyzer for use in gamma-ray dose applications. The dosimeters are sensitive to gamma rays, charged particles, and neutrons in varying degrees. In current application, it is assumed that the fast-neutron sensitivity in the dosimeters using enriched lithium is negligible, although inconsistencies appear in the literature. However, numerous questions remain relative to the unambiguous measurement of gamma-ray heating effects. These include the determination of the neutron and gamma-ray spectrum response of TLD's, and the relationship of these detectors to gas-filled ionization chambers.

Development will continue to improve confidence in the existing TLD measurements, and to evaluate sources of systematic error.

REFERENCE

G. G. Simons, "Thermoluminescent Dosimetry Applied to Gamma Ray Dose Measurements in Critical Assemblies," Applied Physics Division Annual Report: July 1, 1969 to June 30, 1970, ANL-7710, pp. 289-294 (Jan 1971).

3. Statistical Performance of Surveillance and Experimental Counting Channels--K. G. Porges

Experience has indicated that the design and performance evaluation of safety and experimental neutron-counting channels can be improved. Accordingly, the objective of this effort is to develop a semiempirical formula for the distribution obtained with Poisson input at a certain rate and certain processing time constants. On the basis of this formulation, and compared with measurements at a representative number of alarm settings, the false trip rate for these parameter values can then be compared. Effort is made to relate the false trip frequency to the announcement delay and detection probability in the warning trip channels.

These studies will proceed intermittently, as required in the development of new critical-facility instrumentation.

REFERENCES

K. G. A. Porges, "Statistical Performance of Surveillance Count Channels," Reactor Physics Division Annual Report: July 1, 1968 to June 30, 1969, ANL-7610, pp. 419-420 (Jan 1970).

K. G. A. Porges, "Statistical Performance of Digital Count-Rate Meters," Ibid., pp. 420-423 (Jan 1970).

K. G. A. Porges, "Statistical Fluctuations and the False Alarm Frequency of Safety Channels," Applied Physics Division Annual Report: July 1, 1969 to June 30, 1970, ANL-7710, pp. 323-325 (Jan 1971).

K. G. A. Porges and W. Corwin, "Fluctuations of Count Rate Meter Signals," Ibid., pp. 325-327 (Jan 1971).

4. A Method for Automatic Control of Low-power Reactors-- C. E. Cohn

This method was designed for control-rod calibrations, determination of space-dependent sample reactivity worths, and measurements of shutdown reactivity as a function of time after scram. The method also has the capability of taking an assembly through critical to a demand power by means of a driver circuit connected to the motor of a control rod.

With the aid of a small digital computer in conjunction with the critical facility, reactivity measurements can be made by fitting an asymptotic period, or by using an inverse-kinetics algorithm, to determine reactivity versus time from the record of neutron flux versus time. If the position of a control rod or other movable element is recorded, a plot of reactivity versus position is generated, i.e., the typical rod-calibration curve. Using pulses generated by an increment of rod motion (e.g., a relay driven by a stepping motor pulse), a control algorithm was developed to automatically bring the reactor through critical to a demand period and a demand power level.

Although the method has been developed and demonstration-in-principle has been made, safety approval for its routine application has not yet been sought.

REFERENCES

C. E. Cohn, "Automated Data Analysis and Control for Critical Facilities," Proc. Symposium on the Use of Computers in Analysis of Experimental Data and the Control of Nuclear Facilities, CONF-660527 (May 1967).

C. E. Cohn, A Method for Startup of a Nuclear Reactor Utilizing a Digital Computer, U.S. Patent 3,242,653 (Jan 28, 1969).

XI. INSTRUMENT TEST FACILITIES

The environmental conditions of temperature, neutron flux, and gamma flux that will exist in the LMFBR's are more severe than encountered in any existing reactors. This section describes two facilities that have been constructed at the EBR-II to provide prototypical conditions for testing LMFBR instrumentation.

A. Nuclear Instrument Test Facility (NITF)--R. E. Rice

The NITF is used primarily for evaluating prototype neutron sensors, cables, and circuits described in Sec. V. As shown in Fig. XI-1, the NITF consists of two instrument thimbles, O-1 and J-2, which are immersed in 700°F sodium in the EBR-II primary tank. These thimbles originally contained neutron detectors used in the plant instrumentation system and were forced-air cooled to maintain a temperature of 125°F. Preparation of the O-1 thimble for use in the NITF consisted of relocating the existing detectors in other thimbles, removal of a neutron shadow shield, and installation of devices permitting fine control of the cooling air.

Fig. XI-1. Location of O-1 and J-2 Thimbles in NITF

Conversion of the J-2 thimble to NITF use was a major project. All the existing thimble internals were removed and replaced with an insulated oven-shield plug of unique design. In addition to maintaining a given temperature between 700 and 1200°F, provisions have been made for insertion of auxiliary gamma sources to yield a gamma flux of 10^6 R/hr during reactor startup.

Listed below are typical characteristics of the thimbles at the core midplane for a reactor operating power of 62.5 MWt.

Characteristic	O-1 Thimble	J-2 Thimble
Neutron flux, n/cm ² -sec	6.4×10^8	8.0×10^{10}
Gamma flux, R/hr	5.5×10^4	1.2×10^6 *
Temperature, °F	125-700	700-1200
Test volume, in.	4.8 ID x 240	6.2 ID x 84

The O-1 thimble is fully operational. The J-2 thimble is undergoing checkout.

REFERENCES

J. D. Cerchione et al., Conceptual and Preliminary System Design Description for the EBR-II High Temperature Out-of-Core Nuclear Instrument Test Facility, internal memorandum, no number (Apr 1969).

J. D. Cerchione et al., "Final System Design Description for the Nuclear Instrument Test Facilities" (report in preparation).

Guide for Irradiation Experiments in EBR-II, Appendix I, NITF (No authors).

B. In-core Instrument Test Facility (INCOT)--E. Hutter

The INCOT facility was designed to enhance the irradiation capability of EBR-II in order to obtain performance data on prototype sensors, sensor cabling, and other materials under typical LMFBR operating conditions. By replacing a control rod and its drive system (Position No. 8, Row No. 5) with a thimble, an experimenter can insert prototype sensors into the EBR-II core and continuously monitor their performance in a fast-neutron flux. Insertion of the thimble into the limited space of a control rod has a minimum effect on other systems installed in the reactor and is fully compatible with the present fuel-handling systems and interlocks.

As shown in Fig. XI-2, the INCOT consists of a thimble assembly (~35 ft long), an inner sensor assembly which contains the test sensors and/or materials, a terminal box assembly, an elevating system, and shielded containers for transporting sensors, sensor assembly, and thimble assembly. Three models are being designed: Model 1 provides individual thimbles for each test sensor in an inert gas; Model 2 provides for one maximum-size (1.4-in.-ID) thimble for all test sensors in an inert gas; and Model 3, presently under construction, provides one maximum-size thimble open to the primary system coolant sodium.

Sodium temperatures between 700 and 1200°F can be obtained, depending on the susceptor mass and primary coolant-flow adjustments. The coolant sodium flow can be adjusted from about 0.6 to 14 gpm in Models 1 and 2.

*Insertion of auxiliary sources will provide 10^6 R/hr with the reactor shutdown, and 2.2×10^6 R/hr with the reactor at full power.

Fig. XI-2. EBR-II INCOT Facility.
ANL Neg. No. 104-175.

and from about 0.6 to 35 gpm in Model 3. Sensor temperatures in an inert gas are higher than those in sodium because of the thermal insulation provided by the inert-gas thickness and other environment features. Gamma and neutron radiation is the only heat source; typical values at the core midplane are $\sim 2 \times 10^{15}$ n/cm²-sec and $\sim 10^9$ R/hr, respectively.

Irradiated sensors and materials will be removed from the primary tank, using a handling container on the operating floor. Removal will be to a storage location in the reactor building, providing a capability for limited tests and checks. Materials for detailed examination will be transferred to the experimenter's coffin for movement in accordance with prior arrangements.

The hardware for the INCOT is being fabricated, with reactor installation scheduled for early 1972.

REFERENCE

E. Hutter and O. Seim, Preliminary System Design Description of the EBR-II In-core Instrument Test Facility, ANL/EBR-023 (June 1970).