UNCLASSIFIED

~~OFFICIAL USE ONLY~~

BNWL-779
5-

[redacted]

TECHNICAL BASES FOR FFTF OPEN TEST POSITION AND CLOSED-LOOP INSTRUMENTATION

Compiled by
J. J. Regimbal

April 1968

[redacted]

AEC RESEARCH &
DEVELOPMENT REPORT

~~OFFICIAL USE ONLY~~

UNCLASSIFIED

BNWL-779

BATTELLE NORTHWEST
BATTELLE MEMORIAL INSTITUTE · PACIFIC NORTHWEST LABORATORY
3000 STEVENS DRIVE, P. O. BOX 999, RICHLAND, WASHINGTON 99352

INFORMATION CONCERNING USE OF THIS REPORT

[redacted] STATUS

This [redacted] since it is transmitted in advance of patent clearance, is made available in confidence solely for [redacted] contracts with the U. S. [redacted] sion. This document is not to be published nor its contents [redacted] purposes other than specified above [redacted] for such release or use has been secured, [redacted] request, [redacted] Group, U. S. Atomic Energy Commission, 9800 So. Cass Ave., Argonne, [redacted]

PRELIMINARY REPORT

This report contains information of a preliminary nature prepared in the course of work under Atomic Energy Commission Contract AT(45-1)-1830. This information is subject to correction or modification upon the collection and evaluation of additional data.

LEGAL NOTICE

PACIFIC NORTHWEST LABORATORY
RICHLAND, WASHINGTON
operated by
BATTELLE MEMORIAL INSTITUTE
for the
UNITED STATES ATOMIC ENERGY COMMISSION UNDER CONTRACT AT(45-1)-1830

PRINTED BY/FOR THE U.S. ATOMIC ENERGY COMMISSION

54-1950-016 (11-67)
AEC-RL RICHLAND, WASH

[redacted]

BNWL-779

TECHNICAL BASES FOR
FFTF OPEN TEST POSITION AND
CLOSED-LOOP INSTRUMENTATION

Compiled By:

J. J. Regimbal

Reactor & Systems Analysis
FFTF Project

Approved By: R.E. Peterson
R. E. Peterson, Manager
Reactor & Systems Analysis

PACIFIC NORTHWEST LABORATORY
Richland, Washington

[redacted]

Principal Contributors:

W. Dalos

C. L. Fies

A. Padilla

R. D. Peak

R. E. Peterson

J. J. Regimbal

D. C. Thompson

M. R. Wood

TABLE OF CONTENTS

Page

TECHNICAL BASES FOR FFTF OPEN TEST POSITION AND CLOSED-LOOP INSTRUMENTATION

I. OBJECTIVES

Some of the instrumentation for the open position and closed-loop irradiation test channels of the FTR will satisfy requirements which correspond to those that have been established for the driver fuel channels.(1) Briefly, these are requirements relating to safety and surveillance. However, core channels which are specifically designated as test facilities must also be fitted to communicate experimental data. It is furthermore considered essential for test positions that the potential not be precluded for sensing and relaying information of a type not yet well defined. Requirements for instrumentation of the latter sort will become more completely determined as details are provided concerning variously proposed experiments, and as plans for testing under related LMFBR programs are formulated.

To the degree that such experiments can be anticipated, an effort is directed toward defining probable test conditions and how they give rise to instrumentation requirements. Somewhat better definition is possible in the case of safety and surveillance devices. The objective of this work, then, is to address in detail the problem of resolving core instrumentation requirements for the test channels and to identify and evaluate those technical factors which influence such requirements.

Open test positions utilize primary reactor system sodium, whereas the closed loops employ individual coolant systems that are isolated from the reactor coolant. An advantage of the latter is the greater latitude and controllability of coolant conditions available to the test specimen. Bases for instrumentation of closed loops must consider the design requirement that the FTR have at least single channel capability to test fuel up to and including failure in dynamic sodium.(2) Meltdown within a loop is the worst consequence of fuel failure and the ability to rapidly recover from this eventuality must be provided for. This requirement is not interpreted as providing for routine meltdown testing. The bases for instrumenting open test positions must also consider fuel failure as an operational probability.

Because of the flexibility afforded by isolation of closed-loop coolant systems, variations in coolant chemistry, temperature and pressure and the use of coolants other than sodium are anticipated. Test channels considered in conceptual design accommodate specimens 3.5 inches in diameter;(3) test powers range from 0.4 to 6.0 megawatts, and bulk sodium outlet temperatures may range to 1400°F.* Packaged closed loops may be accommodated in reflector or core test positions for lower power tests.

Open-loop test channels are limited to conditions that are compatible with the core coolant. The maximum test diameter corresponds to a unit cell dimension in the reference concept of 4.5 inches.(3) Initial core bulk inlet and outlet temperatures are 550°F and 900°F, respectively.* Pressure head available will be near 100 psi.

Instrumentation requirements for the reactor test positions can vary from minimum driver fuel requirements to extremely sophisticated contact instrumentation. As an objective, firm requirements for closed loops and open test positions will be defined only in the sense of minimum requirements, considered to be essential for safety and operation. Experimental instrumentation will be considered in respect to identification of probable needs that may affect core design and for which development effort should be initiated for use in experimental programs commensurate with first core operation of the FFTF.

Technical bases for closed and open-loop instrumentation have been divided into three categories. These are classified according to their objectives: reactor safety, surveillance, and experimentation.

---

* Temperatures achievable within test sections can be increased above the bulk value by appropriately tailoring thermal-hydraulic design.

A. Reactor Safety

Conditions of impending destruction in test positions must be determined through instruments in time to effect measures which assure an acceptable termination of difficulties. To prevent such serious consequences as gross loss of integrity of fuel pieces, sensors must actuate the reactor safety circuit faithfully, and rapidly. As in driver fuel channels, occurrences which initiate and promote damage are characterized as follows:

- Coolant Flow Choking or Blockage
- Fuel Cladding Failure
- Accidental Reactivity Insertion (Overpower)

The FTR operator will specify the instrumentation necessary to assure safety and operability of the reactor for tests to be carried out in the FTR. To obtain the necessary review and approval, the experimenter would communicate test specifications to the operator, including a full materials description, test instrumentation requirements and the computed expectations of behavior and interactions over the testing period. It may be desirable, for the sake of economy and scheduling, that experimenters utilize FTR design instrumentation as experimental sensors wherever possible.

Some of the functional requirements regarding instrumentation for safety purposes will be identical to those which normally will be specified for testing or surveillance applications. There is an obvious incentive, for purposes of economy and design simplification, to relegate such duplicate functions to the same physical instrument. In the interest of safety, however, justification of such overlapping usage should include demonstrating with assuredness that no troublesome complication or compromised redundancy is thereby introduced. It is expected that it will prove difficult to establish the adequate reliability of systems employing a great deal of instrument commonality between safety and experimental functions. Standard guides and safety criteria will be made available to experiment sponsors in order that such limitations can be anticipated by them.

Instrument sensitivity and response speed must be adequate to the task of recognizing low contrast signals of danger and, if necessary, initiating shutdown. One of the objectives of the aforementioned study of instrumentation for driver fuel channels was to establish effects on parameters associated with changes in local environment resulting from the above occurrences. That effort is continued here, taking into account characteristics unique to open test positions and closed loops.

B. Surveillance

If the reactor is to achieve a satisfactory record as a service device, faulty operation must not be permitted to jeopardize the successful conclusion of lengthy experiments, or to sporadically introduce ill-defined test conditions. Instrumentation, then, must be provided not only for safety but also for assured conduct of costly programs, and to prevent obliteration of interesting data which may be available only in a rather irreversible mode. Simply to achieve a high value of power production or "reactor availability" may not suffice. For that purpose, however, a general reactor-condition surveillance record must be compiled also to permit estimates of improvements which might afford more efficient operation.

While the plant and personnel safety instrumentation is expected to react quickly to known signatures of possible difficulty, instrumentation for general surveillance might also be required to give early indication of abnormal or unanticipated operation of a more subtle or complex type. For a potential accident situation that can be well described, deductively ordered safety operations are able to be listed and translated into programmed hardware. However, this is not so neatly done for complex cases where safety judgments can be made only through an inductive process, where, let us say, accident conditions are accruing slowly and something "seems" to be wrong. In such cases the operator must have recourse to information that may permit him to see beyond a snapshot reactor status report to the pattern of what could be a consistently growing malfunction. If such a pattern of reactor behavior or response can be isolated from a swelter of operating data, it may be possible to empirically formulate a trend and identify its causes. Depending upon ordinary procedural criteria, this surveillance information may serve as the basis for at least temporary remedial action.

The availability of data processing equipment makes possible this kind of surveillance with a human interpreter. Key elements here are quick data retrieval and clear display from a detailed operating log which is routinely stored in an accessible memory. Planned periodic indication of the core environment status is also required to permit the reactor to operate closer to safeguards limits and eliminate uninformed and unnecessary conservatism. The quantities to be surveyed at various types of positions include temperature, coolant flow and neutron flux. Surveillance of other measured parameters unique to each test position will further enhance knowledge of local environment. A continuing objective has been to estimate uncertainties and long-term changes in distribution of these indicators in order to set requirements for surveillance instrumentation.

C. Experimentation

Technical bases for test instrumentation requirements generally will correspond to the details of experimental planning for acquisition of data. This means that LMFBR Program plans, as they develop, will provide the opportunity to delineate the various testing goals and methods of achieving them through acceptable technical procedures and, of course, using instruments whose sensory capabilities are fitting. It is desirable to have an early estimate of these needs in order that some adequate provision may be made for them in other contemporary FTR system descriptions. Most obviously also, without such information, one is unable to provide firm requirements for instrument development and procurement studies.

Thus, the objective of the present study in this regard is to estimate the type, quality and disposition of sensors to be used by experimenters for measuring the environment in which test specimens reside.

As a corollary objective, it is desirable to give some early attention to the problem of instrument leads and connections. Connectors will have to accommodate electrical signal and power leads, pneumatic lines for sensing and control, sodium sampling lines and traversing sensor thimbles. Accessibility and connector compatibilty should not preclude exploitation of any foreseeable instrumentation sensor or measurement developments.

Appropriate measurements which can identify the condition of significant process variables in each test facility will promote assurance of reliable safety and operation of all facilities. These measurements typically concern:

- Coolant Flow Rate
- Coolant Inlet Temperature (Reactor Inlet Temperature for Open Test Positions)
- Coolant Outlet Temperature
- Power Generation (Computed)
- Failed Element Detection
- Inlet Pressure (Reactor Inlet Pressure for Open Test Positions)
- Coolant Chemistry (Same as Reactor for Open Test Positions)

Such measurements also provide some indication of test specimen performance and status. More direct information about each specimen will be available from specialized instruments to detect:

- Surface Temperature
- Internal Temperature
- Internal Pressure
- Coolant Pressure Drop
- Position
- Strain
- Vibration
- Local Neutron Flux and Flux Spectrum

Additionally, an overall objective is an assessment of the capabilities of various instruments to meet indicated requirements. Included in this assessment are the response time, sensitivity, resolution and lifetime characteristics based on present technology. Specialized test instrument capability is at present indicated only in general terms, since this will be a function of particular tests, as yet undefined. Current instrument development goals which specifically anticipate the arduous environment of the FTR provide an estimate of improvements which may be expected before instrument procurement.

II. SUMMARY

Instrumentation for open test positions and closed loops in the FFTF has been investigated from the standpoints of reactor safety, surveillance and experimentation. Significant differences between instrumentation requirements for these in-core facilities and requirements for the driver fuels are due to the following.

- Experiments to be conducted in open test positions and closed loops will in general have characteristics which differ from the operational factors associated with the driver fuel channels.
- Open and closed test positions may incorporate bypass flow hydraulics to attemperate outlet coolant temperatures.
- Experiments will require instrumentation of a specialized nature, depending upon experimental goals unique with each tester.

A. Safety

It is concluded that for purposes of reactor safety, the fundamental requirements for temperature, flow and failed fuel detection to protect the core remain the same for open test positions and closed loops as previously identified for driver fuel.(1) Table I summarizes these instrumentation requirements for three types of accidents: power excursions, loss of flow accidents, and fuel cladding failures. It is noted that when flow bypass around the test section is used, sensors should be located to measure the test section coolant temperatures and flow rates instead of the characteristics of the combined flow.

Detailed requirements are unique with each experiment and cannot be defined more precisely without knowledge of test characteristics. As with present testing programs in fast reactors, such as EBR-II and Dounreay, and in thermal test reactors, each test must be qualified separately. Part of the qualification process will be to establish the levels and responses required for these basic sensors in the core test positions. Certainly in those instances where the test characteristics are close to those for driver fuel, the technical bases for flow, temperature and failed fuel are applicable.

TABLE I
INSTRUMENTATION REQUIREMENTS FOR OPEN LOOPS AND CLOSED TEST POSITIONS

REACTOR SAFETY

Accident	Parameter Sensed	Sensor	Required Response	Present Capability	Required Development
A. Power Excursion					
Limiting Condition: Open Loops - Incipient Melting (Initial Core)	1. Core Neutron Flux	Ion Chamber	Response time <100 msec from 10-1000MW; range-shutdown - 300% design power.	Adequacy uncertain for high gamma background for startup and intermediate ranges.	Improve detection of low neutron levels in high gamma background.
Closed Loops - Test Failure	2. Neutron Flux Period/Rate	Ion Chamber	Period detection from ∞ to 5 seconds. Response time not set.	" " "	" " "
	3. Coolant Temperature	Thermocouple*	Response time <1 sec for slow transients. Range-ambient to 1650°F.	Adequate except for fast transients.	Reliability and accuracy; T/C materials and insulation; repeatability in fast flux.
B. Loss Of Flow					
1. Flow Coastdown Limiting Condition: Open Loops - Coolant Boiling	1. Loop Flow Rate	PM and/or DP Flowmeter	Response time less than one second.	Adequate for acceptable L/D and $T < 1000$°F.	Prove accuracy, linearity for higher temperature devices in fast flux.
Closed Loops - Test Failure	2. Pump Speed	Speed Sensing	One-second response to speed drop.	Adequate	None

* Where flow bypass around test section is used, sensors must be mounted at test section outlet.

Table I (Continued)

Accident	Parameter Sensed	Sensor	Required Response	Present Capability	Required Development
(Flow Coastdown)	3. Test Section Coolant Temperature	Thermocouple*	System response less than one second.	Same as A.3.	Same as A.3.
	4. Test Section Flow Rate	Flowmeter*	Response in less than one second.	Same as B.1.1	Same as B.1.1.
	5. Pump Discharge Pressure	Pressure Switch	One-second response to pressure change.	Adequate	None
2. Test Section Blockage	1. Test Section Flow Rate	Flowmeter* (In Cell)	Detection of threshold flow. Response 1 sec.	Same as B.1.1.	Same B.1.1.
	2. Boiling Noise	Acoustic Sensor	Pre to post-boiling indication.	Experimental Stage	Long-range LMFBR Program.
	3. Temperature Fluctuation	Thermocouple*	Need not defined.	Experimental-fast response requirement limiting.	None underway.
C. Cladding Failure Limiting Condition: Clad Failure - <∿0.04 Inch Equivalent Diameter	1. Noble Gas Fission Products	Gas Chromatography, Charged Wire Detector, or Gross Gamma	Location of failed fuel subassembly. Response time not defined.	Feasibility established.	Fission product separation and sampling method improvement
	2. Delayed Neutrons	Neutron Counters	Location of failed fuel subassembly. Response time not defined.	Feasible for special applications. Experimental stage.	Improvement and optimization of system components.

* Where flow bypass around test section is used, sensors must be mounted at test section outlet.

In the case of closed loops, there still exists a fundamental requirement to protect the core from occurrences within the loop that may induce damage in the remainder of the core. Here again, it is low flow, excessive temperatures, or conditions likely to result in either one which must be sensed. Hydraulic isolation is advantageous from the standpoint of better definition of the coolant path. This permits a failed element detection system to be utilized without the more difficult location requirement. Although detailed requirements are unique to test characteristics, as has been pointed out, closed-loop tests are likely to be conducted at less conservative ratings than those in open test positions. This feature may lead to use of more conservative instrument limits to provide the required degree of protection, again depending on the nature of the test.

Bypass flow to permit high temperatures to be attained in test sections has an adverse effect on instrument sensor capability. This is due to decreased effective sensitivity to changes in test section environment caused by coolant dilution and the consequent dilution of signals input to sensors mounted above the test section. For example, a test section with a coolant inlet temperature of 1000°F and an outlet temperature of 1400°F will require an equal amount of flow as bypass in order to moderate the coolant temperature to 1200°F. A flow reduction through the test section of only 36 percent would increase the coolant temperature of the test section outlet to the normal boiling point of sodium (approximately 1620°F). A 50-percent blockage would result in 400°F increase in the coolant temperature rise across the test section, whereas the combined flow temperature would rise by only 67°F.

Because the combined flow rate itself is also much less responsive to change in test section flow, detection of blockages in the test section is also more difficult. For example, a 50-percent flow blockage in the test section results in a reduction of total flow rate of not more than 25 percent.

Local blockages that might exist in only a few subchannels of a test subassembly are essentially undetectable by either flow or temperature sensors in the combined flow stream. Reliance on a failed fuel detection system or on some sensor which indicates the onset of boiling appears essential for protection against possible propagation of damage from this source.

B. Surveillance

No additional surveillance requirements have been identified provided that periodic or continuous measurement of the environment as required for core safety is obtained from each test position. Power distribution from a flux mapping system, earlier identified as a surveillance requirement for driver fuel, provides an independent check for test position flow - delta-T determinations. Since the neutron flux distribution is not highly sensitive to local perturbation, knowledge gained from NPTF measurements plus periodic surveillance of selected points in the core (not necessarily coincident with test positions) is judged adequate. It should be pointed out that surveillance data from experimental sensors may contribute to more efficient operation as well.

C. Experimentation

Instrumentation requirements for experimental purposes can only be specifically defined when related to well-defined testing objectives. However, because of the necessity to institute fuels and materials testing programs as soon as the FFTF becomes available, it is deemed advisable to identify instrument types and to indicate what might typically be required. It cannot be overstressed that development of this class of instrumentation is essential to exploit the full capability of the FFTF and should not be delayed on the basis that it is not an operational or safety problem. Since it does not appear that such development will be undertaken as a part of the FFTF Project, provision should be made for its early inclusion under LMFBR Program auspices.

Identification of experimental instrumentation was obtained as a result of a survey taken from potential users of the FFTF. Development needs were identified for the following types of experimental measurements:

- Flow
- Fuel Failure
- Pressure
- Vibration
- Temperature
- Stress-Strain
- In-Core Flux
- Radiation

Table II summarizes the instrumentation requirements for experimentation and also presents some of the approximate requirements for precision of the various instruments which were obtained in the survey of potential users. This list is not complete and additional requirements will be identified as the test programs evolve.

For the FTR, an additional requirement imposed in the case of certain materials and fuels tests is the capability to provide contact instrumentation in all open test positions and closed loops. Contact instrumentation is defined as instrumentation that normally will be introduced and removed along with the core piece or test specimen with which it is integrally associated. Tests of the type which measure internal temperatures of test specimens, stress, strain, fission gas pressure and vibration have objectives that clearly support this requirement. Thus, it is likely that the most severe requirements with regard to development program objectives arise from the experimental programs.

Instrument leads and connectors for test position sensors constitute a significant portion of the instrument development effort. Their specification is, of course, highly dependent upon sensor and readout requirements and upon conditions in the core, duct and vessel design which limit access. Minimum requirements in this area must include provision for simple and coaxial signal leads, power leads, sodium sampling lines, fission gas monitoring lines, and flux monitoring thimbles.

TABLE II
INSTRUMENT REQUIREMENTS FOR OPEN LOOPS AND CLOSED TEST POSITIONS

EXPERIMENTATION

Test Type	Parameter Sensed	Sensor	Approximate Response	Present Capability	Required Development
A. Fuel	1. Clad Temperature	Contact T/C	Ambient to 1600°F ± 10°F.	Adequate	None
	2. Fuel Temperature	Contact T/C	Ambient to $\sim$2800°F ± 10% at high T for $\sim$1 full power month.	Adequate if attachment is successful.	Testing for materials compatibility.
	3. Fission Gas Pressure	Bellows/Diaphram Transducer	$< \sim 1000$ psi ± 2%.	Experimental stage.	Long-range LMFBR Program.
	4. Local Neutron Flux	Miniature Ion Chamber or Activation	$10^{12} < \phi < 10^{16} \pm 5\%$.	1/4-In. OD. Reuter-Stokes detectors in MTR/ETR. Foil activation.	Test wires, foils, chambers.
B. Materials	1. Stress/Strain, Creep	Strain Gauge	Not defined.	None >1000°F; bonding problems; solid-state limits.	LMEC Program.
	2. Specimen Temperature	Contact T/C	Same as A.2.	Same as A.2.	Same as A.2.
	3. Local Neutron Flux	Same as A.4.	Same as A.4.	Same as A.4.	Same as A.4.
	4. Experimental Dosimetry	Fission Chamber, Companion Control Materials	Obtain meaningful damage determinants; irradiation to 10^{24} nvt.	Passive monitors used to detect fluence to $\sim 3 \times 10^{22}$ nvt ± 20%.	Better control and analysis
	5. Test Specimen Position, Vibration	Position Gauge, Vibration Transducer	Not defined.	Not defined.	Not defined.

The present status of instrument technology, assessed earlier for driver fuel channel applications,(1) was reviewed for instrument classifications which offer potentially desirable sensor functions in open test positions and closed loops. The previous assessment concerned instrumentation for coolant temperature, coolant flow, failed fuel detection, coolant pressure, in-core flux, and signal and data handling. For FFTF testing applications, we have identified here the status of thermocouples for measuring fuel cladding and meat temperature, some methods of detecting boiling and overheating, fission gas pressure, and vibration and strain. Possibilities for using noise analysis techniques are also examined.

To a considerable degree, the experience acquired in other irradiation test programs may be usefully brought to bear on the question of FFTF needs. A review of such experience with the loop instrumentation in the TREAT facility and in the water-cooled testing reactors (MTR, ETR, and ATR) at the National Reactor Testing Station underscores this fact. Even though these are lower temperature, thermal spectrum machines, the comparison with potential FTR requirements and criteria is at least inductively useful. The relation is especially sharp and valid for purposes of formulating specifications at lower power operating stages and for realizing practical instrument dispositions and procedures in order to ensure a workable system to acquire and control data. Of course, the reliability and performance of the physical instruments themselves involved in these facilities are of direct interest.

III. ANALYSES

A. Reactor Safety

Operational measurements must be made on the test loops to insure reliable operation and safety of the entire facility. It is desirable to make these measurements at the test section itself so that the time delay in detecting abnormal conditions within the test section is minimized. Thus, it can be anticipated that instrumentation access to the test section is an important design requirement. Analyses have been carried out to determine the response of instrumentation to power excursions and loss-of-flow accidents in the driver fuel.(1) The results would be similar for the test loops with the possible exception of the effect of bypass flow. Bypass flow and mixing is required to moderate the coolant temperature at the test section outlet whenever it exceeds the bulk core outlet temperature significantly in the case of open test positions or if it exceeds design temperature for the external loop (heat exchanger, pump, and coolant control equipment) in the case of closed loops. An assessment of this dilution effect would determine whether placement of the coolant temperature and flow sensors to measure the combined test section and bypass flow is acceptable from an operational standpoint.

It is possible that experimental requirements may override any operational considerations. For example, the analysis of data to determine the power generated in the test section becomes less accurate if the coolant flow and temperature rise through the test section must be deduced from measurements on the combined flow. It may be necessary to place the coolant flow and temperature sensors at the lower and upper ends of the test section to attain the required degree of accuracy in computed power generation.

1. Location of Bypass Flow

Figure 1 is a schematic diagram of a reentrant closed loop showing three possible locations for introducing bypass flow. The advantages and disadvantages of each method will be discussed.

a. Around the Test Section

From mechanical design considerations, the simplest arrangement is to allow for bypass flow up through an annular region surrounding the test section because it is then unnecessary to make a connection through the double-walled tube separating the inlet and outlet flow streams. The bypass and test section flows are mixed at the top end of the test section and therefore only the test section itself has to be designed for high-temperature operation. The disadvantages of this method are:

- The annular bypass flow region may reduce the available test section space. However, the difference in cross-sectional areas between a hexagonal test section and the circular inner flow tube may be sufficient for the required amount of bypass flow.
- This method gives the maximum increase in temperature of the bypass flow. The bypass flow is heated by the outlet stream between the inlet nozzle and the test section and, also, as it flows up the sides of the test section. This increase in temperature requires more bypass flow for the same test section coolant outlet temperature.
- This method gives the maximum pressure drop since the total flow must traverse the entire length of test loop.

The annular bypass flow arrangement does not elminate the possibility of instrumenting for test section coolant flow rate and inlet and outlet temperatures, although this capability may complicate the design considerably.

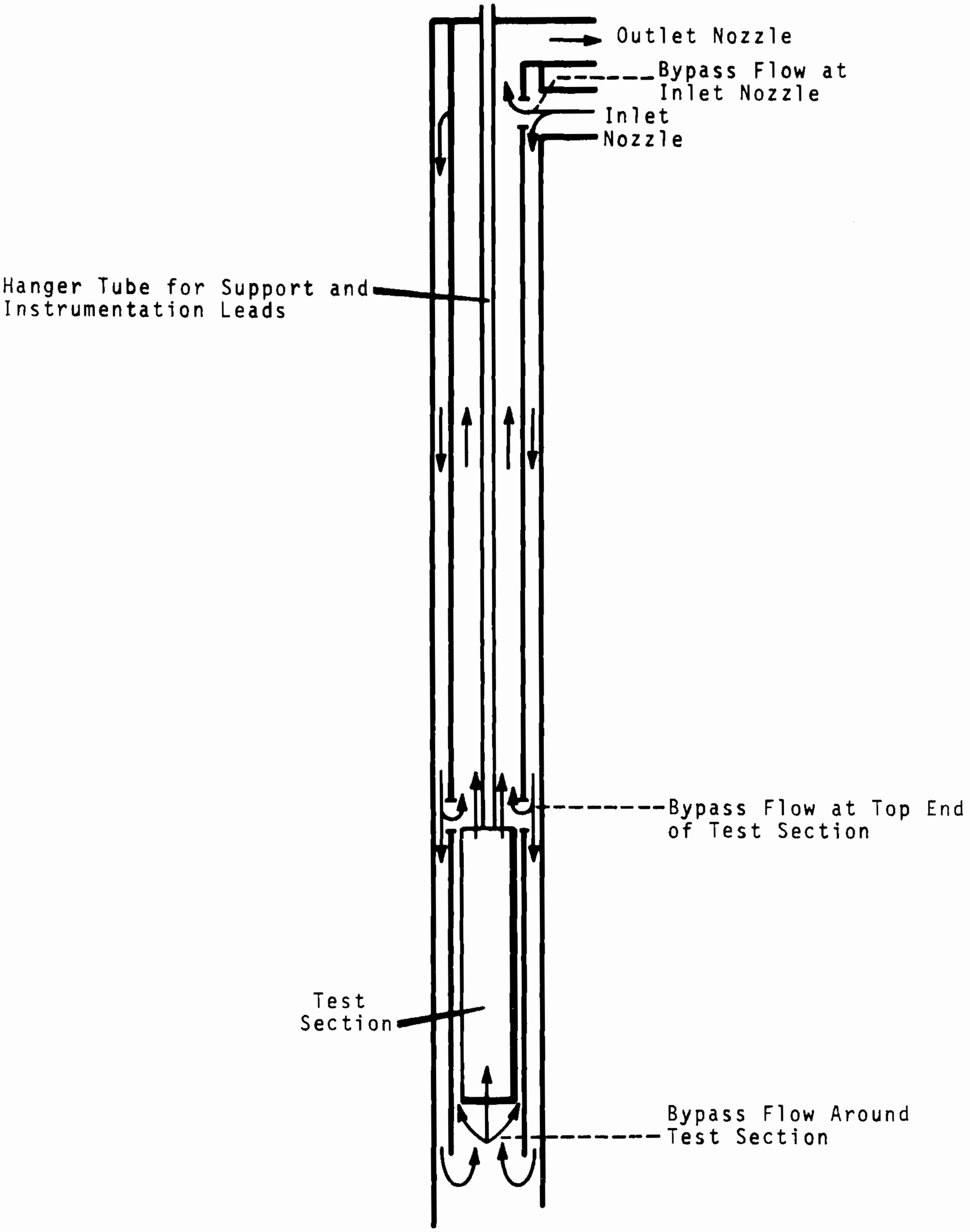

FIGURE 1. Schematic Diagram of Reentrant Closed Loop

b. At the Inlet Nozzle

From thermal and hydraulic considerations, the most efficient bypass flow arrangement is at the inlet nozzle. Less bypass flow is required because of the cooler temperature and the pressure drop will be considerably lower compared to the annular arrangement. The disadvantages of this method are:

- This method may add to the already difficult problem of designing the inlet and outlet nozzle region.
- The entire length above the test section which is in contact with the test section outlet stream must be designed for high-temperature operation.

c. At the Top End of the Test Section

An intermediate case is to introduce the bypass flow immediately above the test section. The available test section space is increased and only the test section itself has to be designed for high-temperature operation. It may be less difficult to effect an opening in the double-walled inner flow tube at this location than at the inlet nozzle.

2. Effect of Bypass Flow on Detection of Accidents

a. Power Excursions

It has been shown that the increase in coolant temperature due to a large power excursion is insufficient for detection of this accident in time to avoid failure of the driver fuel.(1) Nuclear radiation instrumentation must be relied upon to initiate scram in sufficient time to avoid damage to the reactor.

b. Loop Flow Coastdown

Several methods external to the test loop can be used to detect a flow coastdown due to loss of power or pump failure (extended interruption of BPA* power pump speed, and pump discharge pressure) independently of instrumentation within the loop. In the case of coastdown, it has been shown that coolant flow and

---

* Bonneville Power Administration

temperature sensors in the driver fuel subassembly can be used to initiate scram in sufficient time to avoid boiling even for very conservative instrumentation trip settings. Therefore, the exact placement of such instrumentation in the test loop is not crucial regarding the ability to handle a loop flow coastdown.

c. Flow Reduction Due to Flow Blockage

The effect of blockages which results in a reduction of flow to the entire test section may be more severe for a test loop than for a driver fuel assembly because the coolant temperatures during normal operation may be substantially closer to the boiling point of sodium.

Figure 2 shows the effect of flow blockage for one possible operating condition. For the test section outlet temperature of 1400°F and the bypass flow temperature of 1000°F, the bypass flow must be equal to the test section flow in order to moderate the coolant temperature to 1200°F. A flow reduction of only 36 percent is required to increase the coolant temperature at the test section outlet to the normal boiling point of sodium (approximately 1620°F) compared to the 63 percent for a driver fuel assembly previously reported.(1)

The temperature of the combined test section and bypass flow is not very sensitive to the flow blockages. For example, a 50 percent blockage results in a 400°F increase in the test section outlet temperature, whereas the temperature of the combined flow rises by not more than 67°F. The actual temperature will be somewhat lower than the curve for constant bypass flow because part of the flow which would normally flow through the test section will be diverted through the bypass region.

The coolant temperature response to a 63 percent flow blockage is shown in Figure 3. The transport time of almost 1.5 seconds from the test section to the outlet nozzle was calculated

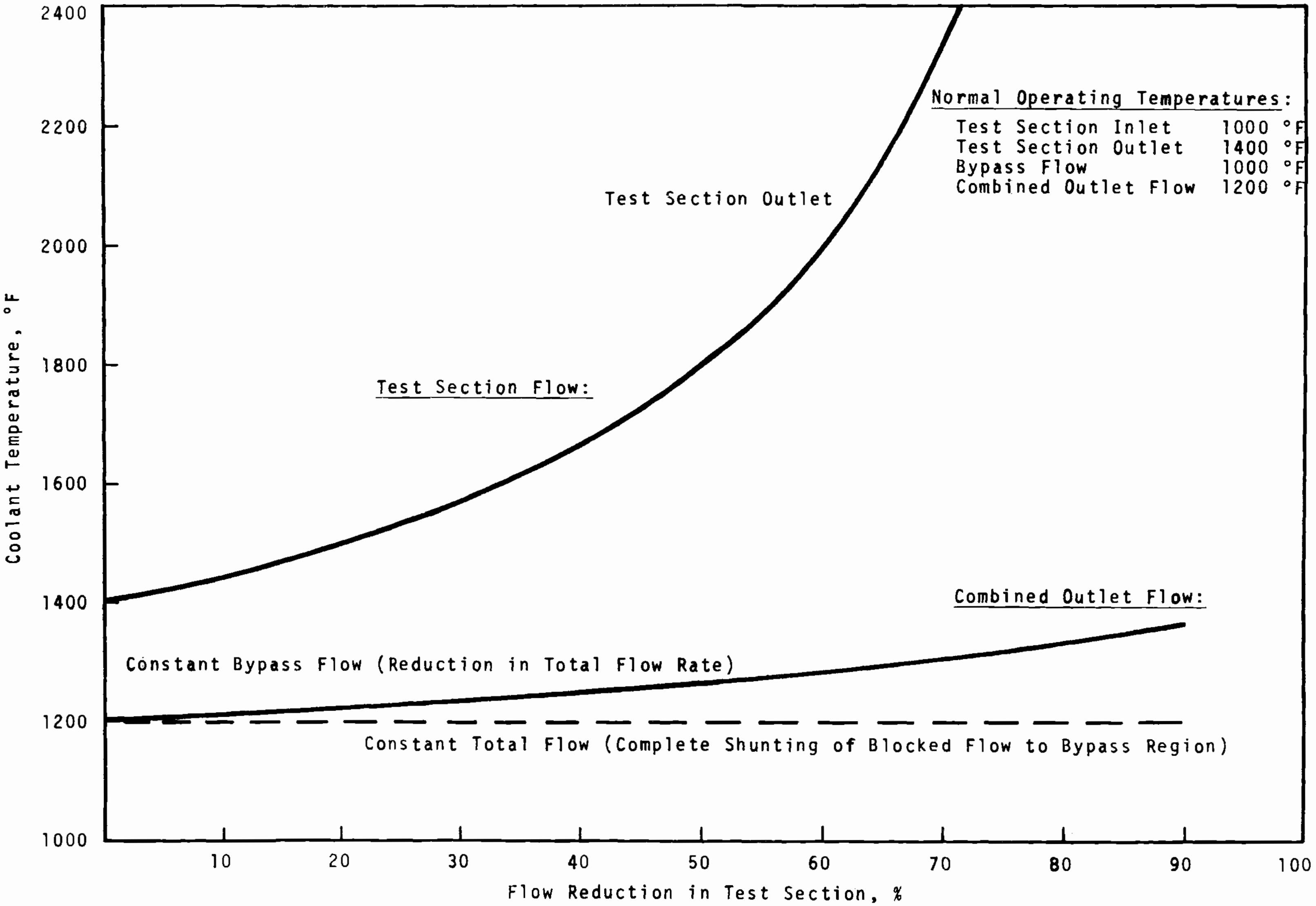

FIGURE 2. Effect of Test Section Flow Blockage on Coolant Temperatures

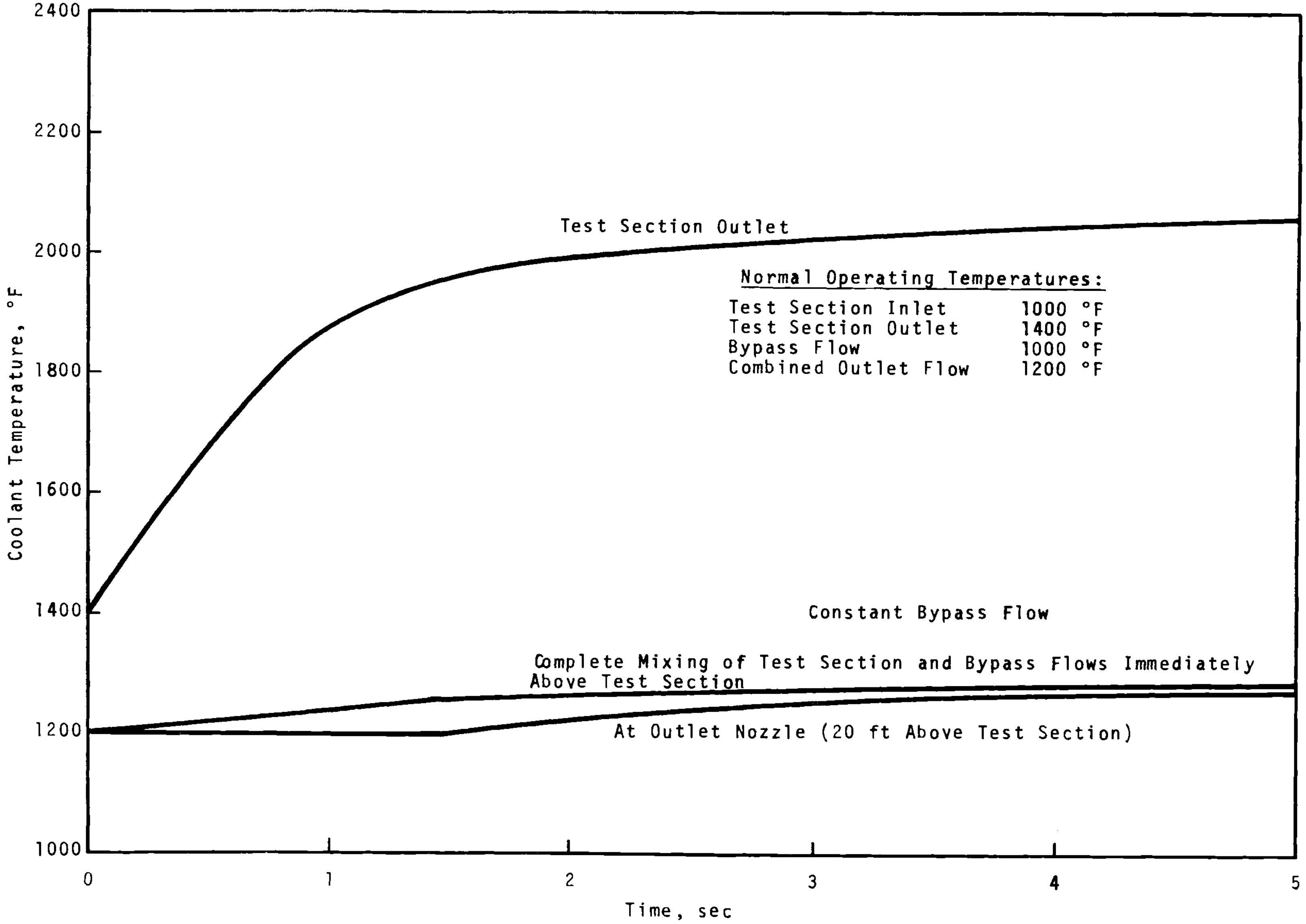

FIGURE 3. Coolant Temperature Response to 63% Flow Reduction in Test Section

assuming the maximum design flow rate before the blockage. However, the transport time could be higher by almost an order of magnitude.

The most sensitive method of detecting large blockages in order to prevent coolant boiling is by direct measurement of the flow through the test section because the combined test section and bypass flow is much less sensitive to test section blockages. For example, a 50 percent flow blockage in the test section results in a reduction in the total flow rate of not more than 25 percent. Less severe blockages for which there is no time requirement for initiating scram to avoid boiling can be detected by coolant temperature measurement. However, the test section outlet temperature provides a much more sensitive indication than the temperature of the combined test section and bypass flow.

Instrumentation arising from experimental requirements may be able to provide the most sensitive indication of decreased flow rates in the test section. For example, fuel pin surface temperature measurements would give a faster response to the flow blockage than temperature sensors located outside the test section.

Therefore, coolant flow and temperature measurement on the combined test section and bypass flow would not be very sensitive in detecting blockages which result in reduction of flow through the test section.

d. Local Blockages within the Test Section

Analyses of local blockages of one and six adjacent coolant subchannels both at the inlet and the mid-core of a driver fuel subassembly show that the increase in local coolant temperature at the end of the pin bundle is relatively small, especially if good turbulent mixing exists.(4) Of course, for poor turbulent mixing, a coolant temperature sensor heated at the end of the pin bundle would not be able to detect a temperature increase unless it was located directly above the blocked subchannel. The combination of test section and bypass flow would make detection of such blockages by coolant temperature measurement practically impossible.

e. Cladding Failure

The maximum activity of fission products expected to be released into the coolant due to failure of a single driver fuel pin has been previously determined.(1) The effect of bypass flow on the ability to detect cladding failure is to dilute the concentration of the fission products and thus reduce the effective sensitivity of the sensor. The reduction in sensitivity is related to the bypass flow fraction. This relationship has not been established with certainty at this time. For simple dilution, the sensitivity loss may be expected to be in proportion to the bypass fraction.

B. Review Of Requirements For Prospective Users

Several prospective users of the FFTF have submitted descriptions of proposed experiments and test facility requirements for fuels, materials and instrumentation development that will provide much needed information for the design and operation of liquid metal cooled fast reactors. The experiments were reviewed to determine the instrumentation facilities that should be provided to fulfill the instrumentation requirements as expressed by the experimenter. Of course, not all experimenters desire the same degree of instrumentation for similar tests, and some experiments demand the use of a certain type of test environment such as a closed loop. The following is a summary of the test facility instrument capability needed to meet the needs of the many and varied experiments as identified in this survey.

Table III is a summary of the instrumentation required by the fuels and materials testers.

TABLE III

REQUIREMENTS FOR PROSPECTIVE USERS

Percent Of Fuel Tests	Percent Of Materials Test	Instrumentation
100	100	Temperature of clad (± 10°F). (May include several places along specimen.)
70-80	100	Temperature of channel (or position) ± 10°F. (Usually outlet temperature; may include inlet.
70	Not Applicable	Fission gas pressure.
75	100	Flux at position (± 10%).
50	75	In-experiment dosimetry.
40	Not Applicable	Coolant radiation level (fission products).
50-90	50-90	Coolant purity control; generally required to know what it is. Some (10-20 percent) tests require purity control.
Not Applicable	60	Pressure means of applying stress.
Not Applicable	50-100	Temperature control of specimens.
Not Applicable	All stress-strain tests	Strain-measuring devices. This measurement is implied in all materials tensile and stress rupture tests.
		Flow. Often implied; usually want to know what it is (± 3 fps).
Small	Small	Vibration

1. Facility Instrument Requirements

a. External Readout

Most, if not all, tests require that one or more variables be monitored continuously to provide indication of incipient failure, to allow the separation of cause and effect, and to allow the correlation of test specimen response with reactor operating conditions. The almost universal instrument requirement is for readout of fuel pin temperature and/or materials test specimen temperature. The important consideration for the facility operator is that access to and from the core test positions should be provided for instrumentation leads and tubing. Tubing is required for pneumatic signals and/or sodium sampling.

The capability to continue the monitoring of a specimen during its removal from the core and storage before examination should be provided. This information is important because the experimenter needs to know the maximum temperature or other test variable to which his test specimen was subjected.

The test facility should provide the instrument readout capability of at least 20 separate leads at each core test position as well as one pneumatic line, one sodium sampling line, and one traversing sensor thimble.

b. Process Control

All the test data required by the experimenters cannot be obtained by instrumenting test specimens. The reactor operating conditions must be known by the experimenter and, in some cases, control of a process system is required to obtain the desired test data. Some typical process variables that must be known by the tester are coolant flow and temperature, neutron flux, coolant purity and reactor operating history. Even though these parameters may not be varied for a particular experiment, the experimenter needs to know what they are. Coolant purity can be correlated with test specimen corrosion.

The FTR operator will direct and perform all closed-loop operation, maintaining, of course, a close liaison with the experimenter in order to expedite his programs. Each closed loop should have its own instrumentation and control equipment to allow greater variation and control of the test specimen environment than can be obtained in the other reactor test positions. Higher temperatures are more easily obtained and controlled in a closed loop.

Some materials tests require that the test specimen be maintained at a specific temperature within a variation of 10°F. This test is used to determine the mechanical characteristics (such as creep, strain, etc.) of reactor materials in a fast flux environment. The temperature of the specimen must be controlled closely for good test results.

c. Data Acquisition

Large amounts of experimental data will be generated for even a small test because the cost of reactor time will tend to promote extensive instrumentation to obtain the maximum amount of information from each test. In addition to the direct test data, the experimenter needs to know the reactor operating conditions so that he can correlate the specimen test data and the specimen environments. The reactor operating conditions, as well as reactor operating history, should be available to a number of different groups of people. An extensive automatic data processing system will be required to collect, process and record this large amount of test data for a number of experimenters.

d. Building Space for Instrumentation and Control

The largest space requirements are for the placement of the instrumentation and controls for the closed loops. Each closed loop should have the capability of having its controls and instrument readout device separated in its own cubicle.

The instrument racks should be designed with a view to the future development of new and improved instruments. Sufficient space should be provided to facilitate the addition of improved instrumentation as it becomes available.

e. Instrument Clean Rooms

A clean room should be provided where thermocouples and other instruments can be attached to test specimens in a contaminant-free environment. Reinstrumentation of some specimens whose instruments have failed may have to be done. This type of facility will expedite the completion of some tests.

2. Functional Tests

The majority of the experiments proposed by users of the FFTF fall into one of three general groups: fuel tests, materials tests, or instrument development. The following is intended to point out the need for instrumentation on these tests.

a. Fuels Tests

At present there is not enough information available to select a "best" type fast reactor fuel. Possible candidates are oxides, carbides, and metallic fuels. A great deal of experimental work needs to be done to determine such fuel properties as burnup, dimensional stability, power, operating temperatures, lifetime and corrosion. A well-instrumented fuel subassembly can shorten testing time and provide considerably more data than just a post-irradiation inspection. Instrumentation that will give a continuous readout of fuel pin temperatures at several places on the pin and fuel pin pressure are the most important measurements. Temperature measurement is almost universally requested for both fuels and materials testing. A means of detecting fuel element failure would be a definite benefit. In addition to specimen instrumentation, process instrumentation provide important test data. The more important process measurements are coolant flow and temperature, flux and coolant purity.

b. Materials Tests

The environment for structural materials in a fast reactor is very severe because of the temperature and flux. There is a need to measure the mechanical properties of structural materials specimens in the core of the reactor. To do this requires control of the test specimen temperature within 5°F and at the same time the specimen must be stressed a known amount and the resulting strain, creep and other mechanical properties measured. In addition, flux level at the test position and total experiment dosimetry should be known by the experimenter.

Control materials for fast reactors also need to be tested in a fast reactor environment and similar materials instrumentation will be required.

c. Instrument Development

A great need exists for the development of instrumentation for fast reactors because data from thermal reactors have not been shown to be applicable to fast flux conditions and the measurement of process variables such as temperature have not been attempted to date in a significantly intense fast flux environment. Improved and new instruments are needed to achieve longer operating cycles, operation nearer maximum limits, and observation and correction of undesirable reactor conditions.

The following is a list of possible areas for instrument development:

- Temperature measurement
- Flow measurement
- Fuel failure instrumentation
- Pressure measurement
- Vibration
- Stress-strain monitoring
- In-core flux monitoring
- Radiation detection.

Emphasis should be given those instruments which provide greatest increase in reactor power and efficiency.

The in-reactor space required for instrument development will include closed loops, open test positions, primary sodium and short-term irradiation facilities because of the wide variety of irradiation required to test different instruments. A means must be provided to allow a large number of electrical leads to be brought out from the core to the external readout equipment. Some tests will require samples of primary sodium and so a sampling system should be provided as well as tubing for pneumatic lines to various in-core positions.

IV. SAFETY CRITERIA

A well-determined set of instrumentation will be required with open and closed-loop tests in order to achieve the general safety objectives of the Fast Test Reactor. It is possible that for some applications this particular instrumentation set may also be used to serve the needs of test sponsors; e.g., with respect to measuring irradiation conditions during a test or the effects of these conditions upon a test specimen. More likely, however, instrumentation having primarily a safety function will not entirely meet the testing needs of any sponsor. Instrumentation provided for open test positions and for closed-loop systems in order to meet safety objectives can be organized into the following four categories:

Category I: Instrumentation for safety objectives common to reactor control, the driver fuel, or the control rods. Examples are as follows:

- Flux monitoring.
- Inlet and outlet temperature monitoring.
- Flow monitoring of individual fuel channels.
- Limiting rate of motion, position monitoring, and fail-safe movement of axial positioners used with test specimens.
- Monitoring and controlling coolant impurities of closed-loop circuits.
- Instrumentation and control of each closed-loop system.
- Reliability and redundancy of sensing instrumentation connected into the reactor safety system.
- Failed fuel element detection and location.

Category II: Instrumentation for safety objectives common to both open and closed-loop tests. Two examples are as follows:

- Flow and temperature measurements in bypass streams around test specimens.
- Pressure drop, inlet and outlet temperatures, and flow through test specimens

Category III: Instrumentation for safety objectives unique to open test positions.

For example, the temperature control of electric heaters used to "trim" inlet conditions or to adjust "outlet conditions" of test specimens to within 50°F of adjacent driver fuel outlet temperatures.

Category IV: Instrumentation for safety objectives unique to closed-loop tests. Three examples are as follows:

- Leakage monitoring between closed-loop coolant and reactor coolant for the in-reactor section of the closed loop.
- Temperature sensing inside and around the molten fuel container, especially if a test specimen has suffered meltdown.
- Boiling detection.

The remainder of this chapter discusses some of the criteria and their bases that have been drafted thus far in order to meet the broad goal of safe reactor design and the general design safety criteria.(2) The drafting of safety criteria will continue because each in-reactor experiment and perhaps even each test specimen may present its own unique safety problems. Such criteria will also identify the conditions which limit or justify in specific instances the use of a single instrument for multiple functions. What is needed in this regard, then, is an experimental design manual for the use of experiment sponsors such as those published for the MTR-ETR-ATR facilities(5) and for the Plum Brook Reactor Facility.(6)

The safety criteria that are presented herein are drafted in fairly general terms, therefore, in order to delineate general problems common to most tests that are considered for the FFTF. Indeed, the criteria may not mention instrumentation at all but, obviously, the criteria cannot be satisfied unless the implied instrumentation and controls are provided with the sensitivity, response, and stability required for each test. The criteria and bases will be presented in the organization of the above categories.

A. Category I

Criteria and discussions of instrumentation for the reactor, driver fuel, and control rods that are immediately applicable to open and closed loops have been given in a number of publications.(1)(7)

What follows are particular features of open test position and closed-loop test instrumentation that have safety implications, but that are still mainly Category I type of instrumentation.

1. Flux Monitoring

The connector for each open test position and closed loop will provide for one traversing sensor thimble. Such thimbles are, conceptually, thin-wall tubes, about the diameter of fuel pins, but extending without interruption from the bottom of the reactor core to outside the reactor vessel. A failure of such a thimble by cracking or fracture poses the possibilities of: (a) introducing outside contaminants into the reactor coolant, or (b) providing means for leaking radioactive reactor coolant. Instrumentation should be provided to detect these failures.

2. Temperature and Flow Monitoring of Individual Tests

The criteria for temperature and flow monitoring of driver fuel assemblies and of control rods would be applied unchanged to open test position and closed-loop specimens except for the provisions to allow bypass flow around test specimens. The effects of bypass flow are considered in Category II. Mainly, it is the temperature and flow sensing instrumentation of individual test specimens which will be connected into the reactor safety system for automatic power setback or reactor scram. Thus, this instrumentation must be provided with the redundancy required to: (a) provide two out of three logic for the reactor safety system, (b) provide logging for environmental conditions, and (c) provide separate input to possible control circuits for controlling open test position or closed-loop conditions.

3. Axial Positioners

The axial positioners for test specimens are, conceptually, very similar to the control rod positioners. Thus, the restrictions on worth, rate of motion, position monitoring, and movement upon failure of positioner are the same as for control rods.(8)

4. Closed Loops

Each closed loop poses nearly all of the safety problems of a nuclear power reactor because it can include fissionable fuel (usually the test specimen); has means for generating appreciable heat (through fission of fuel specimens, gamma heating, pump operation, and possibly electrical "pre-heaters"); has its own heat dissipation, coolant supply, coolant purification, and instrumentation systems, and because it has its own independent control system which may be "slaved" in some degree to the reactor control system. That is, in some respects, the closed loop is a separate system that operates, in part, in the environment of a nuclear reactor. The safety problems of a closed loop embrace the topical areas of (a) installation, (b) integrity, (c) cooling, (d) control, (e) environmental monitoring, (f) radiological safety, (g) post-operational examination, and (h) disposal. Many of the design safety criteria for closed loops recognize that these loops can operate in many ways independently of the reactor and have instrumentation and controls for such operation. The following three criteria, although not firm at this time, illustrate the fact that closed loops are separate systems.

- *The closed-loop system will be designed to operate from essentially zero reactor power to full power as dictated by testing requirements. The design is to incorporate ability to follow power transients occurring during reactor startup, normal shutdown, and scram shutdown.*

- *Electrical heaters will be provided on all piping and equipment for containing sodium in order to raise system temperatures above the sodium freezing temperature (204°F) at a rate which will not exceed thermal stress limitations. Heaters will be zoned to permit melting out of frozen systems progressively beginning at open ends or free surfaces.*
- *Sodium leakage detectors will be provided on piping and components of the closed-loop circuits and where possible, these detectors will be designed and positioned in such manner to give an early indication of the location of the leak.*

These examples serve to illustrate that the closed loops, because they can operate in many ways independently of the reactor, have instrumentation and controls for such operation. Other design safety criteria, not included herein, extend these examples to cover all requirements of the closed-loop system.

Each closed loop installed in the FTR will be operated while the reactor is shut down, if not for the purposes of dissipating decay heat from previous irradiations of the fuel test specimen, then at least for the purposes of "checkout" or "shakedown" in order to discover all possible mechanical and instrumental faults so that these may be corrected and thus assure that the loop and its test specimen are ready for power operation. Then when the reactor is made critical, and during the ascension to full reactor power operation, the loop must be capable of operating to meet safety and experimental objectives with increasing quantities of heat input from its fuel test specimen. Throughout steady reactor power operation the control of the closed loop is fairly smooth unless the testing requirements dictate some sort of cyclic operation through modulating closed-loop flow, coolant temperature, specimen position, or other means which the closed loop may be designed to accomplish. During normal shutdown, the loop must be capable of operating with decreasing quantities of heat input from its fuel test specimen. Finally, thermal stress considerations with respect to the test specimen or the particular closed loop may dictate careful flow control following a reactor scram. Thus, closed loops are separate systems whose control is influenced by the mode of reactor operation.

5. Instrumentation Connected Into the Reactor Safety System

As noted above, the temperatures into and out of specimens and the flow rates through specimens are typically measured by the sensors connected to the reactor safety systems. Typical examples of criteria associated with such instrumentation read as follows:

- *Protective instrumentation will be separate from all other instrumentation including control and regulatory instrumentation. A limited number of signals may be extracted from the protective instrumentation for purposes of recording, calculating, protective instrumentation performance audits, reactor scram history and other noncontrol/regulation functions. Signals for actuating rod interlocks may be extracted from protective circuit instrumentation where required. All signal leads originating in protective instrumentation will be buffered within the instrument cabinet to ensure that no mishandling or misapplication of the signal leads will compromise the performance of the instrumentation.*

Protective instrumentation and control/regulatory instrumentation will be separate, since one of the objectives of the protective system is to provide protection against control/regulatory instrumentation malfunction. Independence permits designing the protective system for protection and the control/regulatory systems for control and regulation. The control/regulatory systems can be optimized for ease and economy of operation including the eventual use of digital control.

- *Protective instrumentation will be provided with the capability to permit the performance of testing and maintenance during reactor operation.*

A testing system will be provided for testing the protective circuits, including the sensor, when possible. The testing system will be designed for convenient and effective usage at whatever frequency deemed necessary to assure functional operability of the system.

- *The control and protective system cables should not occupy the same conduit or raceway where both control and protection are affected by the same process variable.*
- *The conductors to sensors comprising a redundant protective system should not occupy the same conduit or raceway wherever possible.*

Design safety criteria are being prepared to extend the above examples in order to cover instrumentation systems in general.

6. Failed Fuel Element Detection and Location

The functional responsibility for detecting and, perhaps, locating a fuel assembly which has failed to the extent of leaking fission products (assuming that "vented" fuel is not being used in the reactor) resides in the Fuel Failure Monitoring System. The conceptual design description for this system is being prepared but the associated technology requires so much development that no definitive criteria have been drafted except for the statement that such a system will be installed and used in the FTR. Conceptually, the Fuel Failure Monitoring System will include the instrumentation provided for the reactor driver fuel, the open test positions, and the closed-loop tests.

The requirements for fuel failure detection are somewhat different for closed loops as compared to driver fuel and open test positions because the very isolation of the closed-loop cooling circuits makes relatively easy the application of available and developable technology for determining the presence of fission products in the loop coolant if, indeed, these fission products derive from pin specimens that have failed. The detection instrumentation would, of course, be associated with the out-of-reactor portion of the closed-loop circuits. However, the technology of "vented" fuel (if desired by some sponsor) will be developed through irradiation tests in closed loops before these types of fuel are operated in open test positions or as driver fuel. The criteria for designating fuel failure becomes significantly different for fuel pins that are designed to "vent" gaseous and vaporous fission products as compared to similar criteria for pins that should not leak such products. Generally then, the fuel failure detection instrumentation for each closed loop will depend upon the type of fuel test specimen and the objectives of the closed-loop experiment. Also, the data derived from the detection instrumentation will be logged for information purposes with the operating procedures for each particular experiment dictating the cognizance and actions to be taken upon discovery of a fuel failure.

However, the timeliness and significance of a failure signal and the reliability of the associated detection instrumentation may be such that the experimental objectives can be better met by putting this instrumentation into the reactor control or reactor safety systems. This topic must be explored for each closed-loop experiment.

The primary problem for failed fuel detection by "bulk monitoring" of the primary coolant from the reactor driver fuel, reflector elements, and open test positions is that of sensitivity; the fission products in the coolant streams from the one or few leaky pins are diluted by the coolant from the thousands of unfailed pins. Also, "bulk monitoring" can only signal the occurrence of one or more fuel pin failures somewhere in the reactor core. The present objectives of the failure detection system are to monitor each of the 127 or so outlet streams from driver fuel, reflector elements, and open test positions so as to pinpoint the location of the fuel pin failure. Since an objective of the FFTF is to make interchangeable the hardware, equipment, and positions provided for driver fuel and open test positions, it follows that the design of open-loop test specimens must be compatible with the failed fuel detection system ultimately provided for the reactor. The types of detection systems contemplated for the reactor are characterized by slow response times; many seconds, even minutes, are required before the onset of a fission product leak occurring in the core is detected by the instrumentation. The significance of this information is negated by the slowness of its receipt and therefore no input to the reactor control or reactor safety system is planned; the detection instrumentation will be for information only and operating procedures will have to dictate the appropriate operative actions required.

B. Category II

The bypass streams and extra components of open test positions and closed loops introduce safety implications that require further consideration. Generally, the safety objectives of temperature, flow, and pressure sensors surrounding the test specimens are to detect abnormal conditions in time to take effective action to save the test specimen, or at least avoid the economic damage of a prolonged reactor shutdown to salvage and cleanup after a specimen failure.

Bypass streams around test specimens, however useful they may be for controlling temperatures of components around (e.g., ducts) and downstream of test specimens, introduce confusion and loss of sensitivity to instrumentation provided to monitor test specimen conditions. Confusion arises when the monitoring instrumentation can sense only the combined streams of flow through and bypassing the specimen. For instance, a flowmeter placed to sense the combined flows may indicate a change in flow rates due to (a) conditions in the specimen, (b) conditions controlling the bypass flow, (c) changes common to both streams;

typically, the assumption is made that (a) prevails in the absence of (c). Loss of sensitivity arises again when the monitoring instrumentation can sense only the combined streams of flow through and bypassing the specimen. For instance, thermocouples placed to sense the temperature of the combined flows may not indicate small changes in specimen outlet temperature. Thus, bypass streams give rise to the following criteria.

- *Generally, temperature sensors in open test positions and closed loops that are to monitor test specimen conditions and are to actuate the reactor safety system will be located so as to sense only the conditions of the test specimen.*
- *The flowmeter provided for each open test position and which is connected to the reactor safety system will be located so as to sense only the flow through the test specimen.*

Note that the second criterion is specific to the open test position because the hazard is greater for these open test positions, than for the closed loops, for causing economic damage to the reactor in case of fuel failure. The corresponding criterion for closed loops is typically Category I.

- *Instrumentation will be provided for the closed loops to verify adequate cooling flow for the closed loop test specimen at a reactor power level below that which could cause sodium vaporization in a plugged or partially plugged specimen.*

Both the open test positions and the closed-loop, in-reactor sections may have extra equipment for the purposes of the experiment. This equipment may be additional instrumentation, positioners, flow control devices, heaters, etc. Generally, the criteria given above for temperature and flowmeters should be sufficient. However, if pressure drop instrumentation is to be connected to the reactor safety system, then further consideration is required because the instrumentation may sense the pressure drop across the test specimen and also across the extra equipment. Such additional consideration as is required must await for better definition of the extra equipment planned for each test.

The complications introduced by such extra equipment may not make immediately obvious the conditions sensed by pressure drop, temperature, and flow sensors located adjacent to the test specimen.

C. Category III

Design considerations for thermal stress and fatigue which may accrue due to the proximity and mixing of sodium streams of differing temperature in the outlet region of the reactor have imposed the following requirement for open-loop test positions: "*Initial open test position outlet temperature shall equal core bulk outlet coolant temperature within ±50°F.*"(9) This requirement could necessitate flow restriction through a low powered test specimen or could possibly form the basis for such an artifice as using electrical heaters in the open test position, either below or above the test specimen. The electrical heaters pose some additional safety considerations.

Electrical heaters pose two hazards to the reactor: (a) failure of the heater will introduce contaminants, both soluble and solid, into the reactor coolant, and (b) an uncontrolled heating condition due to too high electrical power or too low a sodium flow rate through the heater may lead to sodium boiling. Both hazards are to be avoided by imposing on electrical heaters the same temperature and flow instrumentation requirements that are imposed on driver fuel by Category I considerations. However, these temperature and flow sensors, rather than actuating the reactor safety system, can be connected to simply disconnect the electric heater from its power supply.

D. Category IV

The very nature of the isolated test conditions provided by the closed loops and the implied intention to run the more hazardous experiments in the closed loops requires further safety considerations.

However, the present discussion of these considerations is restricted at this time to the use of sodium as the closed-loop coolant because the additional considerations for alternative loop coolants(10) have not been completely resolved. The safety criteria for instrumentation objectives for sodium coolant read as follows:

- *The closed loop will include instrumentation to continuously monitor the leaktight integrity of the in-reactor section of the loop through pressure, tracer, or other means.*

There are two comments with respect to this criterion: (1) There is no other requirement for in-service surveillance to periodically inspect or test the structural and leaktight integrity of this in-reactor section because any doubt in this regard can be removed by periodic replacement of the questioned component. (2) The appropriate action to be taken once the instrumentation indicates a leak in the in-reactor section of the loop is not specified; presumably, the instrumentation would be connected to the reactor safety system to initiate a scram shutdown but other considerations pertinent to the particular test involved may dictate alternate actions.

- *The in-reactor section of the closed loop will include a container for catching and holding the materials resulting from a meltdown failure of the test fuel specimen. A reliable means of cooling this failed fuel container will be provided so that the test failure will not penetrate into the reactor coolant.*

The most reliable means of cooling this failed fuel container appears to be by conduction through the walls of the closed-loop tube to dissipate the heat into the reactor coolant. It follows that in order to determine if the failed fuel container is indeed operating properly, there must be thermocouples in and around this container, and further, that these thermocouples must be designed to continue operation during and after a meltdown accident.

- *The support structures for instrumentation systems supplying signals from the closed loop to the reactor safety system will maintain their integrity under accident conditions at least to the functional limit of the instruments.*

Sodium boiling is more apt to occur in the closed loops than in other test areas of the core or in the driver core itself due to the nature of the closed-loop tests. Sodium boiling poses important safety problems with respect to (a) avoiding, if possible, gross meltdown failure of the test specimen, (b) limiting the propagation of the hydrodynamic shock and gas/vapor pressure effects to within the in-reactor section so that the ability to shut down the reactor is not impaired, (c) assuring that damage does not progress beyond the initially affected closed loop through hydraulic or reactivity effects, and (d) assuring that the closed-loop system provides for removal of failed test fuel specimens which are warped, bulged, or even melted, all which may occur due to the conditions causing or resulting from sodium boiling.

The opposite to sodium boiling, namely adequate coolant flow, is covered by Category I criteria through the two important phases of operations: (1) during startup and (2) during steady power production. For instance, during startup when coolant conditions may be changing continuously, instrumentation will be required to verify adequate cooling flow at a reactor power level below that which could cause sodium vaporization in a plugged specimen. For a closed loop without bypass flow in the in-reactor section, such flow instrumenation is particularly easy to provide because it can be mounted almost anywhere in the loop outside the reactor. The complications introduced by having bypass flow have already been discussed.

During steady power production, the most direct measure of adequate cooling flow appears to be the specimen outlet coolant temperature. This temperature also provides an indirect indication of flow conditions within the specimen and a gradual deterioration in flow may be detected. Generally, plugging of the flow passages in the specimen sufficient to cause significant reduction in loop flow should be detected in time for corrective action unless the plugging is both rapid and extensive.

There remains the question of the utility of sodium boiling detection in closed loops by means other than temperature and flow sensors. The best answer should be the following: development of boiling detectors suitable for use on every closed loop will be carried out; the extent to which these will be incorporated in the final loop designs will be established in studies of potential conditions for loss of loop flow, potential consequences of loss-of-flow for any test, and detection and response capability of possible instrumentation.

V. STATUS OF TECHNOLOGY

A. Assessment of Present Instrument Technology

Instrumentation for coolant temperature, coolant flow, failed fuel detection, coolant pressure, in-core flux, and signal and data handling were previously discussed for driver instrumentation.(1) The following assessment deals with five additional classifications of instrumentation (mainly sensors) applicable to closed or open-loop testing.

1. Fuel Cladding and Meat Temperature

A survey report(11) for thermocouples for this application indicates that for 5000°F fuel meat thermocouples, the problem is one of materials selection and availability. The thermoelements, insulation, and sheath materials, each, are significant problems. Two thermoelements which appear to be most promising are tungsten/tungsten with three-percent rhenium, and (W/W-25% Re) combinations. Addition of the three-percent rhenium is required because pure tungsten is very fragile after junction welding. However, the properties of these combinations are not fully defined. These thermoelements require further study to determine their long-term thermoelectric stability, stability in a fast neutron flux, and their compatibility with various insulators and sheath materials.

For electrical insulation the only suitable material at 5000°F seems to be thoria. For lower temperature fuels, other materials such as hafnia, beryllia, and alumina may be more suitable. These materials also require further study as to their temperature/resistivity properties, compatibility with thermoelements and sheath materials, and their behavior in nuclear radiation. The reason further study is required is that there is not good agreement on the resistivity property and there is a scarcity of data for the other properties.

The sheath material is perhaps the most critical because it must be in contact with the fuel and its incompatibility with the fuel material or cladding could lead to a fuel pin rupture. From a temperature standpoint, only tungsten, rhenium, tantalum and some alloys of these metals could be used at 5000°F and at 4500°F molybdenum could be used as a sheath material. However, from a compatibility standpoint, there is insufficient information to make a choice of sheath materials. Compatibility tests with simulated conditions will have to be made before the final sheath selection is made and before the thermocouple is tried in the reactor. Another problem is that, of the sheath materials discussed, only tantalum is a readily available and workable material.

In short, for fuel meat temperature thermocouples, additional development and testing is required, mainly because of the materials compatibility problem at the high temperatures involved. Other problems exist such as the shunting effect of the insulation at high temperatures, how to seal the fuel cladding to the sheath material, and how to obtain high quality thermocouples from the manufacturer. These are probably of secondary importance compared to the materials compatibility problem. Either the materials discussed, or new materials will have to be tested in combination under the proper conditions to find answers to this problem.

In-reactor tests(12) on a W-5% Re/W-26% Re base thermocouple in 2.8×10^{20} nvt thermal flux and 3000°F showed a change in calibration from about five percent low at 800°F to 0.1 percent high at 3000°F. In the same test, two beryllia and two thoria insulated W-3% Re/W-25% Re thermocouples were monitored continuously in-pile for 300 hours at 4200°F and 900 hours at 4400°F. The beryllia insulated couples responded even after the melting of the beryllia insulation. The thoria-insulated couples were stable throughout the test and the thoria was in good condition after the test. The information indicates that acceptable life can be obtained with such couples. However, apparently no tests were made to determine compatibility of the sheath with different fuel materials.

In England(13) A W-5% Re/W-26% Re, magnesia-insulated, molybdenum sheathed thermocouple of 0.060 in O.D. was used to measure the center temperature (about 2800°F) of a mixed-oxide $(Pu,U)O_2$ fuel element in the Dounreay fast reactor. The thermocouple operation was successful for about 1400 hours after which distinct reduction of output was apparent, accompanied by severe oscillations. Loop resistance had increased by a factor of two or three but no explanation for the operation of the couples has been given. The flux at the couple was given as 1.5×10^{15} n/cm^2-sec and 6×10^{14} n/cm^2-sec at the ceramic seal for the lead-in at the top of the fuel pin. This gave a dose of 1.27×10^{22} nvt and 5.17×10^{21} nvt, respectively, for the 14-week period.

Molybdenum sheath was chosen because previous in-pile tests had shown the compatibility of molybdenum with mixed-oxide to be clearly superior to that of tantalum. Magnesia insulation was chosen because beryllia required glovebox handling due to its toxicity, and because thoria has nuclear self-heating. If the temperature of the fuel had been higher than expected, beryllia most likely would have been the next most suitable insulation choice.

In this same test conventional chromel/alumel, magnesia-insulated, and stainless-steel sheathed thermocouples were attached to the cladding at several points along the fuel element length. Apparently no significant problems were encountered. Other sources indicate that measurement of the fuel cladding temperatures will not be a problem from the standpoint of the thermocouple itself. However, the choice of the attachment method and the location of the couple (inside the core or outside) will require study to reduce the possibility of rupturing the can. This consideration will force a choice of a small (such as 0.020 in. O.D.) thermocouple to avoid disturbing coolant flow characteristics or the relationship of the fuel and the cladding.

Expected accuracy of the fuel temperature thermocouples for SEFOR(14) is given as plus or minus five percent. This is for the short-cycle operating conditions of SEFOR. Accuracy over the longer term operation in the FTR (for one full power month, for example) probably cannot be expected to be better than plus or minus 10 percent over the whole operating period.

Response time for the fuel thermocouple should be less than a few seconds, even if ungrounded. Response time for the clad thermocouples should be in the region of one second.

Other methods such as the rhenium bulb pressure transducer(15) have been used to measure fuel pin temperature. It utilizes pressure measurement and the pressure-temperature relationship to infer temperature.

2. Boiling and Overheating Detection

Related to item one above are other temperature measurement methods which can be related to boiling detection or other purposes.

a. Microwave

Two methods measure high temperatures by means of microwaves.(16) One method, the frequency shift method, is by installing a special metal cavity at the point of temperature measurement and then connecting this by a waveguide to a source of radio energy. The size of the cavity will change with temperature and the resonant frequency for the cavity will change with temperature and the resonant frequency for the cavity can be determined by a frequency sweep and related to temperature. The cavity is made of high expansion nickel-chromium steel. Several different-sized cavities could be installed in one fuel element and connected to the same waveguide for temperature measurement at several points. The problem with this method is that conventional waveguides are made of copper which corrodes and oxidizes excessively in temperatures above 1800°F.

A second measurement by microwave is the radiometric method. The microwave frequency naturally emitted from a heat source in the reactor is fed through a waveguide to a very sensitive microwave receiver, or radiometer. Measurement of the amount of microwave energy can indicate the temperature of the heat source. Both methods require the waveguide and for higher temperature measurement, new high-temperature and non-corrosive waveguides would be required. Theoretically attainable sensitivity of the frequency shift method is given as plus or minus 0.050°C. Both methods show promise but each requires additional waveguide development for temperatures beyond 1800°F.

b. Sonic Echo

Frequently, a submarine will receive sonar reflections from regions in the ocean which have different temperatures. In the same way, sonic waves transmitted from a transponder through a metal rod can be reflected from a hot spot on fuel cladding. Such a method for detecting cladding overtemperature (possibly before coolant boiling starts) has been proposed.(17) One advantage of this method is that potentially it has the ability to detect the cladding hot spot anywhere along the length of the fuel pin and without multiple thermocouples. A potential problem is that it will be difficult to transmit sufficient sonic energy across the mechanical joints between the fuel pins and the subassembly housing and then to receive the small reflections which must be transmitted across the same inefficient joints.

c. Boiling

Coolant boiling can be detected by the audio noise given off by the coolant itself and from the adjacent metal which produce sounds when heat transfer or other coefficients change, as boiling is approached. In one test,(18) done out of pile with sodium-potassium cooling and electrical heaters, a capacitance type microphone and accelerometers were used to listen for boiling noises. Boiling did occur and the noises were easily recognized over the background flow and pump noises. The boiling in this case led to severe mechanical vibrations. Audio frequencies amplitude-peaked in the frequency ranges of 320 and 5700 Hz were recorded for this test. Similar test work has been done in the Dounreay Reactor. However, it should be noted that this reactor uses electromagnetic pumps so background noise is low.

Detection of boiling by this method requires considerable experience to analyze the results. One approach is to use a "signature analysis" to decide whether the coolant for the assembly was in the boiling, non-boiling, or approach-to-boiling condition by learning to recognize abnormal sounds.

Experiences with detection of boiling in a sodium loop(30) showed that a magnetic flowmeter was superior to the acoustic detection method. Boiling was detected by means of the "noise" spikes generated in the flowmeter output whenever incipient boiling bubbles passed through the flowmeter.

3. Fission Gas Pressure

Fuel pin pressure can be measured after removal from the reactor and during reactor operation.(19) For the in-reactor method, two methods of measuring this pressure are given.

- Booth-Cromer null-point indication method. A known signal gas pressure is bucked against a bellows or diaphram having the fission gas on the other side. When the null point is reached, this can be detected with the opening or closing of a contact at the diaphragm or bellows.

- Pressure transmission method. Sodium-potassium is used as the pressure transmitting medium, to a point where this NaK can be measured.

Because of the small fuel pins (about 1/4 inch O.D.) used in FTR (probable approximate size of experimenter's fuel), a bellows unit probably cannot be installed inside the fuel pin. An acceptable alternative to this would be to obtain a larger bellows (such as 1/2 inch O.D.) and install it in the space just above the fuel pins. It would then be connected by means of capillary tubing to the end of the fuel pin.

Accuracy of the two methods is expected to be one or two percent and anticipated pressures are in the range of 1000 psi.

4. Vibration and Strain

High temperature strain and vibration sensors for a sodium environment are almost nonexistent. Two high-temperature strain gauges have been investigated(20) and the conclusions are that presently there are no suitable gauges for use at 1200°F. One of the gauges was suitable at 900°F on austenitic stainless steel under both steady-state and transient conditions, for heating rates up to at least 30°F/second. The other gauge was not suitable at its rated 1200°F temperature at heating rates in excess of 5°F/second. Other problems, such as that of canning the strain gauge to keep sodium away from the gauge materials, must be solved before suitable strain gauge applications for open and closed-loop components can be made.

Vibration sensors often use strain gauges as part of the sensor, so the same remarks of inadequacy at high temperatures would apply to these sensors. However, the vibration sensor has additional problems with other component parts such as cantilever springs, connecting wires, and piezoelectric materials (used in place of resistance strain elements) at the higher temperatures. Therefore, it is reasonable to conclude that vibration sensors generally are unavailable or unsatisfactory for temperatures over 600°F. It should be understood that the term "vibration sensor" as used here includes displacement sensors and accelerators.

5. Miscellaneous Instrument Technology

There are several techniques available today, which can potentially extract additional information from sensors installed for reactor operation or for open or closed-loop testing. One such technique is noise analysis which has been used to some extent(21) for reactors in order to obtain reactor transfer functions without the use of special rod oscillator tests. Such analysis is concerned with obtaining additional information from the signal variations (or noise) which may appear in a "steady-state" signal such as a recording of neutron flux level. This analysis may proceed in the time domain or in the frequency domain. Obtaining the Fourier spectrum is a chief aim of noise ananalysis. This function of frequency is a direct measure of stability and safety in high-power reactors.

If experience has shown useful results from such reactor noise analysis, it follows that similar value can be obtained from analysis of the noise, or signal variations, obtained in the signals from coolant and clad thermocouples, magnetic flowmeters and similar sensors. In addition, signal variations from different thermocouples (for example) can be cross-correlated to obtain knowledge of coolant flow patterns under different power levels. In the Halden Reactor(22) turbine flowmeters at both the channel inlet and outlet are used not only to determine the channel flow rate, but also the exit void fraction. This is an example of correlation of signals, but with dual sensors.

Special equipment, such as filters, narrow-band, constant-bandwidth wave analyzers, and cross-correlators, is available from several manufacturers for such noise analysis. Such equipment can produce (among other items) a power density spectrum which can be mathematically related to other measurements to obtain information from the signals which did not appear from conventional amplitude-time signal analysis.

Much of this type of noise analysis can be performed with a digital computer. Such a computer in the FTR, when programmed for the special scanning and for the special calculations required, could provide such analysis, perhaps without requiring the special noise analysis equipment.

B. Development Of Instrumentation For Test Positions

A number of the previously mentioned problems have been recognized for many years and much data exists in the literature. However, it is obvious that in many cases no adequately reliable instrument exists for the stringent applications envisioned. Therefore, the magnitude of the development required to provide reliable instruments for FFTF test facilities can be enormous. The LMFBR Program Office has identified many of these problem areas and has called for development programs. Some of these and other programs are identified below.

1. Existing Sensor Development Programs

a. Fuel Pin Temperature

Both Argonne National Laboratory and General Electric have active programs to measure centerline fuel temperature in the range from 2000 to 3000°C. ANL's program is directed toward LMFBR's as well as instrumenting EBR-II. GE's efforts are aimed more towards the basic research of materials. The major problems are thermoelectric stability, materials compatibility and the low insulation resistance at the high temperature of the mineral oxides.

To date, there is no data on long time (10,000 hours) stability of the limited choice of thermoelectric elements. It will be close to the end of fiscal year 1970 before this data is available.

The effects of radiation (10^{22} to 10^{23} nvt fast) on the life and accuracy of thermocouples will not be known for many years.

b. Fuel Pin Fission Gas Pressure

There are three basic approaches to the measurement of fission gas pressure: (1) convert to an electrical signal at the point of measurement or (2) transmit a pressure signal to a more favorable environment, and (3) a combination of both. The problem is further complicated by the requirement to measure pressure in a one-quarter inch fuel pin.

A number of companies have been and are working on development programs for practical instruments. The most promising devices are the bellows or diaphragm with an electrical contact, and the fluid-filled bellows or diaphragm in which the pressure signal is transmitted by a filled capillary. Most of the testing has been done at temperatures of up to 1500°F and pressures to 100 psig with accuracies of ± 1/4 psig up to ± 2 percent. Relatively little work is reported at 1200°F, 1000 psig and 10^{21} nvt.

ANL expects to finish testing (ex-reactor) a one-eighth inch bellows/capillary-type transducer by mid FY 1969; radiation testing will continue into FY 1970.

It appears that a satisfactory instrument will be available in three to four years to measure fission gas pressure in the reactor environment.

c. Noise Analysis

Information determined by noise analysis is not available for "early warning" applications using present techniques, as it takes a fairly long time to process the data. The signals to be sensed may be induced or inherent, periodic or random fluctuations in such phenomena as flux, temperature, conductivity, flowrate, or vibrations. Usually sensed by an electronic transducer, these variations are amplified, filtered, recorded and analyzed. Comparative functions also require some prior knowledge of the frequency spectrum of normal and abnormal signals.

In order for noise analysis to become a very useful operating tool, two developments must occur: The system speed must be increased (regarding both sensor response and information processing), and a sensor must be developed to withstand the expected environment. Both of these seem to be several years away from achievement.

d. Temperature Measurement by Microwaves

One of the major problems is the waveguide. The waveguide needs to be a good conductor for a low loss transmission. Practically all metals increase resistance with temperature. Also, not many metals have sufficient strength or are compatible with sodium at high temperatures.

There is a program underway at the present time at PNL which uses the change of frequency of a tuned cavity to measure temperature. It is expected that, due to the magnitude of the problems, no useful instrument will be developed within three to five years.

e. Strain Gauge Development

The major problems hindering the development of a high temperature (above 1000°F) strain gauge are the bonding problem, the unstable change of resistance with temperature and time, and the lead wire problem.

The ceramic cement generally becomes very weak as the temperature approaches 1000°F. It also becomes very brittle. In many cases, field installation of a gauge is difficult or impractical.

Welding a strain gauge onto a structure also presents problems. The weld itself sets up strain. The welding process may cause corrosion.

Flame-coating a covering over the strain gauge has been shown to be a feasible way to bond. The process has not yet had an extensive period of testing.

The metallurgical changes in the gauge-sensing element is perhaps the more serious problem. The temperature coefficient of resistance changes with temperature. Another aspect is the instability of the sensing element at elevated temperatures, which results in a seemingly never-ending resistance change. The sensing wires also undergo a metallurgical phase change. This is more serious as the alloys become more complicated.

Thermocouple effect, lead-wire instability, lead-wire temperature coefficient and desensitizing of the strain gauge by the lead wire resistance all add to the lead wire problem.

Another problem is the inability so far to provide adequate temperature compensation.

Nevertheless, there are extensive programs underway to develop commercially available strain gauges for use in a high temperature, high radiation field. The Liquid Metals Engineering Center (Atomics International) has an active program which seeks to be able to demonstrate a useful gauge in mid-1970.

2. Development Programs Suggested

a. Temperature Measurements

It has been suggested that the average temperature of the fuel cladding can be measured by ultrasonics. This is based on the fact that some ultrasonic energy can be reflected from a temperature gradient zone in a material, the velocity of sound in a material being a function of temperature. By using this technique in reactor applications, the average temperature of fuel cladding may be deduced from the time required for a signal to traverse the length of the cladding (through it) and return. It has also been claimed that the onset of surface boiling could be detected. Any sharp change in temperature along the length would show up as a reflected pulse, amplitude being proportional to temperature. It has been demonstrated that a reflection of 3-1/2 percent can be achieved from an approximate 1200°F hot spot (1/2 inch long) for a transmission distance of three feet along a tube.

In a reactor like the FTR, there are problems of transmitting a sound pulse down a rod or tube from the fuel subassembly nozzle area to the fuel pins (supported by the rod) and seeing a return signal. There are many places along the rod where sound energy would be lost or reflected. Nevertheless, the idea should be pursued and investigated further.

There is one known commercially available instrument using sound or ultrasonics to measure temperature. This instrument measures the length change due to temperature expansion of metal.

b. Boiling Detection

Some starts have been made on efforts to develop instruments for boiling and void inception detection in liquid sodium. Sodium boiling in LMFBR cores may be the earliest indication of coolant blockage. The need for its early detection stems from the likelihood of mechanical failure due to the lower heat removal capacity of vaporized sodium and from the consequences of a possible positive void coefficient of reactivity in the region of boiling. The tendency of liquid sodium to superheat before boiling occurs is an additional incentive for spurring activity on this task. The consequence of superheat is violent boiling with expulsion of coolant. This can occur very rapidly and may result in baring or voiding sections of the reactor core.

An ultrasonic probe for the detection of incipient boiling has been developed by Aeroprojects, Inc.(23) for test on the Molten Salt Reactor Experiment (MSRE). The probe operation is based on the principle of measuring the ultrasonic energy necessary to produce cavitation. The method is appropriate, but requires placement of the probe close to the point of measurement, a difficult feat in-core.

"Listening" by use of a "microphone" or other modified sonic detector has resulted in the successful detection of boiling and vibrations. Successful detection of boiling has been confined to simple quiet environments and does not assure success in a LMFBR application. The necessary high temperature "listening" equipment has not been developed.

Noise analysis, particularly neutron noise analysis, has been used with moderate success. Dependent on the reactivity effects of small voids, neutron noise analysis requires the use of detectors placed close to the core in order to achieve a high efficiency. If the voids have a zero or small reactivity coefficient, detection is not likely. The needed high efficiency detectors are not presently available for use close to the reactor core.

Accelerometers, microphones, and related equipment are well developed and commercially available for low temperature range. Generally useful in the measurement of vibration, they require development for use in liquid sodium systems.

c. <u>Bypass Flowmeter for Closed Loops</u>

A program is needed to look at how one can measure the flow past the samples in a closed loop where bypass flow is used to keep the exit temperatures down. At this point in time, it is doubtful that a permanent magnet flowmeter can be developed due to the lack of high-temperature permanent magnet material. Temperature and radiation effects both tend to impair the operation of an eddy-current flowmeter. It could be used for short time irradiations. Nevertheless, some error in output would result from the combination environment.

Measuring flow by measuring the pressure before and after the test specimen can lead to erroneous data. As the flow increases, so does the pressure difference; likewise as the flow is blocked, the pressure rises. One cannot tell the difference. This objection can be overcome somewhat by using three taps but this introduces additional complexity.

d. Flux Measurements

An "intrinsic" thermocouple is being developed by LASL. It has been used to measure the neutron flux of a reactor as the reactor is self-destructing. The intrinsic thermocouple has a piece of fissionable material in the junction so that heat is generated there. An ordinary thermocouple measures the heat that is generated outside the junction and flows into it. In theory, the neutron spectrum can be measured by use of different materials in an intrinsic thermocouple. The ambient and gamma heating compensation is achieved by the use of a bucking junction.

The LASL Program appears to be directed toward the fast response (one microsecond) thermocouples. Nevertheless, there has been some effort directed toward making these thermocouples larger and more rugged for use in a reactor. This program should be supported and part of its effort directed more toward a flux probe which is energy sensitive.

e. Fission Product Release Mechanisms

Experiments at Argonne show that the surface tension of sodium can seal small holes in the cladding up to several hundred psi internal pressure. The rate of release of the fission gas could have an influence on the design of a gas disengagement device. It will also have an influence on the choice of failed fuel detection and location instrumentation. If the release is very slow, such as helium leakage through the wall of a balloon, a rather sensitive detector is required. If the release occurs in one big bubble, a less sensitive detector could be used. There is concern that sodium-bonded fuels release fission products differently than non-bonded fuels.

It is interesting to note that the volume released recently in EBR-II was under 50 milliliters.(24) The fission gas was monitored by the charged wire detector but not by the delayed neutron detector.

C. Existing Or Planned Loop Instrumentation

Test loops in sodium-cooled reactors do not exist, so loop instrumentation for such reactors cannot be discussed. However, the instrumentation known to be used for other investigative purposes in sodium-cooled fast reactors will be included. In addition, the loop instrumentation used in TREAT and the water-cooled testing reactors will be discussed where such inclusion can be useful for comparison with probable FFTF needs.

1. TREAT(25)

Treat is a small thermal flux reactor which makes rapid transient tests for fuel elements for EBR-II and for other needs. It is cooled by sodium, usually held to a temperature less than 500°F, but which can, on transient occasions, rise to 1000°F. An operating cycle may last only for seconds. Therefore, operating conditions are considerably different than those planned for FTR. Their testing experiences, which are discussed below, should be considered with these conditions in mind.

a. Experimenters from offsite supply their own instrumented test assembly with sensors installed. The TREAT facility may supply amplifiers and recorders for the test.

b. They have had no sodium boiling detection tests.

c. One Atomics International assembly was equipped with fuel pin pressure instrumentation consisting of tubing from the fuel pin to a variable magnetic pickup which was located in the vessel but away from the core to avoid the high transient core temperatures. This instrumentation apparently was successful for the short period of use.

d. Fuel clad temperatures have been measured with thermocouples without major problems, but again, not with long operating cycles.

e. Fuel meat temperatures have been measured with tungsten-rhenium thermocouples but the results were often not satisfactory.

f. In-core flux detectors are not regularly used. Flux maps are made at low power and the results are extrapolated to high power conditions. Mapping is done with a one-half inch square fission chamber, rather than wire activation techniques, in order to obtain the more meaningful "fissile isotope fission rates".

g. Their in-core thermocouples and other sensors are connected to the control room amplifiers and recorders by signal leads about forty feet long. There have been few noise pickup problems and one of the reasons is that power and signal leads were separately routed.

h. Test data are gathered mainly by recorders, some of which are high speed, due to the transient nature of the tests.

2. General For MTR, ETR and ATR(26)(27)(28)(29)

These three light-water-cooled thermal flux reactors at the National Reactor Testing Station have certain similarities which can be grouped for discussion. Differences among them are discussed in the sections assigned to the individual reactors.

a. Reactor Comparisons

	MTR	ETR	ATR
Power (MW)	40	175	250
Flux, n/cm^2-sec	10^{14}	1.6×10^{14}	10^{15}
Assemblies			
No.	24	52	40
Size	24 x 2.996 x 3.168"	36 x 3 x 3"	48" long
Coolant Conditions			
Inlet	100°F + 43 psig	100°F + 200 psig	130°F + 300 psig
Outlet	112°F + 0 psig	133°F + 167 psig	187°F + 208 psig
Assembly Coolant Velocity		32 Ft/Sec	44 Ft/Sec

b. The flux values are subject to different interpretations because of different methods of classifying flux as fast and thermal and because the flux will change with different fuel loadings. The MTR started operation in 1952, ETR in 1958, and ATR has yet to attain successful operation. Availability for MTR is high (up to 80 percent) but that of ETR is lower (about 45 percent). The lower availability for ETR is due to: (1) more experiments, and (2) because refueling and experiment changes require removal of the vessel cover and some shielding, installation of a work platform over the vessel, and reversal of the process after completion. Thus, even though the MTR flux is lower, an experimenter can obtain approximately as much irradiation experience in MTR as in ETR.

c. All three reactors have an automatic flux regulating system consisting mainly of one flux chamber and one regulating rod and there is a second such system for backup purposes. These flux monitor channels are referred to as the "servo channels".

d. MTR has no vertical closed loops but does have three horizontal holes which can be used for loop testing. ETR has seven vertical closed loops and ATR has six, with a seventh proposed. MTR has many "lead" tests which are equivalent to the proposed open test positions for FTR in that generally the test assembly is cooled by the reactor coolant. ETR has some of these lead tests but ATR will initially have none.

e. The closed-loop equipment is built into the usual primary cell behind a shielding door. An adjacent secondary or sample cell is provided which can be entered during reactor operation to take coolant samples or to calibrate or check instrument components such as differential pressure transducers located in this cell. Loop control systems are usually supplied by the experimenter but the facility will supply the system and the hardware if requested. In ATR the loop control equipment for the six similar closed loops is supplied as part of the reactor facility because the experimenter and his needs were known beforehand.

f. Monitoring signals from the experimenter's tests are assigned to one or more of the four setback or scram circuits or to the annunciator circuits depending on the importance of the signal. This assignment is made by a Safeguards Committee made up of Idaho Nuclear personnel.

g. Signals from open or closed-loop tests include many thermocouple signals which are fed to temperature compensation panels supplied by the facility. The signals are then routed to the experimenter's recorder or data loggers, unless the Safeguards Committee directs that some of the signals are to be routed to the annunciator or to one or more of the safety circuits. Their experience is that some experimenters do not require continuous recording of their test signals. They are satisfied with periodic readings logged by the reactor operator.

h. Vibration has been measured with strain gauges and a high-speed recorder, and in some cases with an accelerometer fed to magnetic tape. The tests were usually required for reactor vibration analysis rather than for loop vibration problems. Unbonded strain gauges have been used for high-temperature applications. Also, they have had some experience with fuel meat thermocouples. These were of the tungsten-rhenium type and gave good performance once the techniques of mounting were better understood.

i. In-core flux in MTR and ETR has been mapped many times by means of wires. These were inserted between fuel elements during shutdown, the reactor was then operated at low power, and then shut down for removal and counting of the activity of the wires. One experiment had a 5/16 in. thimble tube installed so wires could be inserted and withdrawn with a hand-cranked inserter during reactor operation. Some trouble was encountered with the inserter. During the past year, much of their in-core flux mapping has been done with Reuter Stokes miniature (1/4 in. O.D. and smaller) self-powered neutron detectors because of their good experience with them. However, wires and foils are used to some extent, with foils preferred over wires. In addition, they have used a very reliable boron thermopile with internal gamma compensation. Its size is 1/2 in. O.D. x 6 in. long. Speed of response is only one second, so it is not used for control purposes. It requires at least 10^{12} nv of flux for proper operation. The self-generating chamber may not be usable in FTR because of the higher temperatures which lowers the shunt resistance. The thermopile may not be usable at FTR temperatures due to the difficulty of making sufficient temperature compensation.

j. Sensors used in loop instrumentation are conventional. Thermocouples or resistance temperature detectors are used for temperature sensing. An orifice in the closed-loop line is used for flow measurement. Pressure measurement is done with a tap line connected to a transmitter, either pneumatic or electric. Gamma chambers are used for loop activity buildup detection.

k. Instrumentation used for control of the three reactors is similar and conventional. Primary bulk flow is measured with Gentile (venturi) flow tubes. Power is calculated from flow and delta-T obtained from RTD bulbs. Neutron chambers in MTR and ETR operate in 10^3 gamma fields. Because the ATR gamma background is 10 to 100 times greater, gamma compensation will be used.

3. MTR

a. Most of the tests performed in this reactor are of the open or "lead" type, apparently so-called because the assemblies have signal wires leading out the side ports on the vessel. The lead test assemblies consist of a stainless steel tube of about 1 in. I.D. attached to the test assembly. The tube protects the signal wires from the assembly sensors, which are mainly thermocouples.

b. The assembly is shipped to the facility with the wires sticking out the upper end of the tube. The technicians then bend this tube to fit a prescribed position in the core. The in-core section is vertical and the leadout part of the tube emerges from the vessel side port at an angle. After installation of the flange plate and gland nut, a lead connector box is attached, and the assembly is fed through the vessel port. The flange plate is then bolted to the vessel port flange and gland nut, a lead connector box is attached, and the assembly is fed through the vessel port. The flange plate is then bolted to the vessel port flange and wiring is connected from the leadout box to the instrumenter's recorders which for MTR are adjacent to the vessel top.

c. Data are usually collected on chart recorders of the single, dual or multipoint types. These are not in the control room. Certain signals will cause annunciation in the control room so that the lower floor operator can be alerted to investigate the cause of the unusual condition.

d. MTR has a unique method for detection of boiling. Boiling shows up on the chart recording of the linear or servo flux channels as small "pips" with a period of one-half to two seconds. When the special Brush recorder is connected, the peaks show up as an apparent neutron increase of about one percent, whenever the boiling appears. When the reactor power is decreased, the indications disappear. This apparent increase in flux is apparently due to the void creation which either creates a local reactivity increase or else reduces the shielding between this fuel element and the out-of-vessel flux chambers.

e. Detection of FTR sodium coolant boiling by this method probably is not feasible because of the smaller reactivity changes from sodium voids. However, with proper techniques and depending on flux chamber position relative to the core, it may be possible to detect the onset of boiling. But, of course, the potential difficulties associated with sodium coolant boiling are much more serious than with water coolant boiling.

f. One other distinction between MTR and the other two test reactors is that it has flow and temperature monitoring for each subassembly. The device consists of a pitot tube on which is mounted chromel/alumel thermcouples. It is inserted into the bottom of the vessel and extends into the bottom of each fuel assembly. Flow of reactor coolant is downwards. Also, the device can produce a coolant sample from each assembly for rupture location purposes. These samples are passed through 100-second holdup coils to decay the N^{16} activity, and then to an ion chamber for measurement of the residual activity. A fuel element which has ruptured can be easily identified in this way. Fuel element temperature is measured relative to the bulk outlet temperature so a positive difference of 15°F or more is taken as an indication of a blocked assembly.

4. ETR

a. Several of the ETR closed loops were installed several years after reactor startup. All loops are equipped with coolant flow monitoring instrumentation equipped with trips for either high or low flow. All loops are equipped with supply pressure and exit temperature monitoring. Exit temperature is usually the controlled condition. Some open-loop testing is also done in this reactor.

b. A large number of large instrument panels have been installed for controlling the experiments and especially for recording all of the test data. Part of the reason for the large panels is that there are many large chart recorders which together take up a considerable amount of space. Usually, these panels are supplied by the experimenter.

c. ETR is equipped with a 300-point Honeywell data logger which logs at the rate of six points per second and prints out at the rate of two per second. However, its accuracy is in question and experimenters generally mistrust it. Apparently the problem occurs in the stepping switches located at the input of the logger. Although the switch contacts are immersed in oil, the contacts create erratic or transient noise to disturb the input signals. The other internal switching is with mercury-wetted relays which operate satisfactorily. The logger accepts millivolt signals directly without preamplification.

5. ATR
   a. Operating experience has not, of course, been accumulated at this reactor. However, its plans and instrumentation arrangement have some potential application for FTR.
   b. No open-loop experiments are planned for this reactor. There are six closed loops, with their cells and control panels arranged in a radial pattern around the reactor. Each loop's control panel is physically isolated from those for the other loops. The panels are smaller, partly because many miniature recorders are used in place of the larger recorders used in MTR and ETR. The control panels are mainly electrical, receiving the electrical signals from (for example) delta-P to electrical transducers located in the secondary cell.
   c. In addition to the chart recorders for the main data collection, ATR has a Control Data 636 computer and data logger which can scan 600 analog points per second and store the data in memory. It can scan 900 digital points in about one second. About 300 analog and 900 digital data connections are made to the computer's multiplexer. The computer will also make power and reactivity calculations as an aid to better operation. The computer is considered to be vital to reactor operation. One other noteworthy point is that all signal inputs are required to connect to the computer through small, quick-acting fuses to ensure that the computer will not be damaged from accidental overvoltage on the signal leads.
   d. Although the closed-loop experiments could apparently operate without the computer, the computer has the ability of making a rapid scan and printout of all of the experimenter's data in a condensed form.

e. The ATR Reactor, unlike the other two, is equipped with a reactor top count-rate meter for use during reactor shutdown when fuel or loop assemblies are being changed. It is an indicator mounted on the reactor top with both a visible and an audible alarm. The indicator can be switched to monitor either of the count-rate channels, which are also used for reactor startup.

REFERENCES

1. R. E. Peterson, et al, "Technical Basis for Driver Fuel Instrumentation, BNWL-555, September 1967.
2. C. C. Steele, et al, "Fast Flux Test Facility Overall Conceptual Systems Design Description," BNWL-500, July 7, 1967.
3. F. J. Kempf, "FFTF Conceptual Component Design Description for the Reactor Core - System No. 31," Preliminary Issue, November 29, 1967.
4. "FFTF Monthly Informal Technical Progress Report, November 1967," BNWL-638, December 7, 1967.
5. "Engineering and Design Considerations for In-Pile Tests," Fundamentals in the Operation of Nuclear Test Reactors, Volume 4, IDO-16871-4, July 1965.
6. "Standard Guides to the Design of Experiments for the Plum Brook Reactor Facility," No Document Number, National Aeronautics and Space Administration, Lewis Research Center, Plum Brook Station, Sandusky, Ohio, February 8, 1965.
7. J. W. Hagan and D. E. Simpson, "Design Safety Criteria for the FFTF Reactor Systems," Preliminary Information Support Document S-4 of Document A-0036, December 1, 1967.
8. J. D. Herb, "FFTF Conceptual Component Design Description for Reactor Nuclear Control--System No. 33," Not Yet Issued.
9. M. K. Mahaffey, "Conceptual Facility Design Description for the Open Positions Facility, No. 67," Preliminary Information Support Document for Document A-0022-R, January 5, 1968, Item 1.2.2.D.
10. R. J. Hennig, "Functional Testing Requirements for the FFTF," Internal Document A-0030-R, November 22, 1967.
11. A. E. Knox and G. F. Popper, ANL, "A Survey and Status Report on Fuel Pin Thermocouples for Operation in the FFTF," March 1967.
12. P. E. Novack and R. R. Asamato, APO, GE, "The Effect of High Temperature and a Nuclear Environment on the Tungsten Rhenium Thermocouples," Abstract for the American Ceramic Society Meeting, July 1967.
13. L. Fisher and G. French, Dounreay, "Fuel Centre Temperature Measurements in DFR and DMTR," International Symposium on In-Pile Irradiation Equipment and Techniques, Harwell, England, Paper F.5, May 1966.

14. G. R. Pflasterer and L. Caldarola, "Description of Planned Tests," SEFOR Experimental Program Planning, Volume II, August 1966.

15. H. Bryant, LMFBR Task No. 8, July 1967.

16. T. R. Billeter and D. P. Brown, "Microwave Measurement of High Temperatures within Nuclear Reactors," PNL, Battelle-Northwest, October 1967.

17. Aerojet Proposal, ANU-67-39, "Program to Develop a Reactor Core Monitoring System for Liquid-Metal Cooled Reactors with Pin-Type Fuel Elements," August 1967.

18. T. J. Ledwidge and E. R. Adam, "Boiling Noise Investigation in the Four-Inch Loop, D.E.R.E., Experiment No. 1," Dounreay, December 1965.

19. J. R. Folkrod, "FFTF Fission Gas Pressure Transducer Development - Initial Study and Evaluation Report," ANL, May 1967.

20. M. M. Lemcoe, "Characteristics of Two Commercial High-Temperature Electric Resistance Strain Gages," NAA-SR-12118, August 1967.

21. J. A. Thie, Reactor Noise, AEC Monograph, 1963.

22. Atomprexis 11, Heft, September 10, 1965.

23. "Applications of Ultrasonic Energy: Ultrasonic Instrumentation for Nuclear Applications," Bimonthly Progress Report No. 32, Aeroprojects, Incorporated, February 1967.

24. E. R. Ebersole and F. S. Kirn, et al, "EBR-II Fission Product Release Incidents for the Period May 1-June 15, 1967," Undocumented Report, Argonne National Laboratory. June 16, 1967.

25. J. F. Boland, ANL, to W. Dalos,PNL, Telephone Conversation Record on TREAT Instrumentation, October 11, 1967.

26. W. Dalos, "Trip Report, Visit to MTR, ETR, and ATR Reactors, Idaho Falls, October 23, 1967.

27. "Materials Testing Reactor Design and Operation," Fundamentals in the Operation of Nuclear Test Reactors, Volume 2, IDO-16871, October 1963.

28. "Engineering Test Reactor Design and Operation," Fundamentals in the Operation of Nuclear Test Reactors, Volume 3, IDO-16871-3, July 1964.

29. "Advanced Test Reactor Design and Operation," Fundamentals in the Operation of Nuclear Test Reactors, Volume 5, IDO-16871-5, November 1965.

30. R. L. Randall and D. Logan, "Application of Noise-Analysis Techniques to Hydraulic Measurements in Liquid-Metal Systems," Proceedings of the Symposium on Liquid Metal Instrumentation and Control, ANL-7380, March 1967.

DISTRIBUTION

30 U.S. Atomic Energy Commission
Division of Reactor Dev. & Tech.
M. Shaw, Director, RDT
Asst. Dir for Nuclear Safety
Analysis & Evaluation Br., RDT:NS
Environmental & Sanitary Engrg.
Br., RDT:NS
Research & Develop. Br., RDT:NS
Asst. Dir. for Plant Engrg., RDT
Application & Facilities Br.,
RDT:PE
Components Br., RDT:PE
Instrumentation & Control Br.,
RDT:PE
Systems Engineering, Br., RDT:PE
Asst. Dir. for Program Analysis, RDT
Asst. Dir. for Project Mgmt., RDT
Liquid Metals Projects Br., RDT:PM
Core Design Branch, RDT:RE (2)
FFTF Project Manager, RDT:PM (3)
Asst. Dir. for Reactor Engineering
Control Mechanisms Br., RDT:
Fuel Fabrication Br., RDT:RE
Fuel Handling Branch, RDT:RE
Reactor Vessels Branch, RDT:RE
Asst. Dir. for Reactor Tech.
Chemistry & Chemical Separations
Branch, RDT:RT (2)
Fuels & Materials Branch, RDT:RT
Reactor Physics Branch, RDT:RT
Special Technology Branch, RDT:RT
Asst. Dir. for Engrg. Standards

2 AEC Chicago Patent Group
GH Lee, Chief
RK Sharp, Richland

1 AEC Idaho Operations Office
Nuclear Technology Division
CW Bills, Director

3 AEC Richland Operations Office
FFTF Program
JM Shivley

1 AEC San Francisco Operations Office
Director, Reactor Division

4 AEC Site Representatives, PNL
PG Holsted (2)
LR Lucas
AD Toth

4 AEC Site Representatives
Argonne National Laboratory

Atomics International

Atomic Power Development
Associates

General Electric Company
(Sunnyvale)

2 Argonne National Laboratory
RA Jaross
LMFBR Program Office

2 Atomics International
LE Glasgow
Liquid Metal Engrg. Center

RW Dickinson

1 Atomic Power Development Assoc.
Document Librarian

2 Babcock & Wilcox Company
Atomic Energy Division
SH Esleeck

Boiler Division
TP Farrell

1 Combustion Engineering
1000 MWe Follow-on Study
WP Staker, Project Manager

2 Gulf General Atomic Inc.
General Atomic Division
D Coburn

5 General Electric Company
Advanced Products Operation
Karl Cohen (3)
Betram Wolfe

Nuclear Systems Programs
DH Ahmann

1 PNL Representative
NA Hill (ZPR III)

1 Stanford University
Nuclear Division
Division of Mechanical Engrg.
R Sher

5 Westinghouse Electric Corporation
Atomic Power Division
Advanced Reactor Systems
JCR Kelly

1 Idaho Nuclear Corporation
DR de Boisblanc

90 Battelle-Northwest

WG Albert - 703
SO Arneson - 703
ER Astley - 703
JM Batch - 328
T Bauman - 3201
RA Bennett - 703
CL Boyd - 703
CA Burgess - 308
BA Chandler - 308
DC Boyd - 703
WL Bunch - 703
CM Cantrell - 703
JR Carrell - 703
WE Cawley - 703
WL Chase - 703
PD Cohn - 3702
DL Condotta - 703
W Dalos - 703
GJ Dau - ROB
JM Davidson - ROB
DR Doman - 703
GE Driver - Math. Bldg.
RV Dulin - 703
CL Fies - 703
LM Finch - 703
VW Gustafson - Fed. Bldg.
RA Harvey - 703
BR Hayward - 308
JW Helm - 703
RJ Hennig - 703
PL Hofmann - 703
BM Johnson - 703
HG Johnson - 703
EM Johnston - 713
FJ Kempf - 703
JH Kinginger - 703
HD Linkersdorfer - 703
CW Lindenmeier - 703
WW Little - 703
CE Love - 703
WB McDonald - 703
CA Munro - 703
CR Nash - 703
A Padilla - 703
RD Peak - 703
RE Peterson - 703
JJ Regimbal - 703 (10)
WE Roake - 308
DW Shannon - 324
DE Simpson - 324
CRF Smith - 703
RJ Squires - 703
DD Stepnewski - 703
GH Strong - 703
CD Swanson - 703
GG Thieme - 703
JP Thomas - 703
DC Thompson - 703
JC Tobin - 703
KG Toyoda - 703
RW Truitt - 703
MA Vogel - 703
RC Walker - 703
GR Waymire - 703
JH Westsik - 703
LA Whinery - 703
TW Withers - 703
NG Wittenbrock - Fed. Bldg.
MR Wood - 703
FW Woodfield - 703
JM Yatabe - 703
EA Evans - 308
FFTF Files - 703 (2)
Tech. Info. - 3760 (5)

Battelle-Northwest (Continued)

J. J. Regimbal - 703 (10)
W. E. Roake - 308
D. W. Shannon - 324
D. E. Simpson - 324
C. R. F. Smith - 703
R. J. Squires - 703
D. D. Stepnewski - 703
G. H. Strong - 703
C. D. Swanson - 703
G. G. Thieme - 703
J. P. Thomas - 703
D. C. Thompson - 703
J. C. Tobin - 703
K. G. Toyoda - 703
R. W. Truitt - 703
M. A. Vogel - 703
R. C. Walker - 703
G. R. Waymire - 703
J. H. Westsik - 703
L. A. Whinery - 703
T. W. Withers - 703
N. G. Wittenbrock - Fed. Bldg.
M. R. Wood - 703
F. W. Woodfield - 703
J. M. Yatabe - 703
FFTF Files (2) - 703
E. A. Evans - 308
Tech. Info. (5) - 3760