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MEASUREMENTS OF THERMAL-HYDRAULIC PARAMETERS IN LIQUID-METAL-COOLED FAST-BREEDER REACTORS

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MEASUREMENTS OF THERMAL-HYDRAULIC PARAMETERS IN LIQUID-METAL-COOLED FAST BREEDER REACTORS

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ABSTRACT

This paper discusses instrumentation for liquid-metal-cooled fast breeder reactors (LMFBR's). Included is instrumentation to measure sodium flow, pressure, temperature, acoustic noise, sodium purity, and leakage. The paper identifies the overall instrumentation requirements for LMFBR's and those aspects of instrumentation which are unique or of special concern to LMFBR systems. It also gives an overview of the status of instrument design and performance.

1. INTRODUCTION

LMFBR's present unique instrumentation requirements because of the high-temperature sodium coolant. Certain properties of sodium, for example good thermal and electrical conductivity, allow for novel application of instrumentation, notably magnetic flowmeters. Other properties, for example chemical reactivity with water and opaqueness, require unique instrumentation to ensure plant operability and safety.

Sodium flow can be monitored by a number of methods including standard ΔP techniques (flow orifices, venturies), and electromagnetic, ultrasonic, and tracer techniques.[1,2,3] These techniques have been used in LMFBR plants with varying levels of success. The major objective is to provide reliable flow instrumentation that can survive the high temperatures of sodium, requiring minimal maintenance over a 40-year plant life. Some plants provide flowmetering of individual fuel subassemblies where, in addition to concerns for high temperature, radiation damage is also a major consideration.

Pressure in sodium systems can be measured by relatively conventional means, for example with NaK-filled capillary tubes from pressure transducers. The major challenge is to avoid oxygen contamination in the NaK capillary tubes, which causes blockage. Extremely careful quality assurance during the installation of pressure leads is necessary to avoid this problem, but such systems, once successfully installed, have been found to operate reliably.

A major emphasis in temperature monitoring for LMFBR plants has been the development of reliable fast-response thermocouples[4] (time constants of 0.5 s or less). In particular, much attention has been given to the ability to detect rapid temperature fluctuations associated with a developing flow blockage or the onset of sodium boiling.) Likewise, the development of acoustic monitors to detect sodium boiling in individual fuel subassemblies has been pursued as a backup to temperature or flow monitoring in individual subassemblies.[5]

Because sodium is opaque and reacts with oxygen, operations within the primary system must be conducted remotely without the benefit of direct vision. For this reason, attention has been given to development of under-sodium viewing devices which depend on ultrasonic signal transmission for their operation. These viewing devices have been successfully tested in a number of sodium systems, most notably by the British at the PFR.[5,6]

The acoustic monitors associated with development of under-sodium viewing systems are also potentially valuable for detecting loose mechanical parts or for monitoring such mechanical operations in the primary system as fuel handling. This has proven to be of great benefit at EBR-II, for example.

Sodium purity is of special concern in sodium systems because of the chemical reactivity of sodium with oxygen. Too much contamination of the sodium with oxygen can lead to problems of corrosion in the primary system or, if severe enough, the blockage of small flow passages when the temperature of the sodium is decreased. Consequently, instruments to measure the level of oxygen contamination (as well as other impurities) have been developed and extensively tested.[7]

The performance of steam generators in LMFBR's is of concern because of the highly energetic reaction that takes place between sodium and water. It is important to provide a highly reliable leaktight boundary between sodium and water in the steam-generating system. Likewise, it is important to provide instrumentation to detect leaks so that if they do occur, appropriate actions can be taken (such as rapidly draining the sodium lines). The most common method of leak detection is to monitor the sodium for the presence of hydrogen that results from the reaction of sodium and water.[8] Another approach is to provide acoustic sensors to monitor for the leakage of steam to the sodium system.[9]

2. MONITORING FLOW AND TEMPERATURE IN THE SODIUM COOLANT CIRCUITS

2.1 General Instrument Requirements

LMFBR power plants include both a primary heat-transport system (PHTS) and an intermediate heat-transport system (IHTS) filled with sodium. The secondary heat system serves to isolate the radioactive primary system from the effects of a leak at the interface between the IHTS and steam system.

A typical arrangement, along with flow and temperature values, is shown in Fig. 1 (the French plant, Super-Phenix). Also shown is a similar diagram for EBR-II, the world's longest-operating LMFBR power plant. The arrangements of the PHTS are of two basic types, loop and pool. This difference is important because the challenges presented for plant instrumentation are different. Shown in Fig. 3 is a plant of the loop type, the Fast Flux Test Facility (FFTF). In the loop system, the primary piping and major components (pumps, intermediate heat exchangers, and flowmeters) are more easily accessible for maintenance and repair. In the pool system, the primary piping and major PHTS components are submerged in a tank of sodium, which makes instrumentation somewhat more difficult. High reliability is needed in such a system because the components are difficult to remove for inspection.

Instrumentation for the heat-transport systems provide for control, protection, and diagnosis of normal and off-normal conditions. Important components of the system are the piping, pumps, intermediate heat exchanger (IHX), and steam generator. Typically, sodium flow rate is measured in the PHTS and the IHTS by the use of magnetic or ultrasonic flowmeters. Steam and water flows are measured by the use of conventional ΔP flowmeters (venturi or sharp-edge orifice).

Temperature measurements in the sodium systems are typically made at the inlet and outlet of the core (including the outlet of individual subassemblies), inlet and outlet of the IHX, inlet and outlet of the pumps, and inlet and outlet of the steam generators (evaporators and superheaters). Chromel/alumel thermocouples are commonly used, as well as resistance temperature detectors (RTD's) in a few applications.

Pressure measurements in the sodium systems are useful as plant protection inputs. These measurements are typically made at the outlet of the pumps and outlet of the reactor core. (In pool systems, the pressure across the IHX is measured as a difference in height between the hot and cold sodium pools.) Pressure is usually measured in sodium with a NaK-filled line from the sensor.

Other important measurements include sodium level (typically measured by inductive probes), pump speeds and power, leakage of sodium or water, contamination of sodium, and changes in the level or character of acoustic signals.

A major difference in instrumentation between loop and pool systems is in flow monitoring. Because the pool system provides a parallel flow circuit between pumps and intermediate heat exchangers, flow to each component cannot be easily inferred from flow measurements at any one point in the system. (See Fig. 4.) The most challenging aspect is flow monitoring at the outlet of the primary pumps or inlet to the core. Because such flowmeters are submerged deep in the pool of sodium, they must be extremely reliable or provision must be made for their easy removal and repair. Experimental Breeder Reactor II (EBR-II) provides a good example of extensive flow instrumentation in the primary system.

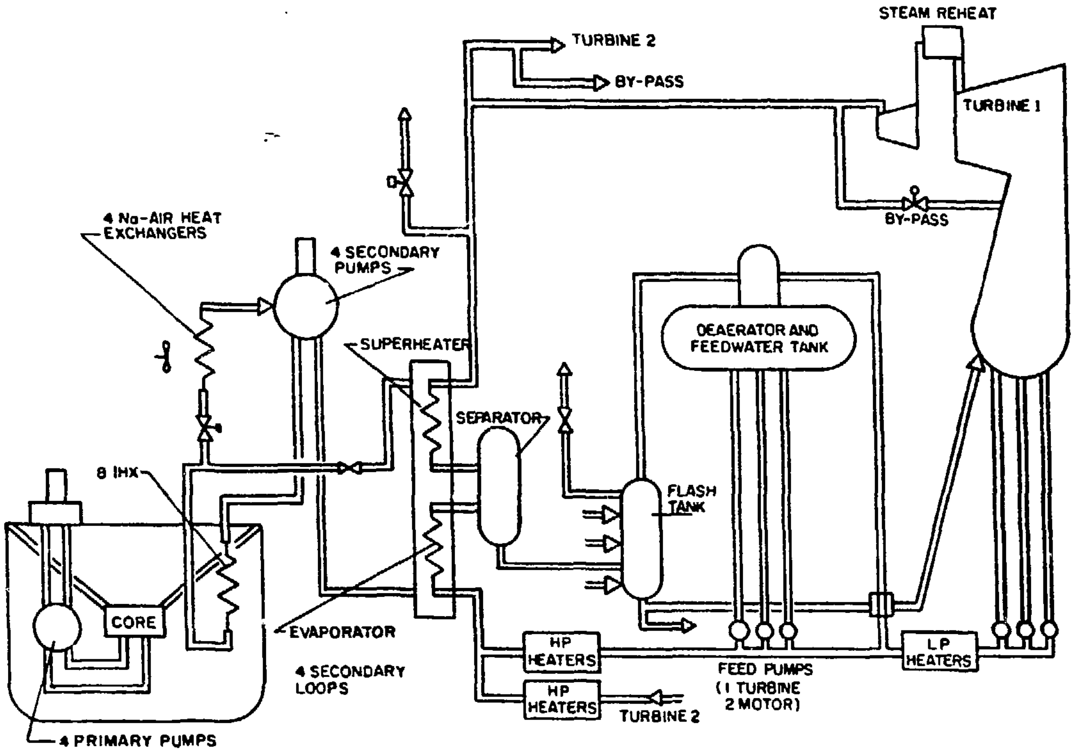

Fig. 1 Simplified Heat Transport Path for Super Phenix

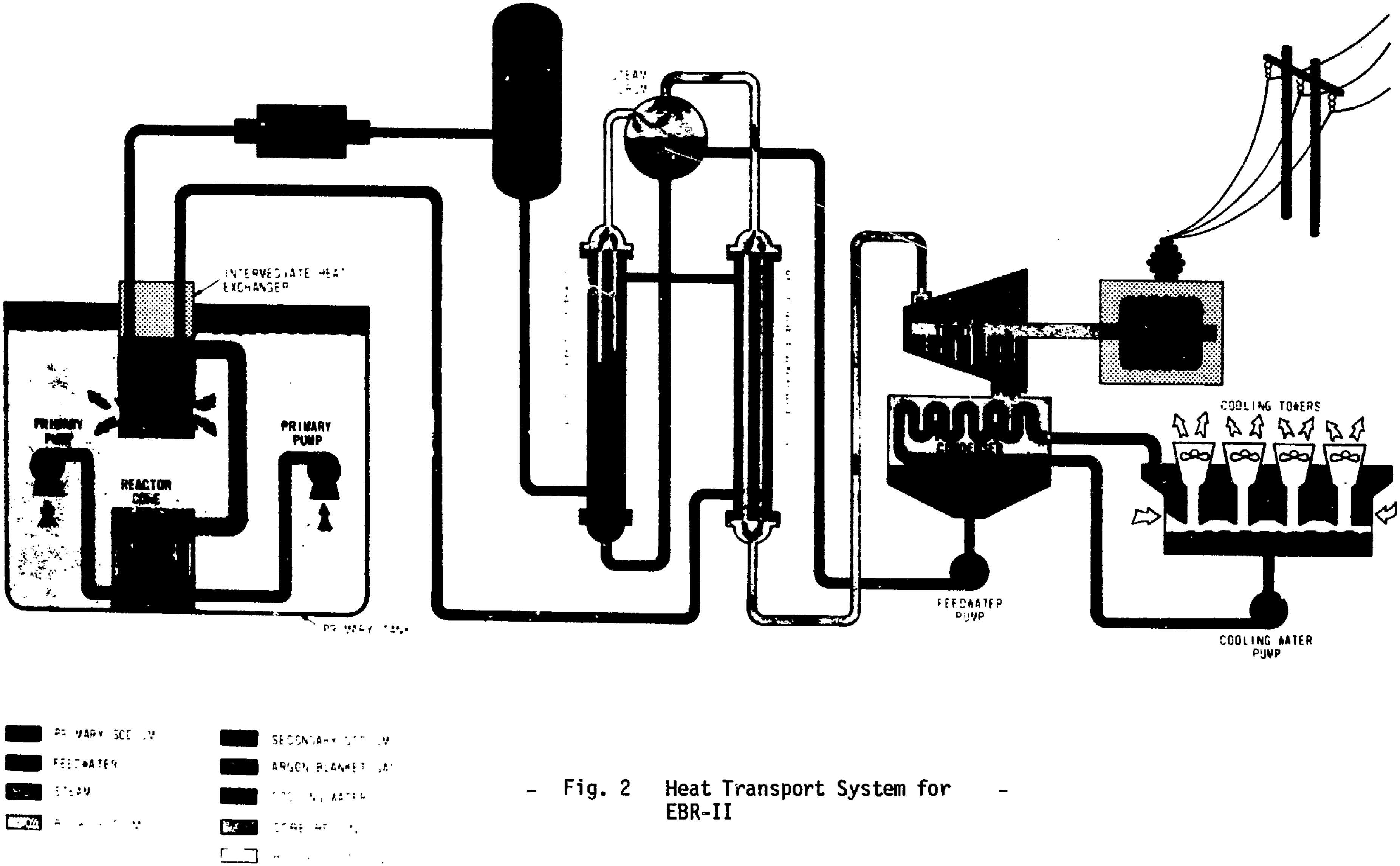

Fig. 2 Heat Transport System for EBR-II

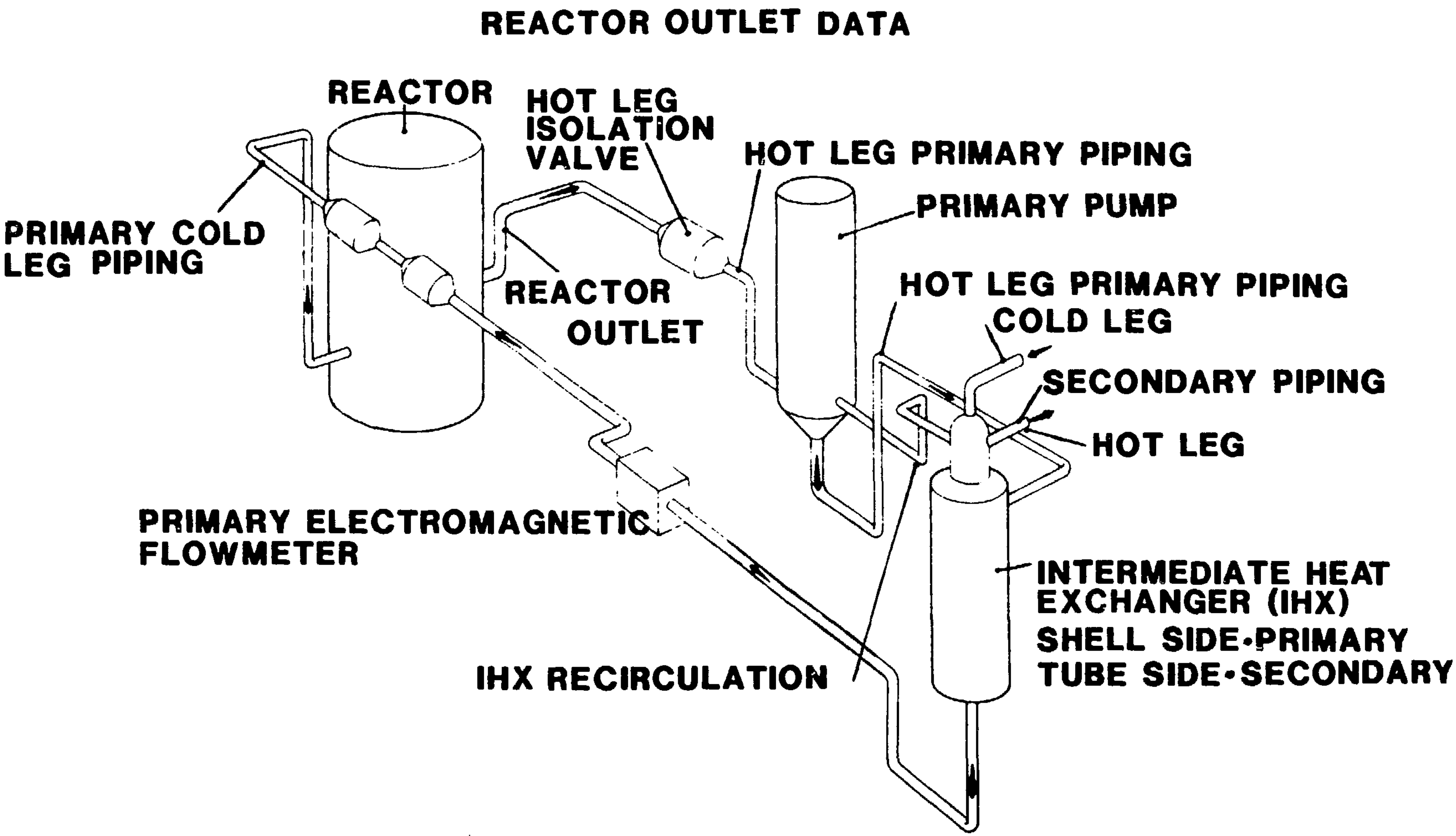

Fig. 3 FFTF HTS PRIMARY LOOP SCHEMATIC DIAGRAM

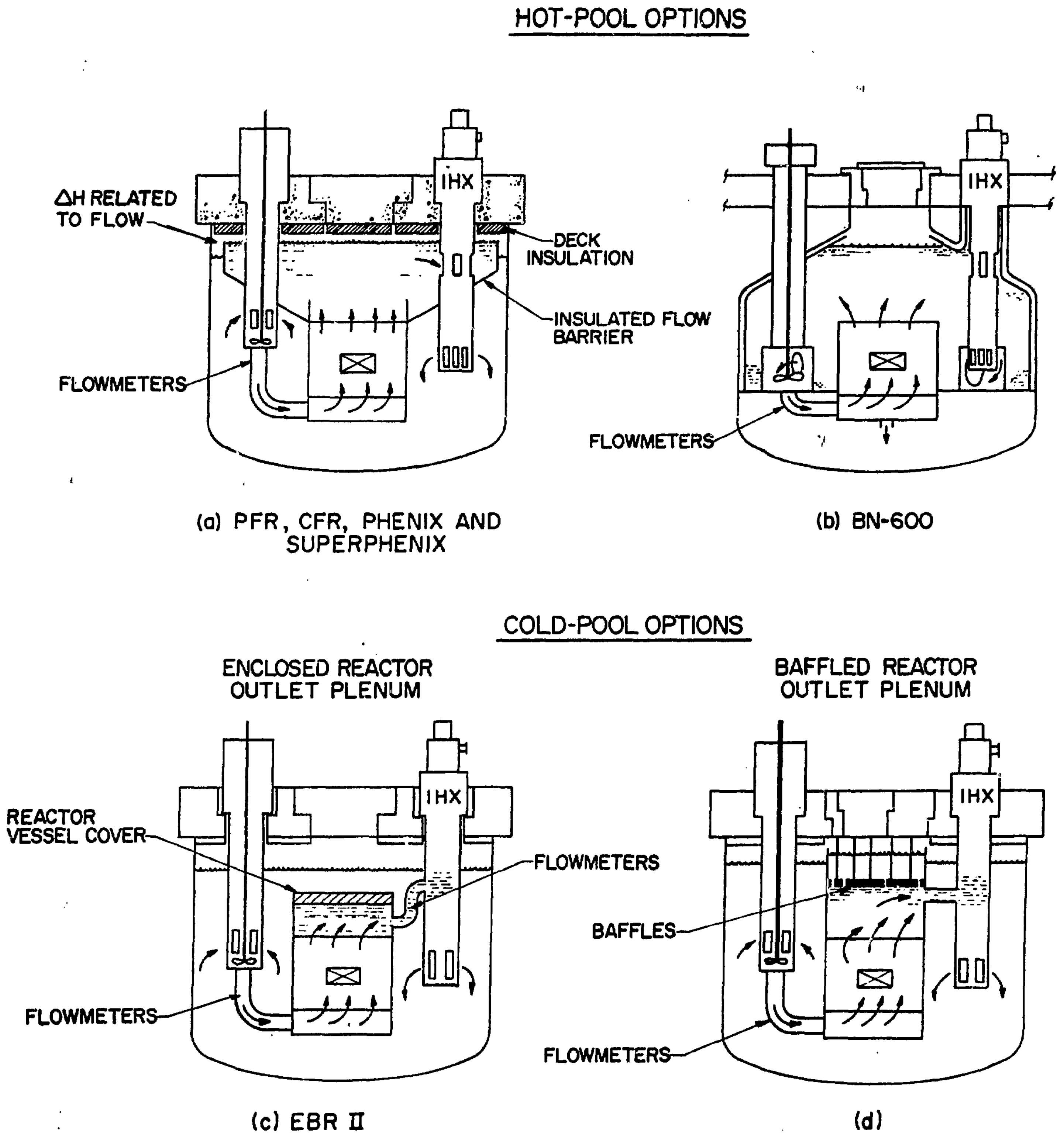

Fig. 4 Several Configurations of the Primary System Heat Transport Path in LMFBR's (from ANL-76-61)

EBR-II is an experimental reactor intended to demonstrate the feasibility of the reliable long-term operation of an LMFBR power plant. An important part of this mission is to develop and demonstrate primary-system instrumentation, especially that instrumentation related to measuring reactor coolant flow and temperature. The original flowmeters for the primary-cooling system were of two types, ΔP flowmeters (Foster flow tubes) and permanent-magnet flowmeters (PM flow sensors). (See Fig. 5.) Each was considered developmental and both were included to provide diversity and improve reliability. Failures of a number of flowmeters of both types over the 19-year operating history of EBR-II has demonstrated the wisdom of this approach.

2.2 Flow Measurement Techniques

The major types of flowmeters that have been used or considered in LMFBR systems are:

1. <u>ΔP flowmeters</u>:

   Venturi
   Sharp-edge orifice

2. <u>Magnetic flowmeters</u>:

   Permanent magnet
   DC electromagnetic
   Eddy current

3. <u>Ultrasonic flowmeters</u>:

4. <u>Time-of-Flight flowmeters</u>:

   Pulsed-neutron activation
   Correlation of temperature noise
   Correlation of magnetic-flowmeter noise

Of the ΔP devices, the venturi flowmeter has been the most successful. It is generally accepted as a standard and is used for in-place calibration of magnetic flowmeters. It is, however, potentially large and heavy [typically 1000 lb (454 kg) for a venturi flowmeter of 0.5 m diameter]. To reduce size, a common modification is to shorten the venturi flowmeter and provide fluid "impact" heads around the inside diameter of the Venturi. (See Fig. 6.) Half of the impact heads are positioned facing upstream, and the other half are facing downstream to increase the measured ΔP. The ΔP is measured by NaK-filled capillary tubes leading to a strain gauge.

Such instruments are very accurate at high flow rates, with accuracy of better than 2% and reproducibility of better than 0.3%. However, their range is poor; typically, they do not provide sufficient accuracy for flow levels below about 25% of maximum.

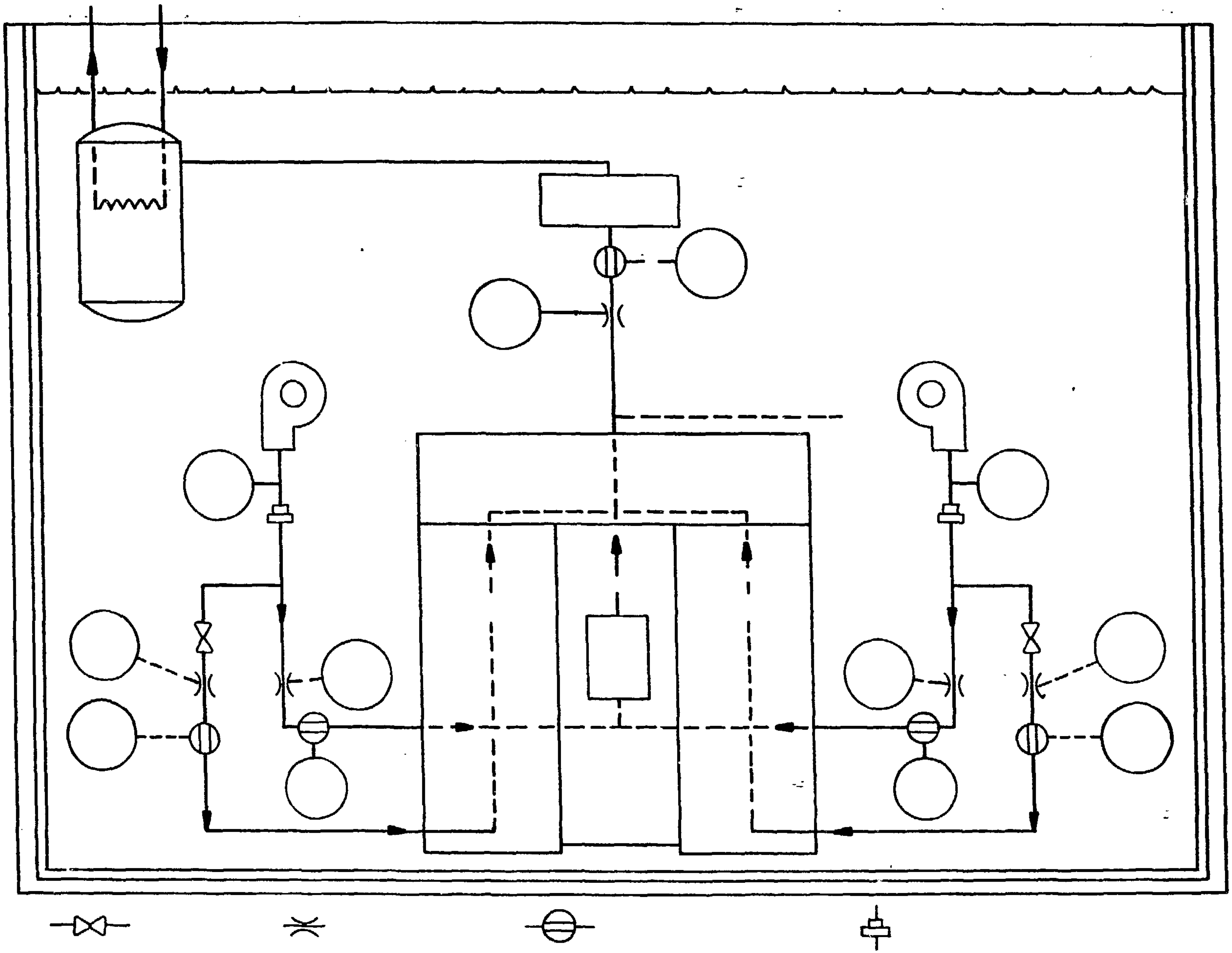

Fig. 5 EBR-II Primary System Flow Instruments

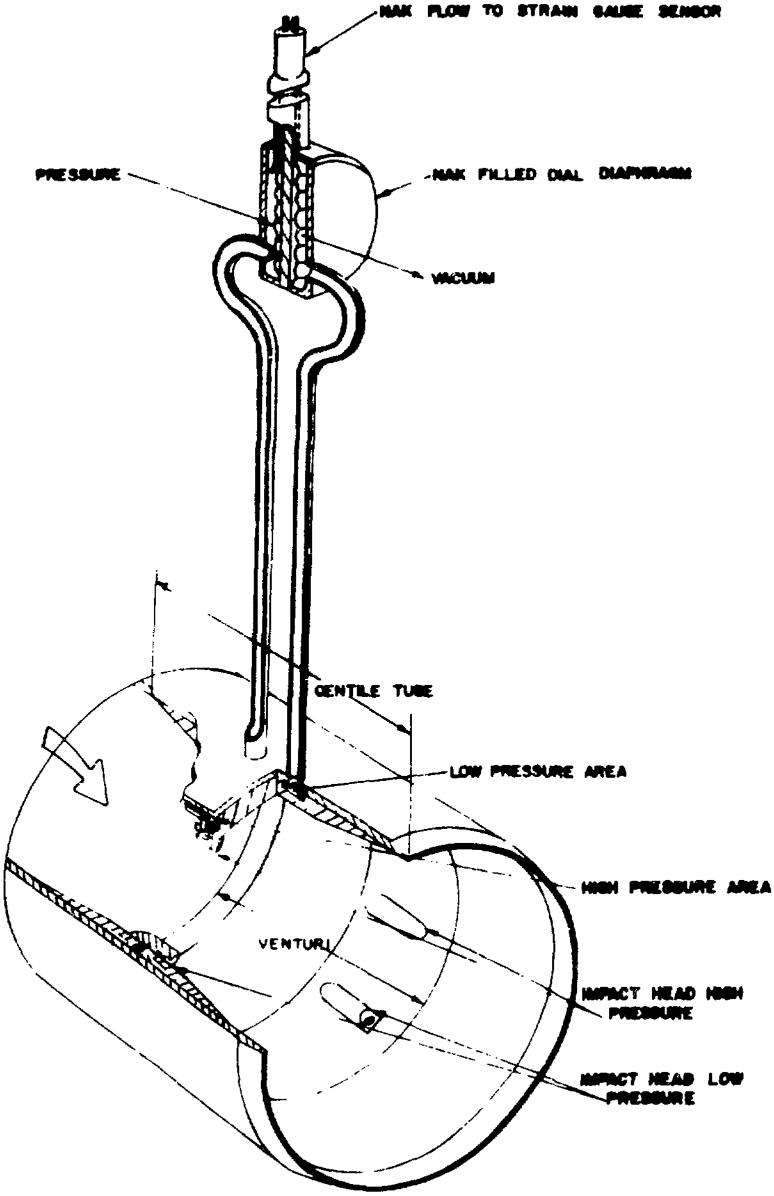

Fig. 6 ΔP FLOWMETERS FOR LARGE PIPING IN SODIUM SYSTEMS

Sharp-edge orifice plate flowmeters are attractive because their weight is low and they are relatively easy to install or replace. However, erosion of the edge can be a problem; this erosion results in a change of calibration of the flowmeters through at least the initial period of plant operation. They also cause large pressure drops in the flow circuit. They are not, therefore, extensively used.

Magnetic flowmeters take advantage of the electrical conductivity of sodium. They are attractive because their range and linearity are excellent, and their impact on the piping is minimal. However, they cannot be precalibrated in a water system. The sensor leads must be insulated from the surrounding sodium if submerged in a pool system, and these leads are affected by changes in sodium temperature. Also, they will not work with magnetic metals for piping.

The simplest is the permanent-magnet flowmeter. Its operation is based on the fact that sodium (as an electrical conducter) produces an electric potential when moving across the magnetic field produced by a magnet located on the periphery of the pipe. (See Fig. 7.) (A good discussion of the theory of magnetic-flowmeter operation is given in Ref. 1.) The voltage generated is directly proportional to the velocity of the sodium and is therefore a measure of flow rate.

The magnetic field can be generated by either permanent or electomagnets. Permanent-magnet flowmeters have been used successfully in most of the LMFBR's now in operation or proposed. These flowmeters are not suitable for use in regions of high radiation because of damage to the magnets.

Another magnetic flowmeter which has gained some attention, and which avoids the installation of heavy permanent magnets, is an electromagnetic flowmeter commonly called saddle-coil flowmeter. As with a permanent magnet flowmeter, the electromagnet is mounted in the outside of the pipe.[1] The saddle-coil flowmeter has the advantage of being somewhat lighter than permanent magnet flowmeters but is not as suitable for remote locations.

Another type of magnetic flowmeter, the eddy-current flowmeter, is of special interest because of its small size, ability to withstand high temperature, and resistance to radiation damage. These characteristics make the eddy-current flowmeter potentially useful for such applications as monitoring flow in individual fueled subassemblies. However, this flowmeter is also highly sensitive to flow turbulence and exhibits some drift in signal with time. Eddy-current flowmeters are now in use at EBR-II, where they measure flow at the outlet of test subassemblies in a special in-core test facility. (See Fig. 8.)

A typical eddy-current flowmeter is made up of three coaxial coils formed on a metallic spool and enclosed in a tube placed axially along the flow path. The center coil forms the primary or excitation coil, and the two coils on either side of the primary coil form the secondary or

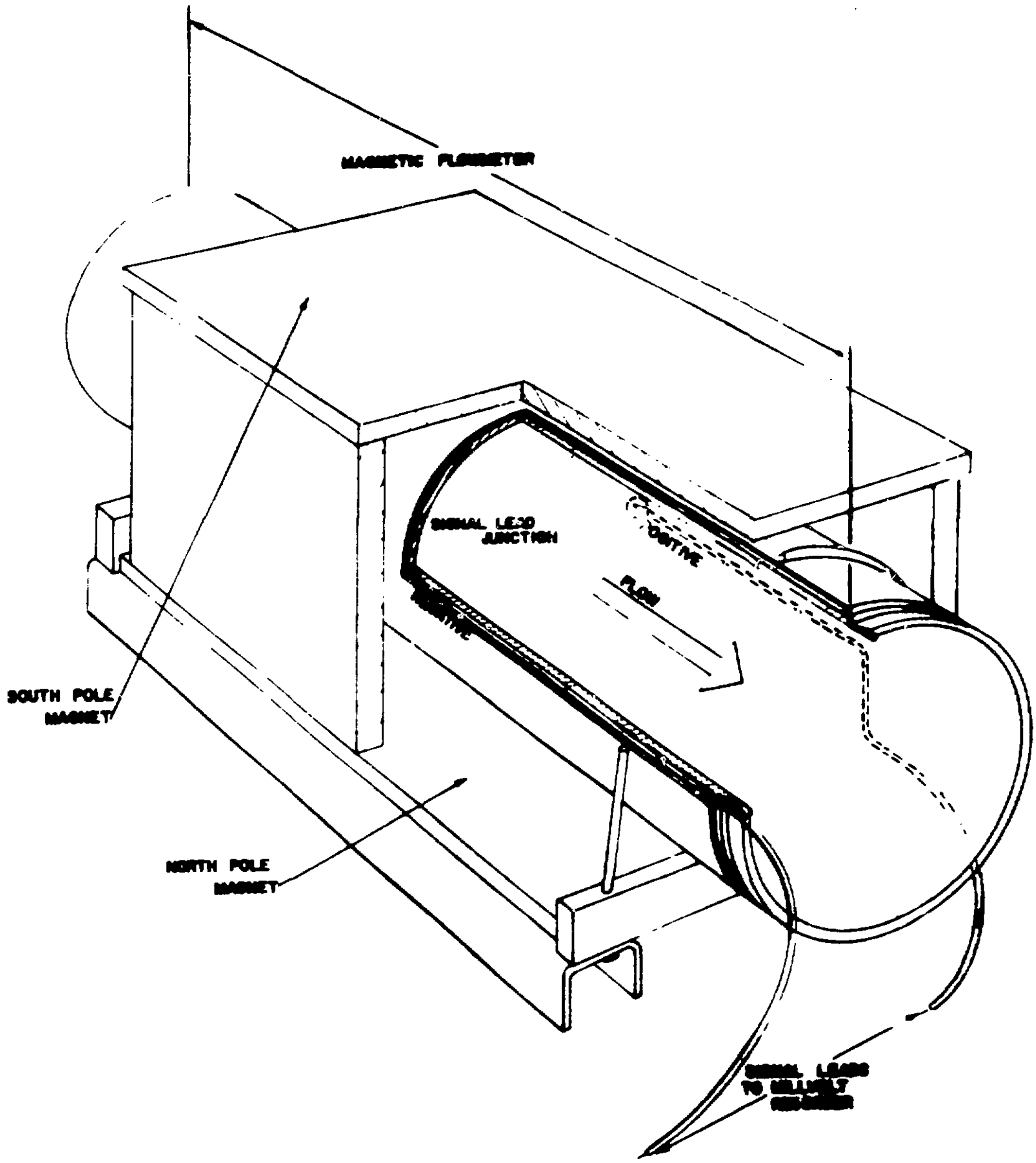

Fig. 7 TYPICAL PERMANENT MAGNET FLOWMETER

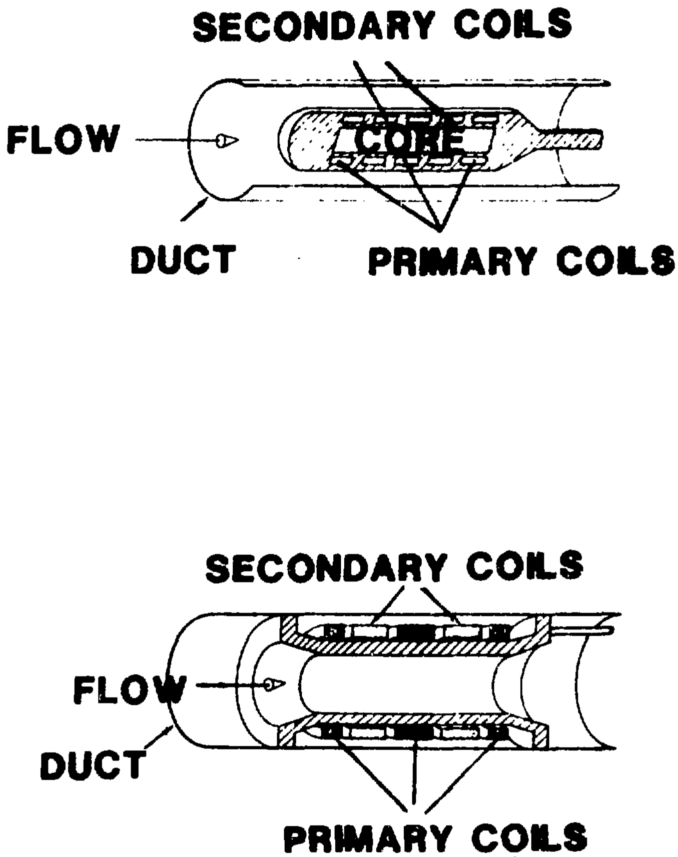

Fig. 8 TWO TYPES OF EDDY CURRENT FLOWMETERS

pickup coils;[3] this flowmeter operates much like a transformer; the primary coil is excited by a high-frequency, low-voltage signal, which induces current in the secondary coils. The magnetic field produced by the primary coil, however, interacts with the moving stream of sodium; this interaction produces electrical eddy-currents, which affect the magnetic field of the primary coil and cause unequal coupling of the two secondary coils. This unequal coupling produces a signal voltage at the output of the two secondary coils.

A disadvantage of the eddy-current flowmeter is that it must be installed in the flow stream and is very sensitive to flow behavior at the immediate surface of the flowmeter, giving essentially a point measurement of flow in the pipe. This flowmeter must be carefully calibrated. However, eddy-current flowmeters have been used in a number of applications with good success. An example at EBR-II is in the measurement of flow in a special fuel test facility shown in Fig. 9.

The ultrasonic flowmeter is another type that offers some significant advantages in LMFBR's.[11] This flowmeter depends on measurement of the velocity of acoustic pulses between two transducers. The major benefits of the ultrasonic flowmeter are stability, capability for self-checking, and fail-safe operation. (The flow signal goes to zero for failure of the transducers or related electronics.)

The ultrasonic flowmeter has been used for some time to measure water flow, particularly in open channels. Its basic configuration is shown in Fig. 10. In the simplest form, two transducers are fixed to the outside of a pipe, placed on opposite sides and separated along the axis of the pipe. Another option is to provide a probe within a pipe with transducers located along the axis of the flow stream. The time of travel of acoustic pulses between transducers is changed by the velocity of the flowing sodium, being a function of the sonic velocity in the sodium and the fluid velocity along the path of transmission. When on the outside of the pipe, the transducers are diametrically opposed in order to provide an integration of flow. (Some applications use multiple passes of signals to facilitate integration of the flow signal.) A typical design for a transducer is shown in Fig. 11.

One of the more successful techniques for measuring time-of-flight flow has been pulsed-neutron activation (PNA).[12,13] This technique is basically an extension of radioisotopic tracer techniques that have been in use for many years and is especially attractive because it is an "absolute" measurement (not requiring flow calibration) and requires no penetration of the piping.

As the name implies, a pulsed-neutron source is used to activate nuclei in the fluid, and these are subsequently detected downstream. A weighted transit time is developed to combine with the measured distance between the activation site and the detection site; this provides a mean fluid velocity. Several measurements of sodium and water flow have been made at EBR-II to test and use the technique. Water flows have been

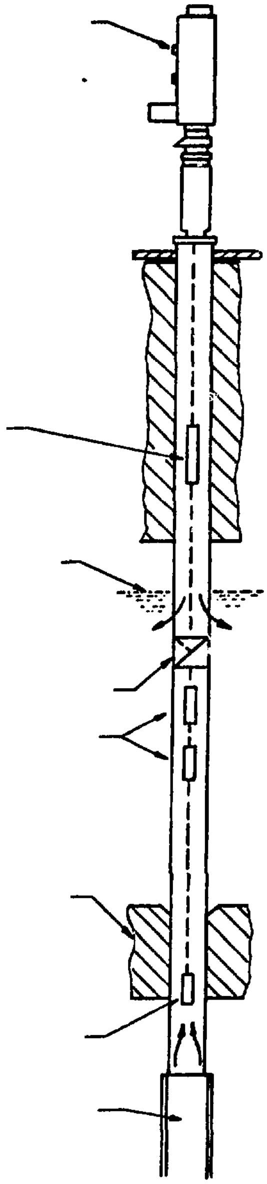

Fig. 9 Schematic of the Fuel Performance Test Facility in EBR-II

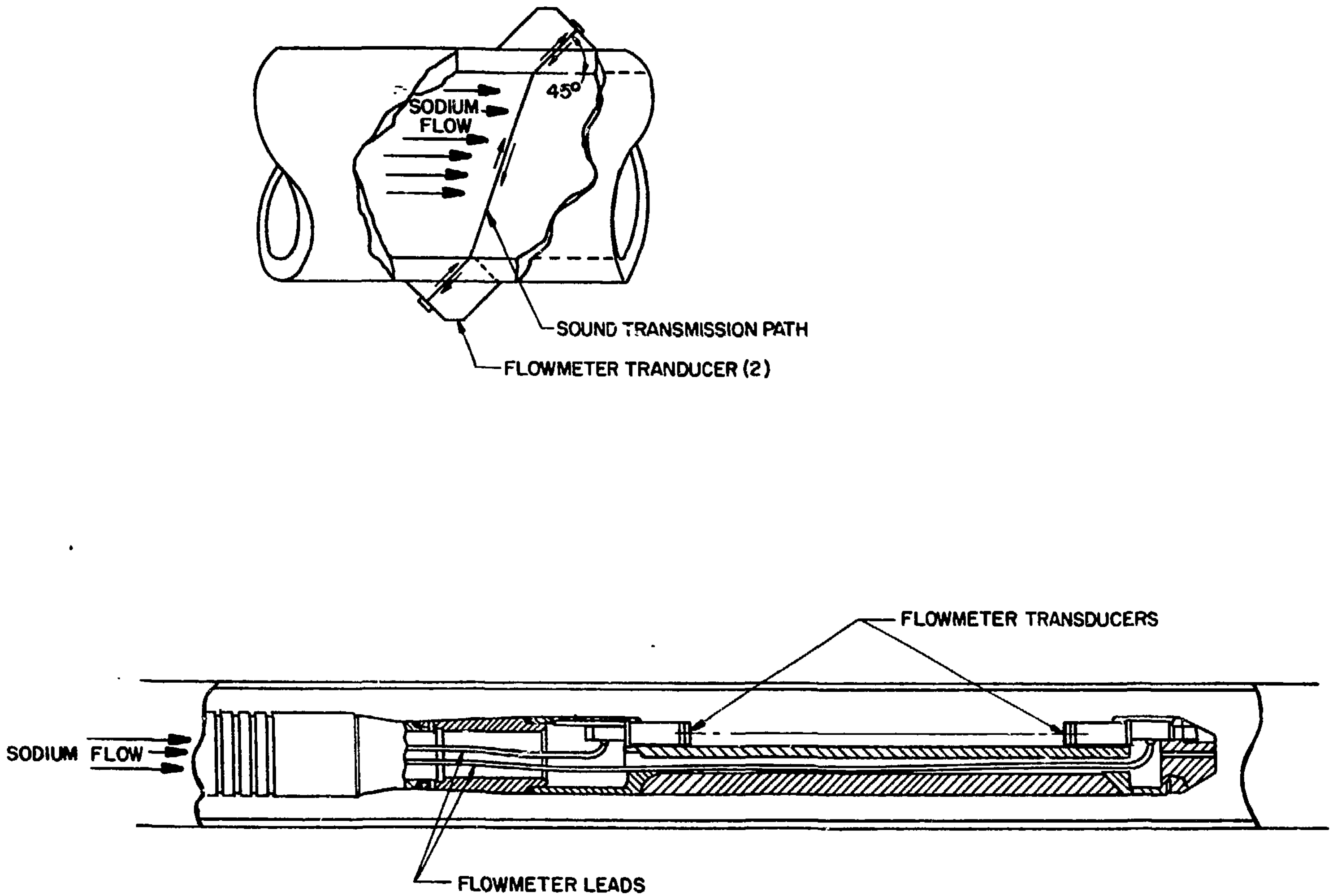

Fig. 10 Two Arrangements for Ultrasonic Flowmeters

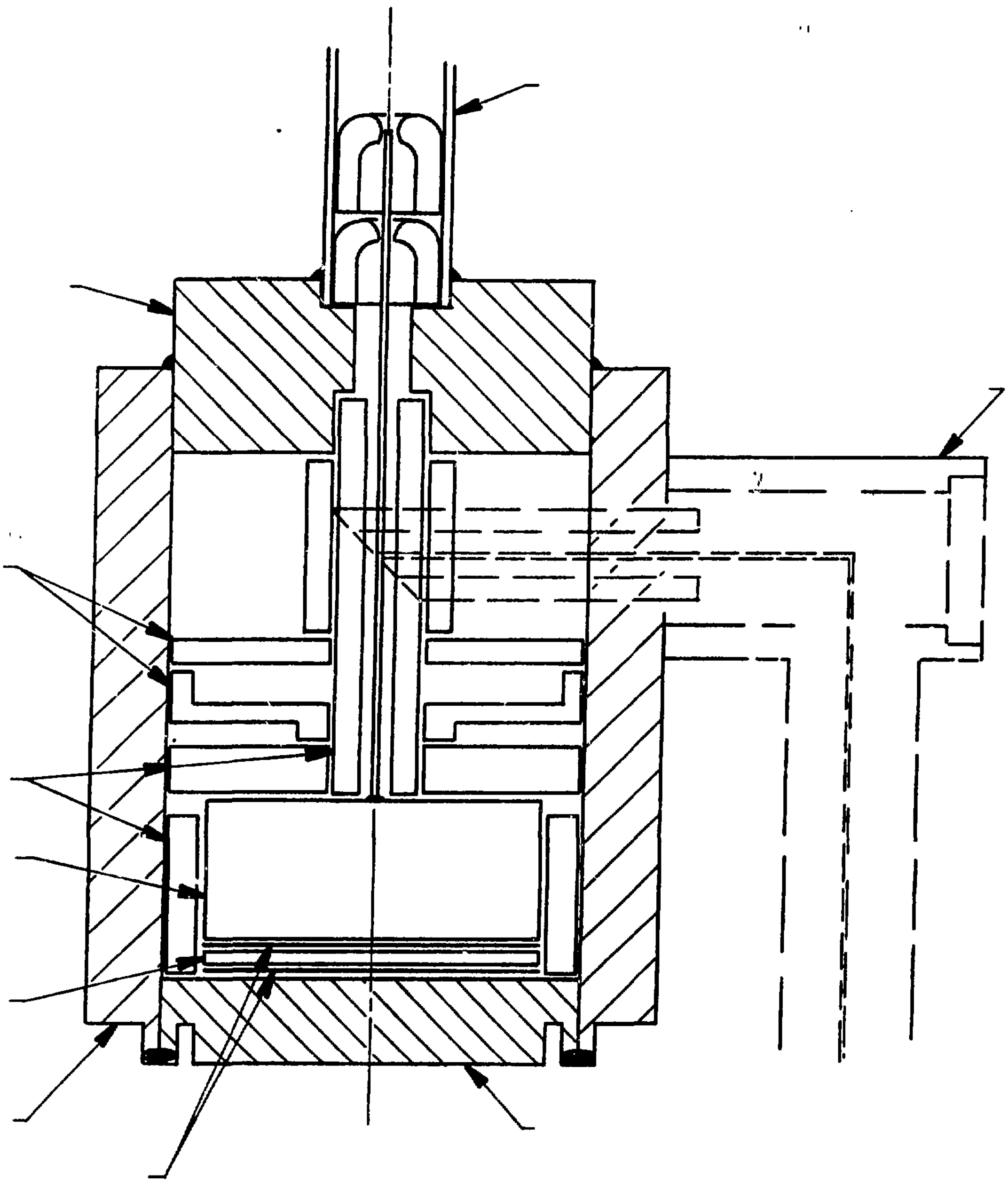

Fig. 11 Typical Transducer Concept for In-sodium Ultrasonic Transducers (courtesy, G. Forster)

measured in the steam system and sodium flow in the intermediate heat-transport system, all with good success.

The instrumentation used for the PNA experiment consists of a gamma-ray detection system, a multiscaler, a pulsed neutron source, and a timing system. A block diagram of the instrumentation system is shown in Fig. 12. The multiscaler provides upper- and lower-level discriminators for rejection of unwanted gamma rays. Timing for the entire system is provided by two pulse generators; this timing allows repetitive pulsing of the systems so that a number of pulses can be used at a selected flow level to improve the counting statistics for the measurement.

The data from the PNA measurement for turbulent flow are reduced using the working relation for the mean reciprocal time

$$1/t = \frac{\sum_{i=1}^{I} \frac{1}{t_i} C(t_i) \exp(\lambda t_i)}{\sum_{i=1}^{I} C(t_i) \exp(\lambda t_i)}$$

where $C(t_i)$ is the number of counts in a multiscaler channel at time t_i. Errors resulting from this technique are found to be in the range of 0.5 to 1.0%.

There has been considerable LMFBR operating experience with most of the above flowmeter types. The French LMFBR Phenix uses small permanent-magnet flowmeters in a bypass line at the outlet of the primary pumps to measure total flow. However, plant control is on the basis of pump speed. Also, the Soviet Union uses permanent magnets in its largest LMFBR (BN-600) to measure primary flow. In the British reactor PFR, eddy-current flowmeters were initally installed in thimbles in the main primary system pipes, but many of these have failed. Saddle coil electromagnetic flowmeters are used in the IHTS in this reactor.

The loop plants likewise have emphasized the use of permanent-magnet flowmeters. The U.S. plants, FFTF and CRBR, and the German plant SNR 300 use permanent-magnet flowmeters in both the PHTTS and IHTS, and venturis are installed in the IHTS for flow calibration. The FFTF flowmeters were calibrated in place with pulsed-neutron activation, as were the EBR-II flowmeters in the IHTS.

The Japanese use an electromagnetic flowmeter in the primary-sodium system for the JOYO plant. For their next plant, MONJU, they are considering the use of ultrasonic flowmeters.

The PNA technique was used very successfully to calibrate in-place flowmeters in the U.S. At EBR-II, the PNA method was used to measure the secondary-sodium flow at seven different flow levels. Normally,

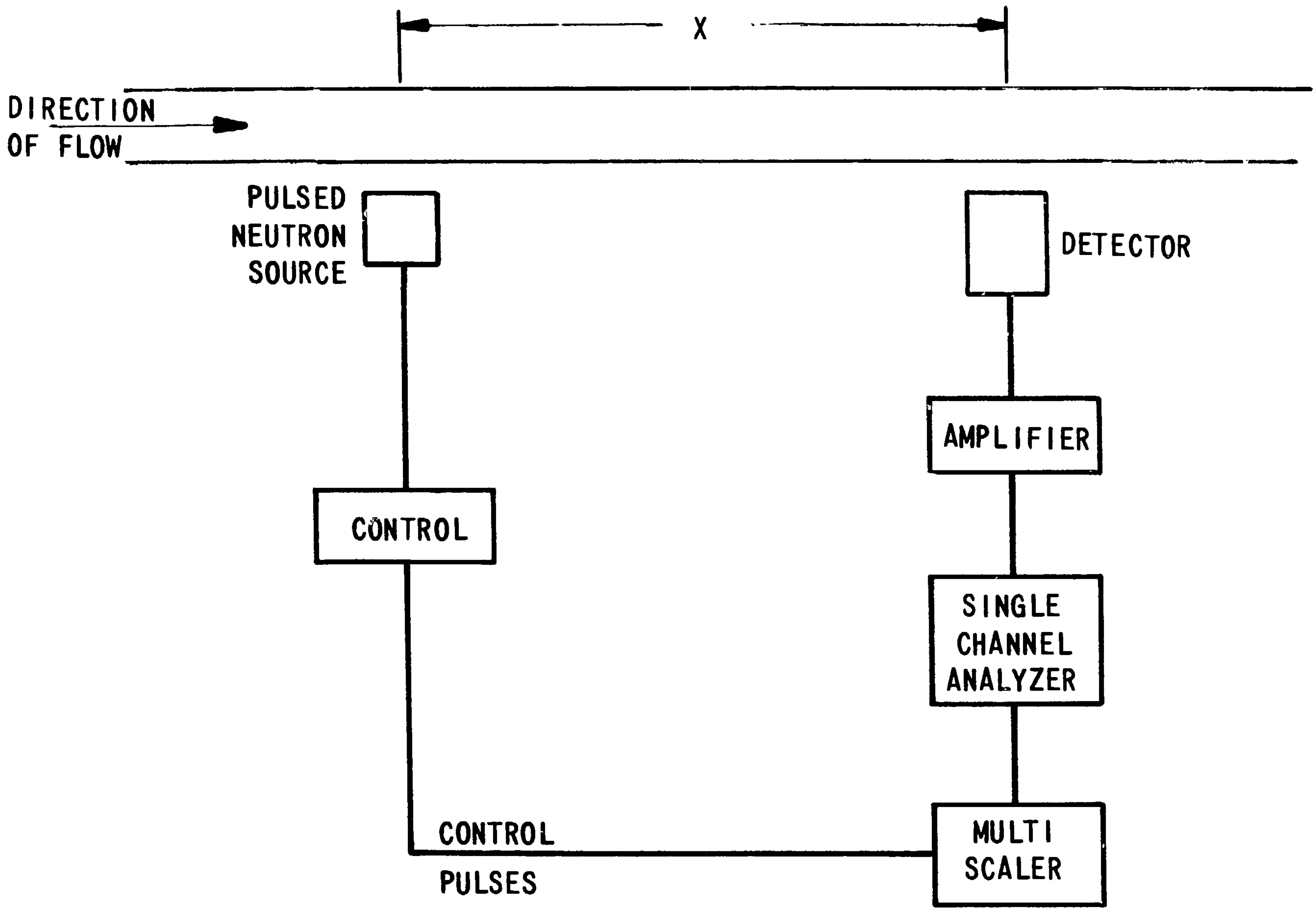

FIG. 12 BLOCK DIAGRAM OF PULSED NEUTRON FLOW MEASURING SYSTEM

the ΔP flowmeter in the secondary sodium system provides the flow indication against which the electromagnetic flowmeter is calibrated (at the 80% flow level); the nominal secondary flow during full-power plant operation is ~38%. After calibration, all operation of the secondary-sodium system is based on the flow-level indication from the electromagnetic flowmeter. Figure 13 shows a typical count history for the secondary-flow measurement. Table I displays the data for the Foster and electromagnetic flowmeter compare to the PNA results at EBR-II. The relatively low uncertainties in flow may be seen.

3. MONITORING FLOW AND TEMPERATURE IN INDIVIDUAL FUEL SUBASSEMBLIES

The LMFBR community has given much attention to thermal-hydraulic monitoring of individual fueled subassemblies.[4,14,15] Of interest are temperature, flow, and acoustic measurements to verify that no local disruption of flow is occurring. This has been an important consideration for reactor safety ever since the flow blockage and melting of fuel occurred in some subassemblies of the FERMI reactor. However, safety experiments conducted over the last 10 years have lessened concerns over this question, showing that local failures within subassemblies will not propagate to surrounding subassemblies.

3.1 Subassembly Temperature Monitoring

Monitoring the outlet-sodium temperature of fuel subassemblies is reasonably easy and is a standard feature of most LMFBR plant designs. Typically, thermocouples are chromel-alumel and are located in wells 2 to 4 cm above the outlet of individual subassemblies. These wells can either be dry (filled with argon of helium gas) or wet (filled with sodium). Wet thermocouple wells have the advantage of improved response time (thermal time constants of between 0.5 and 1.5 s) but are much more difficult to replace because of contamination by sodium.

When a flow blockage occurs, the decrease in flow causes an increase in the subassembly's sodium-outlet temperature. However, this increase in temperature may be hidden by flow from surrounding subassemblies because cross flow influences the temperature reading. This, coupled with the fact that a "significant" flow blockage can occur with only a moderate rise in measured outlet temperature, limits the value of the sodium-outlet temperature as an indicator of flow blockage in a subassembly. For example, a nonporous planar blockage at the midplane of a subassembly fuel bundle would reduce subassembly flow by only approximately 5%, too small to be reliably detected by a change in outlet temperature. Instead, much attention has been given to temperature noise, which is increased with the turbulent flow associated with a partial flow blockage. Several theoretical models have been advanced to predict the magnitude and character of temperature noise in single phase fluids. Also, a number of out-of-reactor tests have been conducted to measure temperature noise, and agreement between theory and test results

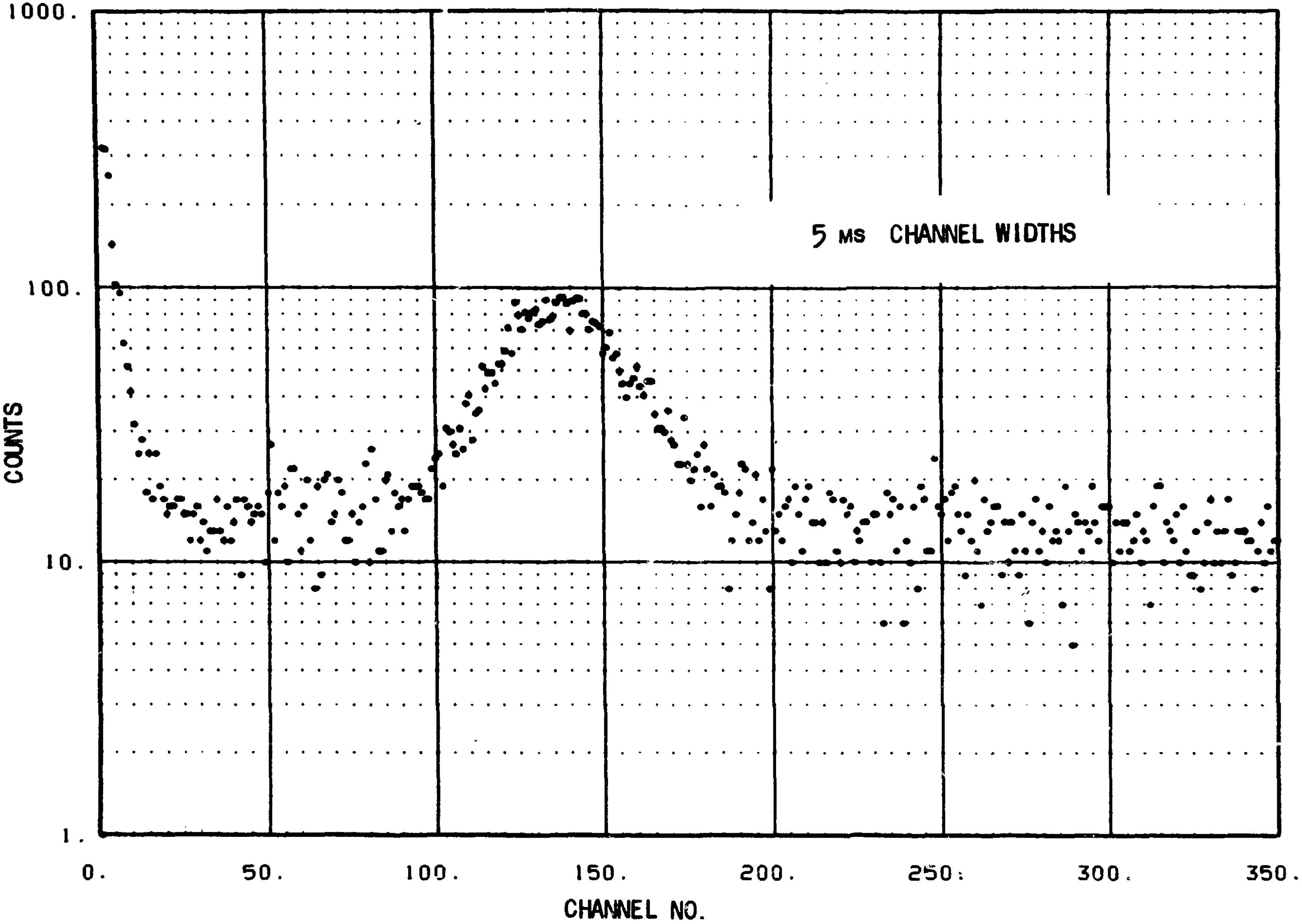

Fig. 13 Multiscaler Data from Measurements of Secondary Sodium with Flow Level at Nominal 90% of Full Flow

Table I (From Ref. 13)

Flow Rates of Secondary-Sodium System in EBR-II
(Sodium at 577 K)

Nominal Secondary-Sodium System Flow Level (%)	Flow Rate (m^3/s)			Relative Neutron Generator Output[c]	PNA Flow Velocity (m/s)	Uncertainty (%)
	EM Flowmeter[a]	Foster Flowmeter[b]	PNA			
0	0.0	0.0	0.0	0.0	0.0	---
10	0.0382	0.0398	0.0390	1.057	0.496	3.3
20	0.0752	0.0759	0.0770	1.029	0.980	2.1
40	0.1497	0.1457	0.1457	0.950	1.940	2.1
60	0.2253	0.2189	0.2320	0.972	2.952	2.1
80	0.3009	0.2982	0.3136	1.029[d]	3.990	2.0
90	0.3376	0.3397	0.3595	1.017	4.575	1.9
95	0.3565	0.3606	0.3830	0.984	4.874	1.9

[a]Determined from: flow = 0.006765 x mV from Table V.

[b]Determined from: flow = 0.2890 x voltage of Table V.

[c]Sum of output monitor indications divided by total number of pulses normalized to the average level of 5.092 per pulse.

[d]Voltage on neutron generator increased at this point for the rest of the test.

has been reasonably good.[3,25,26] (See Fig. 14.) Because of the high frequency of the temperature noise, however, fast-response thermocouples (time constants of 200 ms or less) are required for the reliable measurement of temperature noise associated with partial flow blockage. It is not clear that such thermocouples can be developed for routine use in commercial LMFBR's.

As the extent of flow blockage increases, the measured sodium-outlet temperature may actually drop and temperature noise may decrease because of mixing with flow from surrounding subassemblies. The measurement of sodium-outlet temperature in subassmeblies is, therefore, of limited value for indicating extensive flow blockage, although it can be reliable during the early stages of flow blockage formation.

As noted above, in order to detect temperature noise, it is necessary to provide thermocouples with very short time constants (200 ms or less). Typical chromel-alumel thermocouples have time constants in the range of 5-10 s in dry wells and 0.5 to 1.0 s in wet (sodium-filled) wells.[3] Special designs, such as the "coaxial" thermocouple developed in the UK, can result in time constants for wetted thermocouples in the 40-5 oms range.[16]

Sodium-outlet thermocouples for subassemblies in the Super-Phenix reactor are of two types; these are (1) replaceable conventional thermocouples in dry wells of special designs which should result in time constants of ∿2.5 s and (2) two intrinsic sodium/steel thermocouples with time constants on the order of ∿1 ms. The performance record of the chromel-alumel thermocouples has been good, but the intrinsic sodium/steel thermocouples have not been extensively used.

3.2 Acoustic Monitoring

Because of the difficulty of reliably detecting serious flow blockage or local sodium boiling with outlet thermocouples, attention has been directed to the use of individual flowmeters in subassemblies and the use of acoustic sensors to detect boiling.[6,17] A major problem with using acoustic sensors to detect boiling in an LMFBR system is the prediction of the acoustic coupling between the source of the noise and the detector. Also, the strength and character of the signal itself is sensitive to many details of the boiling process (such as dimensions of the sodium-vapor bubbles, degree of subcooling, size of subassembly). To detect boiling accurately also requires a system with relatively low background noise.

Establishing the feasibility of acoustic monitoring to detect in-subassembly boiling requires in-reactor experiments to characterize background noise, as have been conducted at the PFR, EBR-II, and elsewhere.[17] Results from boiling experiments indicate an optimum detection bandwidth of from 80 to 300 kHz. A problem is that cavitation from pumps can generate an acoustic signal very similar to that associated with boiling; this problem must be precluded in pump design.

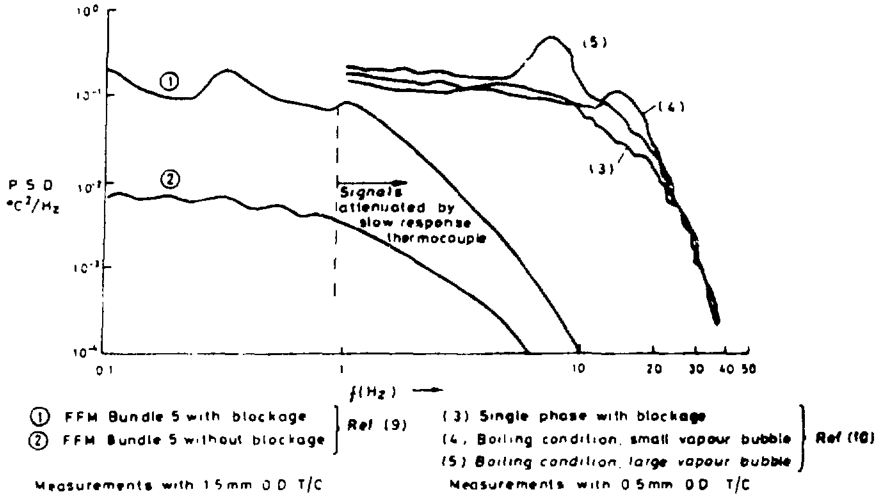

Fig. 14 POWER SPECTRAL DENSITIES OF TEMPERATURE NOISE OBTAINED DURING OUT-OF-PILE BLOCKAGE EXPERIMENTS USING TWO THERMOCOUPLE DESIGNS (from ref. 3)

Early efforts in acoustic monitoring attempted to adapt low-temperature acoustic sensors to LMFBR application through the use of wave guides. Unfortunately, the wave guides distort the frequency spectrum and tend to enhance the background noise of the reactor (because of mechanical coupling with structures). The more recent development and testing of high-temperature monitors has alleviated this problem. At EBR-II, acoustic monitors using lithium niobate transducers have been tested and used productively in mechanical operations with the core.

Lithium niobate ($LiNbO_3$) piezoelectric devices are suitable for liquid sodium use primarily because of their capability to withstand high temperature. However, these are vulnerable to loss of oxygen to the sodium over time and either must be supplied a source of oxygen, Fig. 11, (via a capillary tube) or by careful encapsulation in a noble metal such as platinum. The most common approach is to provide oxygen via a capillary tube.

3.3 Passive Measurement of Subassembly Temperature

Another aspect of LMFBR instrumentation that is the in-core measurement of subassembly temperature by passive means. One of the most successful techniques involves the use of a thermal-expansion- difference temperature monitor (TED).[18] A TED, basically a small capsule filled with sodium, is plastically deformed as the sodium temperature increases (Fig. 15) because the thermal-expansion coefficient of sodium is greater than that of the stainless steel of the capsule. The TED can be calibrated quite accurately out-of-core by measuring its change in volume as a function of temperature. Using TED's, temperature distributions in individual fuel subassemblies and across the core can be measured to within ± 5°C.

An important modification of this device is a gamma-expansion-difference monitor (GEDM)[19] which measures the rates of heat deposition by gamma rays. These measurements are important for assessing the heat load on structural components in the core and for interpreting the results of irradiating structural materials. The GEDM is essentially a TED with a gamma-absorbing material within it. (See Fig. 16.) If the heat-transfer characteristics of the device are known, the rate of gamma-energy deposition can be determined from the temperature of the device. The maximum temperature the GEDM experiences in the reactor core is directly related to its measured volume change, in the same way as the TED's.

4. PRESSURE MEASUREMENT INSTRUMENTS

Because of the use of liquid metals as heat transfer media is rare in industrial applications, standard instruments for these systems are not available as off-the-shelf items. In some instances, existing instrument designs have been modified for use in liquid metal systems; in other instances, the unique properties of liquid metals have been used to develop new types of instruments.

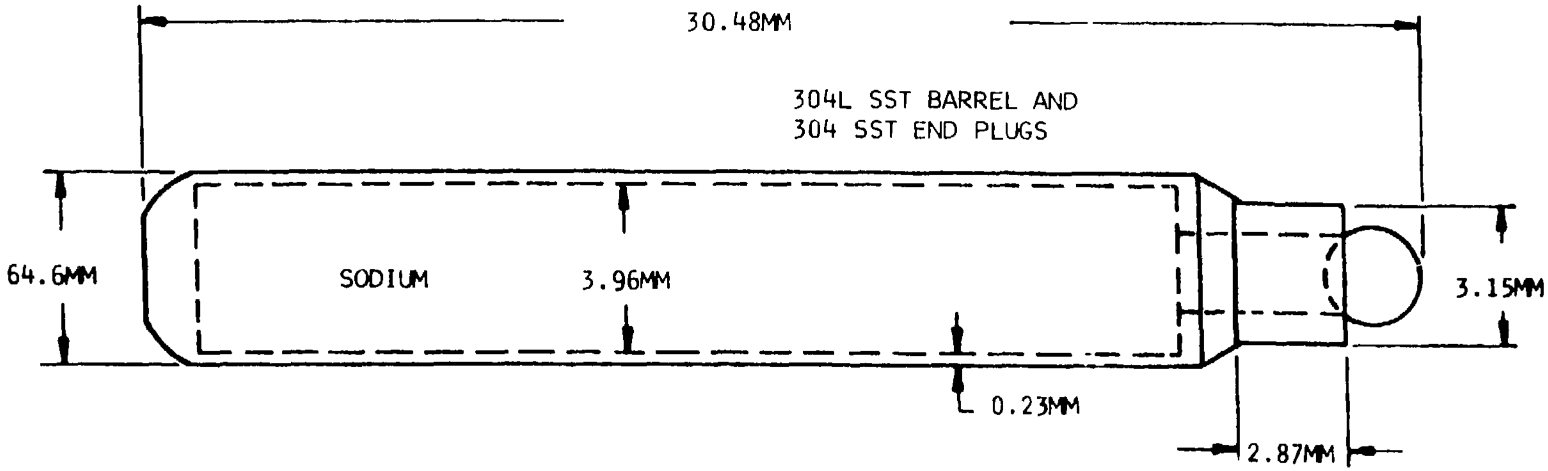

Fig. 15 A TYPICAL EXPANSION DIFFERENCE (TED) TEMPERATURE MONITOR USED AT EBR-II

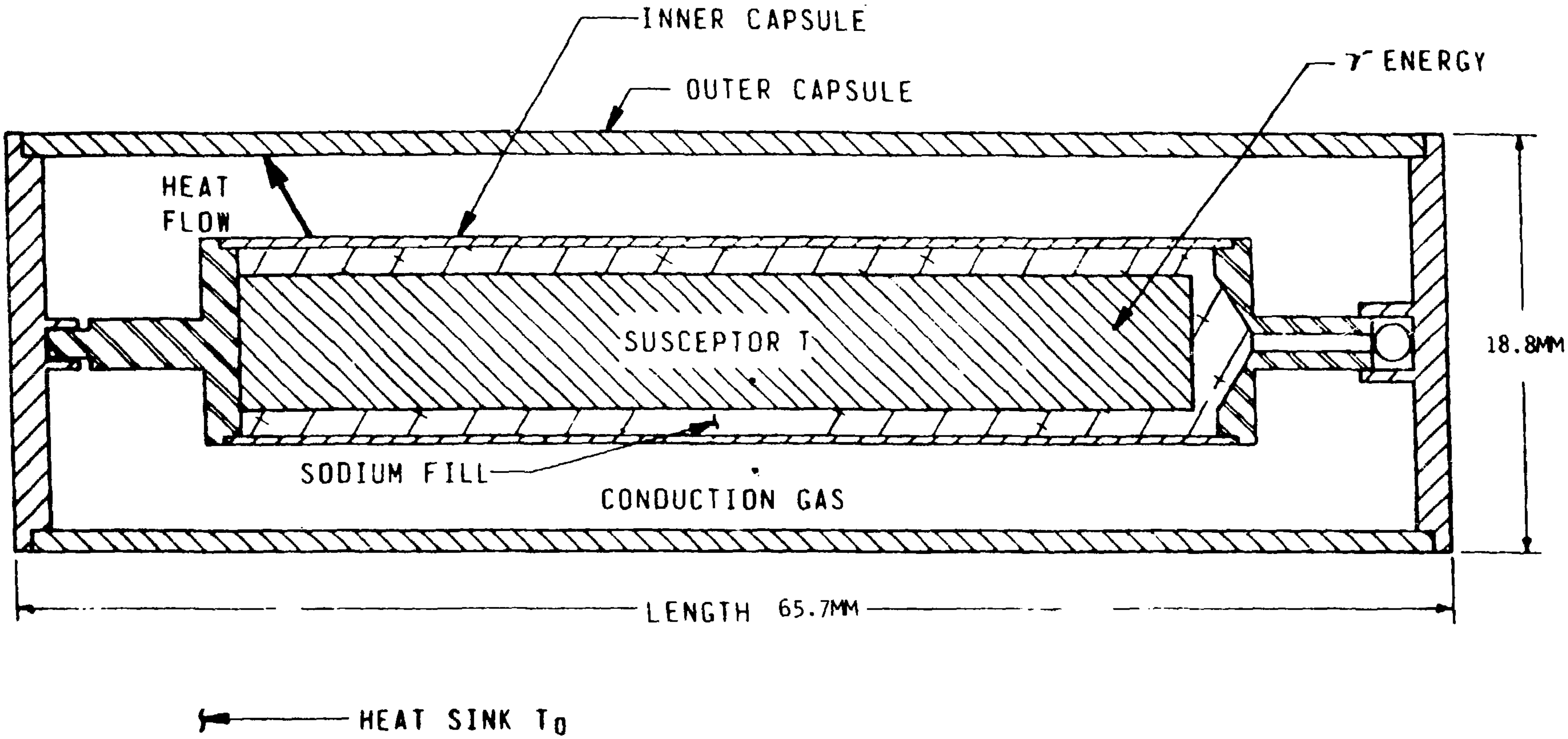

Fig. 16 A TYPICAL GAMMA EXPANSION DIFFERENCE MONITOR (GEDM) USED AT EBR-II

There are three main types of eleastic pressure elements: (1) metallic diaphragm, (2) bellows, and (3) bourdon tube. A metallic diaphragm element is primarily a device for measuring relatively wide pressure ranges, minimum range 0 to 0.0072 psig, maximum range 0 to 400 psig. The diaphragm consists of one or several capsules rigidly connected together, so that when pressurized each capsule deflects. Metallic diaphragms are used in many industrial pressure-measuring instruments, such as differential-pressure cells and pressure gauges.

The bellows element is a one-piece expandable and collapsible element. It is usually formed in one continuous operation from a thin seamless tube into a deeply folded or corrugated seamless unit by either a hydraulic or mechanical method. The bellows element is usually used in applications where a little wider and higher range is required. Minimum range 0 to 0.18 psig, maximum range 0 to 800 psig. The bellows can be used for applications similar to those for diaphragm elements, such as pressure gauges and differential-pressure gauges. The most common use in this area is in pneumatic miniature-recorders and pressure-switches.

The bourdon tube can be described as a flattened tube bent into an arc and closed at one end. When pressure is applied at the open and stationary end, it tends to cause the flattened tube to become circular. This in turn tends to straighten out the tube and in so doing moves the free end an amount proportional to the pressure applied. The bourdon tube can be used in many pressure measuring instruments that require a wide range at high pressure. The minimum range is 0 to 12 psig, and the maximum range of 0 to 100,000 psig. Many combinations of the bourdon principle are used in industrial instrumentation. They will most commonly be seen in high-pressure gauges and high-pressure switches where the movement of the free end activates a microswitch.

Disadvantages of NaK-filled pressure transducers are the difficult installation caused by the one-piece unit, and the instability of the electrical strain gauge. Strain gauges are sensitive to temperature changes and drift over long periods of time. These characteristics make frequent recalibration necessary. However, because of the very small displacement of NaK in this system, the pressure instruments are capable of very high degrees of accuracy; accuracy is approximately 1% of full-scale deflection.

5. INSTRUMENTATION FOR REACTOR SAFETY SYSTEMS

Protection of the core from damage in response to plant transients is the goal of the reactor safety system. The task is to detect first an event with the potential for damaging the core and then to take protective action, which may include shutting down the reactor and ensuring continued rejection of decay heat.

Summarized in Table II is an approach to the design of the Commercial Demonstration Fast Reactor (CDFR) Safety System, a U.K. design (from Ref. 2.0). This approach builds on the very favorable experience of the Prototype Fast Reactor (PFR) at Dounreay. The sensor inputs for reactor shutdown are: (1) High Power Flux, (2) Rate-of-Change of Core Flow, (3) Core Outlet Temperature, (4) Primary Pump Speed, (5) Undervoltage to Primary Pumps, (6) Secondary Pump Speed, (7) Excess Reactivity, (8) Core Outlet Temperature, (9) High Delayed Neutron Signal, (10) Individual Subassembly Outlet Temperature, (11) Acoustic Boiling Noise, (12) Level of Sodium in the Primary Tank, and (13) Reactor Power-to-Flow Ratio.

Scram-initiation criteria for the French LMFBR Super-Phenix are shown in Table III (from Ref. 21).

Signals for low coolant flow come from a permanent-magnet flowmeter at the outlet of the primary pumps. Subassembly-outlet temperature trips are associated with two chromel/alumel thermocouples per subassembly.

The EBR-II reactor-shutdown system is of interest because of the extensive experience with the system and the evolution in its design that has taken place since 1969. Changes were made both to simplify the shutdown system and to accommodate the failure of several flowmeters in the primary flow circuit.[22] Reactor trips deleted from the shutdown system were (1) high temperature in nuclear-instrument thimble, (2) isolation of the reactor building, (3) malfunction of primary pumps, (4) high delayed-neutron signal, (5) high or low bulk-sodium level, (6) high cover gas pressure or temperature, and (7) high reactor-inlet temperature. These events either did not endanger the reactor-allow time for corrective action without the response of the automatic safety system or were protected against other functions in the safety system. The present EBR-II safety system functions are listed in Table IV.

6. STEAM GENERATOR INSTRUMENTATION

LMFBR steam generators must be designed to ensure the complete separation of sodium and water. However, if leaks do occur, they must be detected as early as possible to avoid further damage. Two primary means of detecting such leaks have been pursued; these are the acoustic detection of leaks and the detection of the hydrogen and oxygen that results from the sodium-water reaction. Of these, hydrogen-leak detection has been the most successful and has gained the widest application. An example of the performance of this method is in the detection of the recent series of small steam-generator leaks at the French plant Phenix; all these leaks were reliably detected with hydrogen-leak detectors.

The hydrogen-leak detectors work by the diffusion of hydrogen through a nickel membrane to a detector, which is commonly an ion pump that maintains a vacuum in the system. (See Fig. 17). The hydrogen-leak detector system at EBR-II consists of a sodium-piping system that draws

TABLE II: APPROACH TO SAFETY SYSTEM DESIGN FOR THE CDR

	Trip Initiation	
Incident	Subsystem A	Subsystem B
Loss of electrical power supplies to all primary pumps	Primary pump speed low High rate of change of core flow High Flux/flow ratio High core outlet temp. Power deviation	Primary pump bus bar under voltage. High core outlet temp.
Failure of a coolant duct (Step of 60% reduction in flow)	Power deviation High rate of change in core flow High core outlet temp. High flux flow ratio	High core outlet temp.
Operating rod runaway at reactor startup (Ramp of reactivity of 6×10^{4} $\Delta K/K$ per second at zero power and 20% flow)	Power deviation High core outlet temp.	Flux inverse period LP/IP flux count High core outlet temp.
Error during refueling removal of absorber rod from a near critical reactor	Inverse period Fuel movement Monitoring system	Subcritical LP/IP flux count Flux inverse period

TABLE III: LIST OF SCRAM INITIATION CRITERIA FOR SUPER PHENIX

Initiation Criteria	Sensor
1. Low-range nuclear	Helium-filled radiation counter tube
- High flux trip - Low period	
2. Power-range nuclear - Log range . High flux trip . Low period	Fission chamber
- Linear range . High flux trip . Negative reactivity insertion . Positive reactivity insertion	
3. Primary-pump trip (4 pumps)	Current detection (on each of 3 phases)
4. Reactor flux/Primary flow (P/Q)	Flux: See 3 Magnetic flowmeter
5. Core-inlet temperature (Primary-pump outlet temperature)	Thermocouple
6. Loss of electric power (two buses by channel group)	Undervoltage relay
7. γ activity	Ion chamber
8. Detection of fuel-cladding failure	Helium-filled radiation counter tube
9. Earthquake	Speed and acceleration detection
10. Others	Computer
- High core-inlet temperature	Thermocouple
- Detection of cooling malfunction (by subassemblies group)	
- High fuel-cladding temperature	Thermocouple

TABLE IV: EBR-II Reactor Shutdown System (RSS)

Function	Instrument
Seismic Event	Earthquake detector, Vertical and horizontal motion
Flux level high	Fission chambers
Short period	Fission chambers
Subassembly outlet Temperature high	Subassembly outlet Thermocouples
Primary-coolant flow low	Flowmeters Pressure sensors Pump undervoltage
Reactor building Radiation level high	Compensated ion chamber

sodium past a nickel membrane, a leak-detector system, and the associated electronics and controls.[23] The detection system requires only one penetration into the sodium pipe and is located within the EBR-II steam generating system as shown in Fig. 18.

The rate of diffusion of hydrogen across the membrane is affected by the sodium temperature, which must be controlled if reliable results are to be obtained. (Temperatures are maintained at 735°K). The nickel membrane is 0.25 in. (6.35 mm) thick and the ion pump maintains a vacuum of 10^{-6} to 10^{-8} torr. The most critical mechanical feature of design is the weld of the nickel membrane to the inconel transition piece and the inconel to the stainless steel piping. The early experience with these detectors at EBR-II was poor, with leaks occurring at the weld of the transition piece to the stainless steel. That problem has been corrected, however, and the units have operated very reliably since 1976. They are a standard feature of EBR-II's operating instrumentation, providing alarm for operation action in the event of a leak in the EBR-II steam-generating system. No such leaks have occurred in EBR-II's 19 years of operation.

The response time of hydrogen-leak detectors is relatively fast, depending on hydrogen concentration (related to the size of the leak), location of a leak, and velocity of the flowing sodium. For EBR-II, calculated response times (considering small or moderate leaks) range from 30 s to several minutes. There has been no experimental verification of calculated response times, although such tests could conceivably be conducted by injecting a small amount of water into the sodium stream.

The experience of these detectors at EBR-II and similar systems at other LMFBR's gives confidence in the ability to reliably detect sodium or water leakage in time to avoid extensive damage. An interesting proposal to detect leakage of either sodium or water before they come in contact is to provide duplex tubes (one tube within the other) and flooding the interface with helium. Sodium vapor or steam could be detected if it migrated from either side by monitoring the helium.

7. MEASUREMENT OF IMPURITIES IN SODIUM HEAT TRANSPORT CIRCUITS

As mentioned earlier, the measurement of impurities in sodium heat-transport circuits is important because of the potential for corrosion as well as plugging of flow passages. This latter characteristic, however, can be used to advantage in an instrument called a plugging-temperature indicator (PTI)[24]. Basically, this instrument consists of a small passage through which sodium can be directed. As the temperature of the sodium is reduced, impurities come out of solution and plug the flow passage. The temperature at which this occurs is called the plugging temperature and can be related to the level of impurities in the sodium.

The original PTI's at EBR-II were the fluted-valve type. The plugging element was a globe-type valve with grooves cut in the stem. The valve was opened in the standby condition to dissolve the previously deposited plug and to prepare for the next plugging determination (plugging

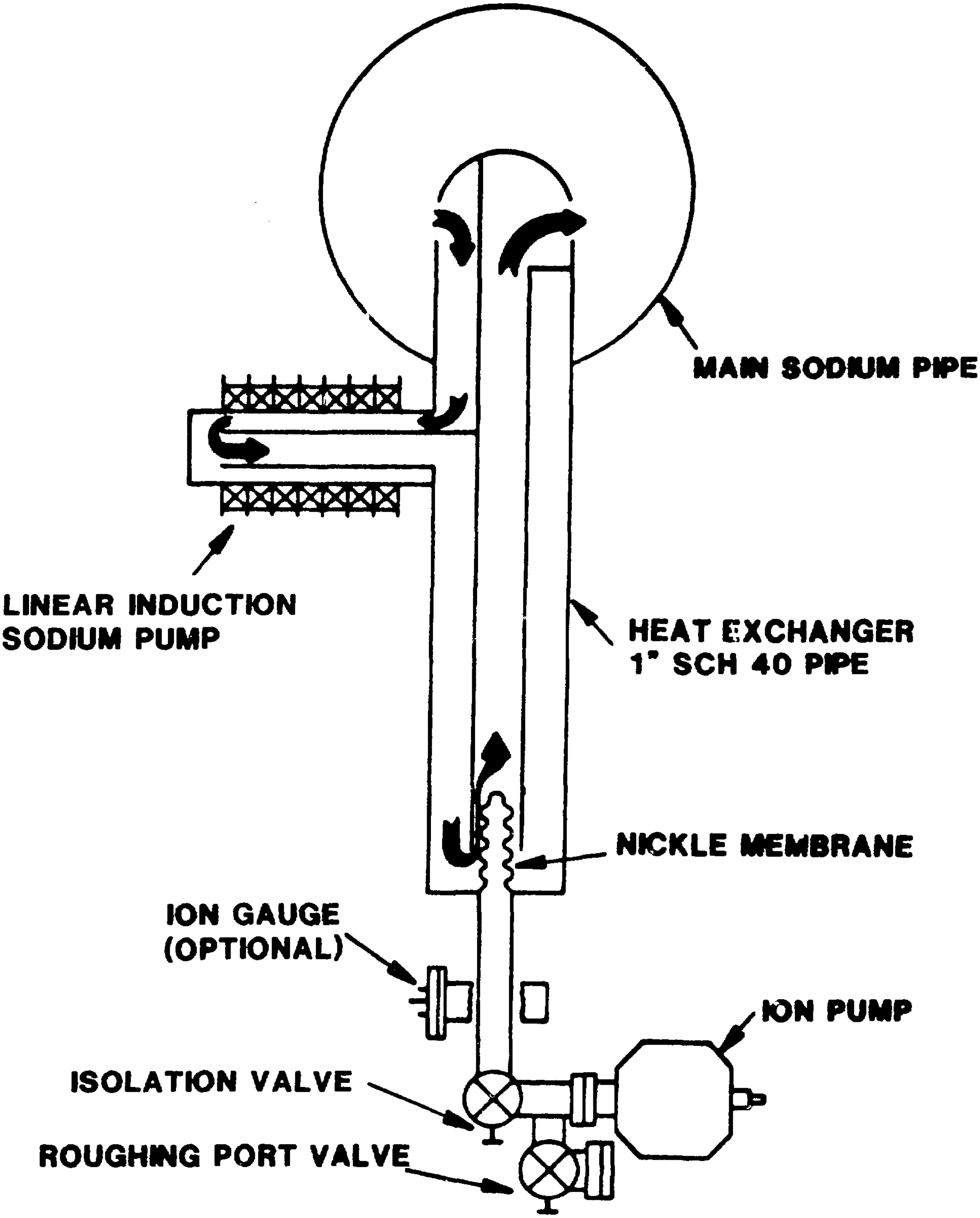

Fig. 17 SCHEMATIC OF HYDROGEN LEAK DETECTOR USED AT EBR-II (from ref. 23)

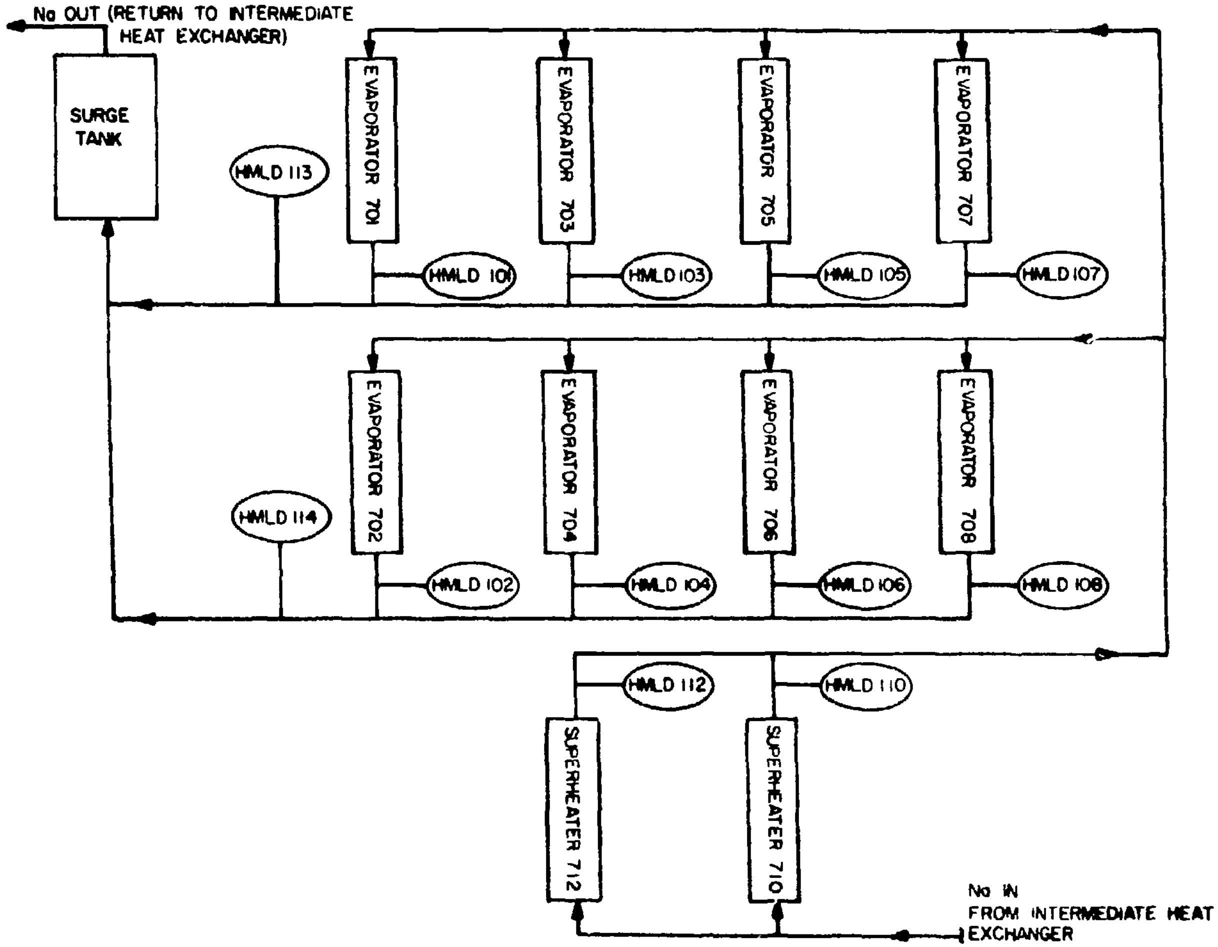

Fig. 18 LOCATION OF HYDROGEN METER LEAK DETECTORS IN THE EBR-II STEAM GENERATING SYSTEM (from ref. 23)

run). During a plugging run, the valve was closed and sodium was forced to flow through the stem grooves.

A plugging run was made by cooling the plugging valve until a gradual flow decrease occurred, or until the temperature reached about 110°C. If a gradual flow decrease occurred, the plugging temperature was reported as the temperature at which this decrease started. If no loss of flow occurred before the temperature reached 110°C, then the plugging temperature was reported as < 110°C.

The fluted-valve PTI's in EBR-II were replaced in 1977 by a new design, the heart of which is a 60-μ filter element.[24] This element is located at the bottom of a combination sodium-to-sodium and sodium-to-air heat exchanger. The heat-exchanger assembly is 1.88 m (74 in.) long, excluding the air-cooling duct. Other dimensions are shown in Fig. 19.

As shown in Fig. 19, sodium flows down the outer annulus of the heat exchanger assembly. At the bottom the stream divides. One stream passes through the filter then flows up through an intermediate annulus, and the other stream bypasses the filter and flows up a center tube.

The new PTI has proved to be a very sensitive device for measuring plugging temperatures in the EBR-II primary- and secondary-sodium systems. The PTI normally indicates the presence of a slow-plugging and a fast-plugging material in both systems. The slow-plugging material normally plugs in the range of 170-180°C and is at present unidentified. The fast-plugging material normally plugs in the range of 120-140°C and correlates very well with the sodium hydride saturation temperature.

8. SUMMARY

The unique characteristics of sodium have required development of much new instrumentation. The experience that has accumulated in the industry demonstrates that LMFBR's are viable, efficient and safe power producers for which reliable instrumentation has been provided. One of the most difficult instrument challenges, detecting leakage in steam generators, has been successfully met with development and testing of hydrogen leak detectors. Likewise, the performance of permanent magnet flowmeters has been shown to be reliable and then have gained wide application in sodium systems. To gain the benefits of reduced weight and more flexibility, development of ultrasonic flowmeters is now being emphasized.

As the design of LMFBR power plants has been improved and confidence gained in their operation and safety, less emphasis is being placed on development of such instrumentation as fast-response thermocouples at the outlet of core subassemblies or acoustic monitors to detect boiling. The emphasis is on those instruments necessary to provide reactor control and surveillance for efficient operation. Therefore, magnetic and ultrasonic flowmeters are being extensively used as are "standard" chromel/alumel thermocouples and hydrogen leak detectors in sodium/water systems.

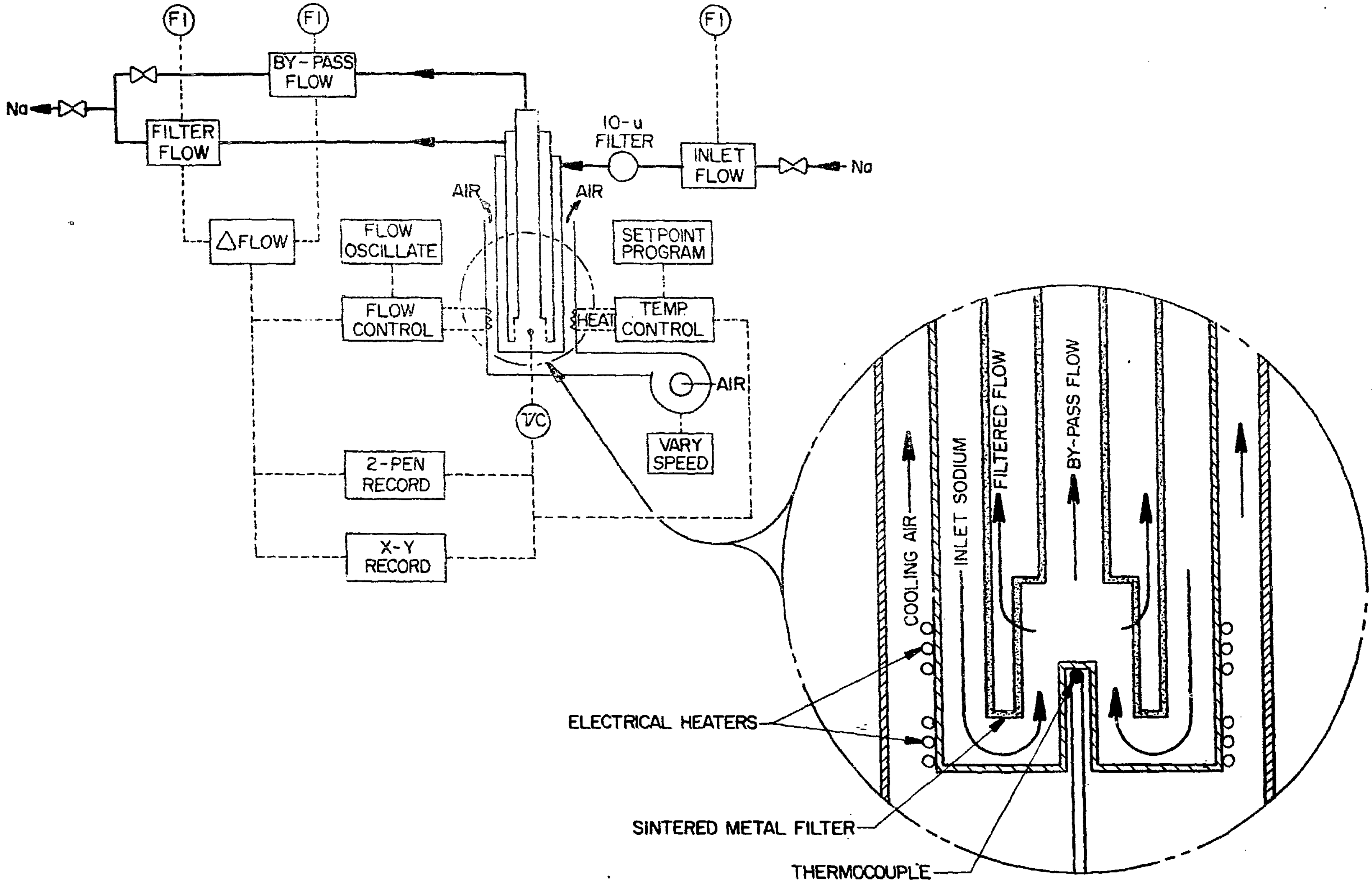

Fig. 19 Schematic of a Frit Type Plugging Temperature Indicator at EBR-II (From Ref. 24)

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