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Argonne National Laboratory

SUMMARY REVIEW OF FLOWMETERS
SUITABLE FOR MEASURING SODIUM FLOW
AT TEMPERATURES UP TO 1200°F IN THE
FAST FLUX TEST FACILITY (FFTF)

by

G. F. Popper, D. E. Wiegand,
and M. C. Glass

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Reactor Engineering Division

December 1967

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TABLE OF CONTENTS

	<u>Page</u>
I. INTRODUCTION	7
II. TYPES OF FLOWMETERS CONSIDERED	9
A. Permanent-magnet (PM) Flowmeter	9
1. Availability.	9
2. Principle of Operation	9
3. Advantages and Disadvantages	10
a. Advantages.	10
b. Disadvantages.	11
4. Theoretical Design Considerations	12
a. Basic Flow Equation	12
b. Correction Factors	12
(1) Flow-tube Wall Effects.	12
(2) Magnetic-field End Effects	12
(3) Nonwetting Effect of Flow-tube Wall	13
(4) Thermal-expansion Effect.	13
(5) Temperature- and Nuclear Radiation-induced Effects.	13
5. Practical Design Considerations.	14
a. Physical Arrangement	14
b. Factors Influencing Magnet Stability.	14
(1) Temperature Change	14
(2) Metallurgical Changes	15
(3) Vibration or Mechanical Impact	16
(4) Reluctance Changes	16
(5) External Magnetic Fields	16
(6) Nuclear Radiation	16
c. Magnet Stabilization.	17
d. Lead Wire, Insulator, and Sheath Materials	18
B. Turbine Flowmeter.	18
1. Availability.	18
2. Principle of Operations.	19
3. Advantages and Disadvantages	20
a. Advantages.	20
b. Disadvantages.	20

TABLE OF CONTENTS

	<u>Page</u>
4. Theoretical Design Considerations of Transient Response.	21
5. Practical Design Considerations	21
a. Magnet Stability	21
b. Bearings	21
c. Sensing Coils	22
d. Extension Lead Wires	22
e. Output Signal Converter	22
C. Eddy-current Flowmeter	23
1. Availability	23
2. Principle of Operation	23
3. Advantages and Disadvantages	23
a. Advantages	23
b. Disadvantages	24
4. Theoretical Design Considerations	24
D. Electromagnetic (EM) Flowmeter	25
E. Thermal Flowmeter	25
F. Transit-time Flowmeter	26
G. Ultrasonic Flowmeter	27
III. CONCLUSIONS	27
REFERENCES	29

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.	Magnetic-flowmeter Configuration for Measuring Flow in FARET Fuel Subassembly	10
2.	Turbine-flowmeter Configuration for Measuring Flow in FARET Fuel Subassembly	19
3.	Thermal-flowmeter Configuration for Measuring Flow in FARET Fuel Subassembly	26

TABLE

<u>No.</u>	<u>Title</u>	<u>Page</u>
I.	Preliminary Environmental Conditions and Design Parameters for FFTF In-core Flowmeter Development Program	8

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I. INTRODUCTION

When completed, the Fast Flux Test Facility (FFTF) will provide a reactor-core environment for evaluating prototype mixed oxide, carbide, nitride, or cermet fuel subassemblies. These fuels are of interest to satisfy the high-burnup, high-power-density, high-temperature, and safety requirements of large, sodium-cooled, fast-breeder-reactor plants currently under development.

Comprehensive evaluation of these fuel subassemblies depends, in part, on the availability of flowmeters that are capable of reliable operation during exposure to steady-state and transient conditions anticipated in the FFTF core. In addition, the flowmeters must be sufficiently sensitive and accurate to provide data required to determine: (1) significant changes in hydraulic characteristics of the fuel-coolant channels; (2) correlations between coolant flow rate and temperature and heat-generation rates in the channels; (3) marked differences in heat-generation rates that are incurred, for example, by fuel-loading errors. Finally, the response time of these flowmeters must be such that, in the event of a rapid flow reduction, adequate time is available to protect the reactor core.

Accordingly, the current in-core flowmeter development program at Argonne has been reoriented consistent with the FFTF experimental requirements summarized in Table I. The program includes several phases of research and development, in the following sequence:

1. A review of current in-core flowmeter technology.
2. Out-of-pile and in-pile screening tests to determine the most promising flowmeter materials and assemblies.
3. Design, fabrication, and similar testing of prototype assemblies to assess their overall performance and useful lifetimes.

4. Preparation of specifications and development of quality-control procedures to ensure expeditious commercial fabrication of consistently reliable and accurate flowmeters at minimum cost.

5. Publication of routine status reports and timely topicals covering significant achievements during the program.

TABLE I. Preliminary Environmental Conditions and Design Parameters for FFTF In-core Flowmeter Development Program

Radiation

Fast neutron	2×10^{14} nv
Thermal neutron	2×10^{12} nv
Gamma	2×10^8 R/hr

Coolant

Type	Sodium
Flow rate per fuel subassembly	1 ft ³ /sec
Maximum nonrecoverable ΔP	10 psi
Maximum temperature	
Above core	1200°F
Below core	900°F
Rate of temperature change	
Reactor scram	200°F/sec
Blocked flow channel	500°F/sec
Flow-channel diameter	3-6 in.

Flowmeter

Maximum length	12 in.
Response time ^a	≤ 0.1 sec
Accuracy ^b	$\pm 10\%$ of full flow
Minimum life	1200 hr
Temperature gradients along flowmeter leads	$\leq 300^\circ\text{F}$
Fast-neutron flux along flowmeter leads	10^{16} nv

^aFor large flow changes ($\geq 20\%$ of full flow).

^bAssuming flow changes of $\pm 1\%$ are detectable.

This report represents completion of phase 1 of the above program. Briefly, it involves a review and evaluation of published information (as of March 1967) on various flow-monitoring devices and concepts in terms of their availability and/or corresponding areas of research and development essential to their potential utility in the FFTF core environment.

II. TYPES OF FLOWMETERS CONSIDERED

A. Permanent-magnet (PM) Flowmeter

1. Availability

PM flowmeters are commercially available for measuring flow of high-temperature liquid metals in out-of-core systems. Their design features and performance characteristics have been analyzed extensively in the open literature.¹⁻¹⁰ However, similar meters for corresponding measurements in liquid-metal-cooled reactor cores are not commercially available. Moreover, successful design, fabrication, and testing of units for measuring flow in FFTF fuel subassemblies represents a marked extension of the usual range of applications for magnetic flowmeters. Nonetheless, there is every indication that such flowmeters can be built.

For example, Fig. 1 shows a PM-flowmeter configuration designed for installation between the inlet nose piece and bottom reflector of a FARET fuel subassembly.¹⁶ The magnetic field was produced by two Alnico V magnets operating in parallel. Other components included fully-annealed soft-iron pole pieces, which may not be essential to this configuration; and a body, electrodes, and extension lead wires, all of Type 304 stainless steel to minimize thermoelectric- and thermal-expansion effects. The lead wires were insulated with high-purity alumina. Finally, the flowmeter internals were backfilled with helium to prevent significant corrosion of the pole pieces and to help remove gamma heat generated in the magnets. A prototype model of the flowmeter had been fabricated for sodium-loop testing when the FARET program terminated.

A similar flowmeter was designed for use in SEFOR instrumented fuel subassemblies.^{17,18} It featured Alnico VI magnets without pole pieces, and three sets of potential taps. These taps were series-connected to increase the signal strength, probably because of the small length-to-diameter ratio of the magnetic circuit. This flowmeter accumulated about 1000 hr of successful operation in a sodium loop at 1000°F before a mechanical failure allowed sodium to enter the body and short out the signal. Further testing will be done when a prototype instrumented fuel subassembly becomes available.

2. Principle of Operation

The principle of PM-flowmeter operation is based upon Faraday's law of induced voltage. As the conducting liquid flows through a tube positioned in a stable magnetic field, a potential is developed across the tube and at right angles to the field. This potential is proportional to the volumetric flow rate of the liquid and the magnetic flux density.

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Fig. 1. Magnetic-flowmeter Configuration for Measuring Flow in FARET Fuel Subassembly
(dimensions are in inches)

3. Advantages and Disadvantages

With respect to their application in the FFTF core, PM flowmeters offer many advantages and several disadvantages.

a. Advantages

- (1) There are no moving parts; an all-welded construction is attainable.

- (2) Size and weight are compatible with expected fuel-subassembly designs.
- (3) No additional pressure drop is introduced in the fuel subassembly.
- (4) Only Type 304 stainless steel is exposed to the sodium.
- (5) A wide range of flow rates, including zero and reverse flow, can be measured.
- (6) The only connection to the meter is an electrical cable.
- (7) The output signal is linear with flow.
- (8) Conventional millivolt indicators and recorders can be used directly to measure the output signal.
- (9) Extraneous electrical-noise signals should be easily rejected.
- (10) Calibration of small-diameter flowmeters is little affected by approach conditions.
- (11) Calibration may be calculated once the design equations are verified.

b. Disadvantages

(1) Calibration is temperature-dependent, and compensation will be required; calibration also depends upon liquid-metal wetting of the flow tube wall.

(2) Electrical resistivity of the flow tube and the liquid influences the calibration. Of the two, the flow tube must have the higher resistivity.

(3) Calculation of the calibration requires accurate measurement of the flow-tube dimensions, and accurate magnetic-flux densities at all temperatures of interest.

(4) Magnets capable of producing a stable flux at temperatures up to 1200°F and in the presence of nuclear radiation are not now available.

(5) The magnetic circuit for each fuel-subassembly design must be optimal.

The uncertainty factors associated with PM-flowmeter performance are accentuated when accuracy requirements are made stringent. Of course, many of these factors can be ignored if the flowmeter is calibrated

in a system that approximates the design flow configuration. However, this procedure becomes expensive and time-consuming. Therefore, sufficient design information must be made available to accurately predict the performance of a PM flowmeter over a wide range of environmental conditions.

4. Theoretical Design Considerations

a. Basic Flow Equation. The most useful, highly idealized, volumetric flow equation is

$$E = 3.17BQ \times 10^{-4}/d, \quad (1)$$

where E is the measured output (in millivolts), B is the magnetic flux density (in Gauss), Q is the flow rate (in gal/min), and d is the inside diameter of the flow tube (in inches).

Equation 1 is valid, provided the output voltage is measured on the inside diameter of a nonconductive channel in an infinite, uniform magnetic field.

b. Correction Factors. Since none of the conditions in the above paragraph can be realized in a practical flowmeter design, several factors must be applied to Eq. 1 to correct for the actual situation encountered in service. Many of the necessary correction factors have been analyzed and reported in the open literature. These include the following:

(1) Flow-tube Wall Effects. In a conductive flow tube, the output-signal electrodes are attached to the outside wall of the tube, rather than the inside wall, as in the ideal case. During flowmeter operation, the conductive wall has a shunting effect on the output voltage. This causes circulating currents, in the liquid and the wall, in planes normal to the flow. Radial variations in the liquid velocity cause additional circulating currents due to the dissimilar voltages generated at these locations. The aggregate loss of voltage results in a measured output signal that is less than that predicted by Eq. 1.

Elrod and Fouse⁶ have theoretically derived a so-called wall-correction factor (K_1), which may be used to correct for the wall effect.

(2) Magnetic-field End Effects. The conditions for validity of Eq. 1 neglect the end effects peculiar to finite, nonuniform magnetic fields that exist in a practical flowmeter. More specifically, a potential gradient is established axially along the flow tube in the region of the pole-face ends. This gradient causes currents to circulate in planes parallel to the liquid

flow and normal to the magnetic field. The magnitude of these end currents depends upon the field distribution along the flow tube. In any event, if these currents reach the signal electrodes, the output voltage is reduced by some factor K_2 . This factor may be determined from a curve developed by Michael.²

Gray and Astley⁷ derived a similar curve by plotting the differences between measured and calculated output signals from a homopolar generator. In each case, the generator consisted of a metal toroid revolving in a magnet air gap. The experimental results are not strictly applicable to practical flowmeters, since both round and rectangular pole faces were used. However, it was determined that if the pole face is at least three pipe diameters long, this correction factor approaches to within a few percent of unity.

(3) Nonwetting Effect of Flow-tube Wall. Validity of Eq. 1 also requires that the inside wall of the flow tube must be completely wetted by the liquid, with essentially zero contact resistance between the liquid and the wall. However, during initial runs at low temperature, it may be necessary to consider the nonwetting effects due to oxide precipitation or other contamination on the flow-tube wall.

Gray and Astley⁷ derived a correction factor for such a case by assuming the presence of a thin cylindrical shell of material, having a given resistivity, just inside the wall. This correction factor is seldom used in practice, but can be applied if necessary.

(4) Thermal-expansion Effect. Flowmeter calibration may be affected by thermal-induced dimensional changes in the flow tube and the magnetic circuit. The effects of these changes also have been considered by Gray and Astley⁷ and can be corrected for, if necessary.

(5) Temperature- and Nuclear Radiation-induced Effects. Magnetic field strength is a function of magnet operating temperature. Therefore the flowmeter calibration must be corrected for the so-called reversible changes in magnetic flux that will occur over the proposed operating-temperature range. Reversible flux changes for most magnets at temperatures up to 1200°F have not been well defined, experimentally. Comprehensive knowledge of these changes is essential to successful design of PM flowmeters.

Effects of nuclear radiation on hard magnetic materials, such as Alnico alloys, have been partially defined, experimentally.¹¹⁻¹³ Reported changes have been small and are usually ignored in practice.^{14,15} The degree of exposures is insufficient for direct extrapolation of magnet decalibration to the large, integrated neutron fluxes expected in the FFTF core.

5. Practical Design Considerations

a. Physical Arrangement. For each fuel subassembly, the flowmeter magnetic circuit must be designed so that (1) a fairly uniform magnetic field exists within the flow tube, and (2) the end effects are made small. Also, the largest volume of magnetic material must be included in the circuit to maximize flowmeter sensitivity.

The complete design procedures, along with some of the material-selection problems, have been reported.¹⁵ With the aid of these procedures, suitable PM flowmeters can be designed and fabricated for FFTF fuel subassemblies.

b. Factors Influencing Magnet Stability. Magnet stability is a prerequisite to successful operation of PM flowmeters. Stability refers to the constancy of magnetic-flux output under conditions known to influence the output.^{19,20} These include temperature changes, metallurgical changes, vibration or mechanical shock, external magnetic fields, reluctance change, and nuclear radiation. No flux changes are caused directly by the passage of time, but any of the aforementioned influences may act gradually or even periodically and thus cause progressive variations in the flux output of an insufficiently stabilized magnet.

(1) Temperature Change. Changes in permanent-magnet flux densities due to heating are of three types: (1) metallurgical changes, which permanently affect the hysteresis loop and therefore remain even after remagnetization; (2) irreversible magnetization losses, which remain when the magnets are cooled but can be regained by remagnetization; and (3) reversible magnetic losses, which disappear when the magnets are cooled.

As the temperature of a permanent magnet is increased, the magnetic energy it can supply decreases. At an elevated temperature, the magnet operates on a demagnetization curve that is below the corresponding plot for normal room temperature. This temperature dependence is attributed to the gradual overcoming, through increased thermal agitation, of forces that contribute to the mechanism of ferromagnetism. The resultant loss of magnetic energy is called reversible because it is completely regained when the temperature is subsequently decreased.

Reversible magnetic-energy losses have been determined for most Alnico magnets at temperatures up to about 1000°F.^{7,19,24-26} A limited amount of useful information is available on reversible losses in Alnico VI and VIII magnets.^{25,26}

Generally, the reversible loss is a function of magnet dimensions (L/D ratio). Alnico magnets with low L/D ratios experience the smallest loss. For magnets having the same L/D ratio, reversible losses in remanence are greater for Alnico VI than for Alnico V.²⁹

Reversible losses for Alnico V, VI, and VIII magnets up to 1200°F remain to be determined. Alnico VIII will probably have the smallest reversible loss, followed by Alnico V and then VI.

Irreversible losses for the Alnico alloys are usually only a few percent up to about 538°C and depend to some extent upon magnet permeance. (Permeance is a measure of the degree of ease with which magnetic flux is produced in a material.) However, the losses above 750°F are not well defined.²³⁻²⁷

To investigate properly the so-called reversible and irreversible effects of temperature upon a permanent magnet, the material must be metallurgically stable within the temperature range in which it is to operate. For when a metallurgically stable magnet is tested at a specific temperature, the demagnetization curve is essentially retraceable, regardless of the time between tests.

(2) Metallurgical Changes. In terms of metallurgical stability, permanent-magnet materials can be divided into two general classes: quench-hardened and precipitation-hardened. Quench-hardened magnet steels will not be discussed because they depend upon carbon to develop magnetic hardness. Perceptible structural changes occur at modest temperatures; hence, these steels are not considered useful for in-core flowmeter applications at high temperature.

Precipitation-hardened materials, such as the Alnico alloys, are of interest because they need no carbon to develop magnetic hardness. Moreover, they are metallurgically stable at temperatures much higher than room ambient temperature. However, prolonged exposure to high temperature sometimes destroys the original heat treatment of the magnet by causing what appears to be overprecipitation of the hardening phase.

If properly heat-treated, Alnico V magnets suffer negligibly small metallurgical changes after 1000 hr at 1000°F.^{21,22} Of the many magnet configurations tested under these conditions, the maximum total loss of remanence (4.5%) was evidenced by a magnet having an L/D ratio of 3. This loss was due predominantly to irreversible magnetic changes, since upon subsequent remagnetization the remanence agreed, within measuring tolerances, with the pre-exposure value. With proper heat treatment, the irreversible magnetic changes can be made as small as $\pm 1\%$.^{23,24}

Metallurgical stability of Alnico alloys above 1000°F has not been firmly established. However, preliminary results of high-temperature tests under way at ANL indicate that Alnico V alloy may be stable up to at least 1200°F. Similar tests are planned for Alnico VI and VIII. Alnico VIII is known to undergo metallurgical changes at 1500°F,²⁶ but little is known about its behavior at lower temperatures.

(3) Vibration or Mechanical Impact. A magnetized bar of steel is demagnetized when subjected to vibration or repeated mechanical impacts. Accordingly, permanent magnets also would be suspected of becoming demagnetized under similar conditions.

Various tests have been conducted to determine the total change in magnetic remanence effected by repeated mechanical shock.²⁰ For Alnico alloy magnets, physical properties, rather than the amount of demagnetization suffered, will probably limit their use under conditions of impact. Only shock data on Alnico V are available in the literature, and these data show a loss of only ~0.5% in remanence after 1000 impacts of predetermined force.

(4) Reluctance Changes. Reluctance is a measure of the difficulty with which magnetic flux is produced in a circuit. Changes in reluctance usually occur because of expansion of metals in the magnetic circuit at high temperature.

(5) External Magnetic Fields. As is to be expected, external magnetic fields profoundly affect the gap flux supplied by the permanent magnet unless proper precautions are taken to minimize these fields.

(6) Nuclear Radiation. Sery, Gordon, and Lundsten^{11,12} conducted the only significant study of radiation damage in permanent magnets. Less-controlled tests at ANL are in substantial agreement with their results.¹³ Alnico V magnets irradiated to integrated neutron fluxes as high as 5×10^{20} nvt showed negligible changes in magnetic properties.

These data lend support to use of Alnico V magnets for PM flowmeters in the FFTF core, since the expected integrated fluxes for a meter lifetime of 1200 hr ($\sim 10^{21}$ nvt fast; 10^{19} nvt thermal) are not appreciably higher. However, further tests would be necessary if the lifetime is to be increased by a factor of three or more, or if Alnico VI or VIII magnets are to be used. In any event, the minimum exposure should be 10^{22} nvt fast at 1000°F or higher.

c. Magnet Stabilization. Although the prime factors that influence magnet stability are well recognized, the procedures required to stabilize magnets for a given environment are not well defined.

For example, several methods are conventionally used to stabilize a magnet for mechanical shock, impact, or vibration. To reduce the effect of magnetic flux change, one method uses ac demagnetization, while another employs heat treatment. The third and probably the most common method is to subject the magnet repeatedly to the shock expected in service until a stable magnetic flux is achieved.

For Alnico V, only a few impacts would be needed. Data on Alnico VI and VIII are not available. The conditions of mechanical shock vary so widely that each magnet application must be treated as a separate problem.

To reduce the total change in flux density and to avoid irreversible losses due to external magnetic fields, the magnet may be given a slight (~5%) ac demagnetization. Thus a degree of stability is achieved by making the magnetic circuit operate on a minor hysteresis loop. Essentially the same effect may be obtained by increasing the reluctance of the circuit so that the magnet will also operate on the desired minor hysteresis loop.

Methods of stabilizing a permanent magnet against reluctance changes are probably self-evident. Before being installed, the magnet is brought into a cyclically magnetized condition by either of two methods. The first method involves a series of ac demagnetizations. In the second method, the magnet is subjected, a number of times, to a reluctance change slightly larger than the maximum expected in service. This is accomplished by closing the magnetic circuit (shorting the poles with a steel keeper) until a constant flux is obtained.

Accordingly, a magnet can be stabilized simultaneously for external magnetic fields and reluctance changes by either of the above-mentioned techniques. However, under dynamic conditions, such stabilization only minimizes the flux changes that are not fully recoverable; it does not seriously affect the reversible flux changes, which depend upon the slope of a minor hysteresis loop. The incremental permeability, which is a measure of magnet stability under a varying external influence, is 2.1 for Alnico VIII, 3.8 for Alnico V, and 5.0 for Alnico VI.²⁵ Therefore, of the three alloys, Alnico VIII should be the most stable to external influences.

Temperature cycling causes irreversible flux changes, even in metallurgically stable magnets. For a particular magnet, the amount of flux change is a function of the maximum temperature encountered.

Usually three to four thermal cycles to this maximum value are required to stabilize the magnet against further irreversible flux changes. After this type of stabilization, the remanence-versus-temperature curve is usually retraceable. Remagnetization of the magnets must be avoided.

d. Lead Wire, Insulator, and Sheath Materials. Selection of combinations of lead wire, insulator, and sheath material must take into account compatibility, minimization of undesirable thermoelectric signals produced by dissimilar metals, and the effects of differential thermal expansion, mechanical instability, and thermal shock induced by the high-power densities and rapid temperature transients characteristic of reactor operation. Radiation-induced swelling, as well as electrical resistivity changes, in oxide insulators due to steady-state operation also must be considered.^{33,34}

Integral sheath-type cables are generally considered best suited for instrument applications at temperatures as high as 1200°F.^{13,15-18} Type 304 stainless steel is usually selected as sheath material for service in high-temperature sodium environments. Both MgO and Al₂O₃ have served as electrical insulators. Type 304 stainless steel lead wires would be used for PM flowmeters. Nickel or other lower-resistance materials could be used for lead wires where minimization of thermoelectric effects is not important, as in turbine flowmeters.

In-pile tests show that sheath-type cables perform well in transient nuclear-radiation environments, and are the least susceptible to ionization effects known to have occurred at the peak fluxes of $\sim 1.5 \times 10^{16}$ nv fast and thermal.³² However, since the specimen cables were only 14 in. long and since longer cables may be used in the FFTF, further transient testing is necessary to assure the acceptability of sheath-type cables for flowmeter applications.

High-quality cable must be used. Preliminary results of high-temperature tests on Type 304 stainless steel-sheathed, alumina-insulated, Type 304 lead wires are encouraging.¹⁵

B. Turbine Flowmeter

1. Availability

Turbine-type flowmeters have been used successfully to measure flow rates in fuel subassemblies of many water-cooled reactors.³⁵⁻³⁸ They have also been used, with limited success, to measure sodium flow rates in out-of-pile loops operating at temperatures up to 1500°F.

With respect to their application in the FFTF core, turbine-type flowmeters show promise of overcoming most signal-generation problems and temperature effects peculiar to the PM-type flowmeter. But fulfillment of this promise is contingent upon resolution of new problems, particularly bearings for operation in the high-temperature sodium, and design and fabrication of high-temperature, nuclear-radiation-tolerant sensing coils.

Figure 2 shows a turbine-flowmeter design that was under development when the FARET program terminated.¹⁶ As for the PM flowmeter, the turbine flowmeter was designed for installation between the inlet nose piece and bottom reflector of a FARET fuel subassembly. Briefly, it consisted of the body, a turbine with a small, four-pole magnet cast into it, and a coil mounted on the body adjacent to the turbine. Except for the bearings, the body and other parts exposed to the sodium were to be fabricated of Type 304 stainless steel. Other component materials included molybdenum-guide-bearing journals, Hastelloy C turbine shafts, and Alnico V magnets. A special miniature high-temperature coil (0.5 in. in diameter, 0.25 in. high) had been designed and was being fabricated when the program terminated.

Fig. 2. Turbine-flowmeter Configuration for Measuring Flow in FARET Fuel Subassembly (dimensions are in inches)

The only turbine flowmeter known to have operated successfully for 1000 hr in sodium at 1500°F featured a Kentanium K152B shaft, Kentanium K168B sodium-lubricated bearings, Inconel rotor, and a variable-reluctance-type pickup coil, which was thermally isolated from the body.⁴²

2. Principle of Operation

When the sodium flows through the meter body, the turbine rotates at a speed determined by the velocity of the sodium flowing through the turbine blades and the blade angle. If permanent magnets are used, an ac voltage is generated in the sensing coil. The frequency of this voltage is proportional to the sodium velocity.

Another variation of the signal-generation scheme is based upon the variable-reluctance principle. In this case, the turbine blades are constructed of a magnetic material. As the blades rotate, a change in the impedance of the sensing coil produces a measurable frequency signal proportional to the sodium velocity.

3. Advantages and Disadvantages

Some of the advantages and disadvantages of the turbine-type flowmeter are as follows:

a. Advantages

- (1) Flowmeter body and turbine assemblies are available commercially.
- (2) Size and weight of the flowmeter are small and compatible with expected fuel-subassembly designs.
- (3) A wide range of flow rates (10:1) can be measured.
- (4) Only a water calibration may be necessary.
- (5) The calibration is very slightly temperature-dependent.
- (6) Resistivity of the liquid or flow tube does not influence the calibration; wetting of the flowmeter inside wall is unimportant.
- (7) Magnetic properties of the signal-generating materials can be both temperature- and nuclear radiation-dependent without loss of calibration.
- (8) The only connection to the meter is an electrical cable.
- (9) The output signal is ac and is linear with liquid flow.

b. Disadvantages

- (1) A pressure drop is added to the fuel subassembly.
- (2) The rotating mechanism could break loose or jam, causing an additional pressure drop.
- (3) Bearings and a miniature sensing coil must be developed for reliable operation in expected high-temperature sodium-nuclear radiation environment.
- (4) Flow rates near zero cannot be measured.
- (5) Reverse flow cannot be determined.
- (6) Relatively complex electronics are required to convert the ac frequency output signal to a dc level signal.

- (7) Electrical ac noise signals may be difficult to reject.
- (8) Transient response of the turbine flowmeter and electronics may not be as good as that of the PM flowmeter.
- (9) Each meter must be calibrated in a water system.

On the assumption that bearings and coils can be developed for reliable operation in the FFTF core, the only significant disadvantage of the turbine flowmeter appears to be the additional pressure drop introduced in the fuel subassembly during normal operation. For a typical turbine flowmeter, the normal pressure drop at maximum flow rate is about 6 psi.³⁹ However, should the turbine jam or stall, this value could increase to as much as 36 psi⁴¹ and seriously alter the flow rate through a fuel subassembly.

4. Theoretical Design Considerations of Transient Response

Transient response of the turbine-type flowmeter has been analyzed and is a function of turbine design, liquid density, and flow rate. The corresponding response to a step change in sodium flow is best described by the time required (time constant) to reach a fraction of the imposed flow-rate increment.

Time constants for many sizes of Potter Aeronautical commercial turbine flowmeters have been computed for water conditions, and these should be almost directly applicable to sodium. For a turbine flowmeter in the nominal size range of 2-6 in., the time constant is about 4 msec when the flowmeter is operating near maximum flow rate, and about 8 msec when operating near 50% of maximum flow rate.³⁹

5. Practical Design Considerations

a. Magnet Stability. The problems associated with magnets and magnetic materials for turbine-type meters are similar to, but not as critical as, those for the PM flowmeters. For example, a 50% change in the flux output of a magnet, or in the magnetic characteristics of a material, would not be considered unreasonable. Therefore, Alnico V, VI, or VIII alloy could be used as the signal generator without further testing.

b. Bearings. Selection of bearing materials and designs for long-term, reliable operation in the FFTF core is a major problem.⁴³⁻⁴⁵ Although correlation between general bearing-lubrication theory and experiment has been improved, a systematic analytical and experimental investigation of sodium-lubricated bearings for specific turbine flowmeter loading conditions remains to be carried out.

Pending completion of such an investigation, and on the basis of their limited performance in 1200°F sodium systems, the Kentanium bearings and shaft mentioned earlier, or a molybdenum guide bearing and Hastelloy C shaft,⁴⁶ are the only component material combinations that could be initially selected for FFTF turbine flowmeters at this time.

c. Sensing Coils. Past experience with turbine flowmeters in the EBWR and BORAX-V reactors has shown that coils supplied by vendors of turbine flowmeters have been unreliable. Because of the unique requirements (both coil size and operational environments), the vendors have tried to develop the capability to produce a small number of relatively complex sensing coils. This has proved expensive and time-consuming. Moreover, reliability was generally sacrificed under these conditions. Therefore, a separate "in-house" effort should be made to develop the necessary sensing-coil configurations.

Such an effort would explore the feasibility of several types of high-temperature, ceramic-insulated magnet wires that are commercially available for operation up to 1200°F.⁴⁷⁻⁵⁰ As mentioned previously, a miniature sensing coil (0.50 in. diameter, 0.25 in. high) was designed and partially tested during the FARET instrument-development program. This coil was of random-wound design, having 1800 turns of 40 AWG heavy Anacote (HGEK) insulated, 20% nickel-clad silver wire, manufactured by the Anaconda Wire and Cable Co.⁴⁸ It was encapsulated with Anacap potting compound manufactured by the same company.

A slightly larger coil (0.50 in. in diameter, 1.0 in. high) was designed for the EBWR turbine flowmeters.⁴⁰ In this case, an unknown number of turns of 40 AWG Cermatemp magnet wire, manufactured by Hitemp Wires,⁵⁰ was random-wound on a bobbin, and the coil was potted with Sauereisen P-1 cement. Preoperational problems were experienced with this coil design: The wires would either short to the case, or they would open-circuit during initial operation at high temperature. The causes of these failures were not thoroughly investigated.

d. Extension Lead Wires. Lead-wire problems discussed under PM flowmeters (p. 18) also apply to turbine-type flowmeters.

e. Output Signal Converter. Further improvements are needed in commercially available converters, since the existing frequency response required to change the ac frequency output signals to corresponding dc levels is not as good as the basic turbine.⁴⁰

C. Eddy-current Flowmeter

1. Availability

An eddy-current-type flowmeter will be used to monitor gross flow failure in the British Prototype Fast Reactor.⁵¹ With further analysis and a concurrent experimental program, most of the reported calibration uncertainties could be evaluated. In such an event, the eddy-current flowmeter may well be upgraded from the status of a mere failure alarm to a competitive device for measuring sodium flow rates in the FFTF core.

2. Principle of Operation

Basically, the eddy-current flowmeter consists of a flow tube (usually made of Type 304 stainless steel) encircled by a normally balanced system of primary and secondary coils that are fixed in space and electromagnetically coupled to the liquid to be monitored.^{52,53}

In operation, an alternating current of predetermined magnitude and frequency is supplied to the primary coils. At zero sodium flow, the symmetrical nature of the eddy currents induced in the sodium produces a balanced condition in the secondary coils, and no voltage component appears. When the sodium flow is increased, the balanced condition is distorted and a voltage signal is generated in the secondary coils. The magnitude and phase of this signal, which is of the same frequency as the primary current, are related to the direction and velocity of the liquid.

3. Advantages and Disadvantages

Some of the advantages and disadvantages of the eddy-current flowmeter are as follows:

a. Advantages

- (1) There are no moving parts; an all-welded construction is attainable.
- (2) Size and weight are compatible with expected fuel-subassembly designs.
- (3) No additional pressure drop is introduced in the fuel subassembly.
- (4) Only Type 304 stainless steel is exposed to the sodium.
- (5) Reverse flow can be determined.
- (6) Only high-temperature wire is needed for the sensing coils. Wire for temperatures up to 1200°F is readily available.⁴⁷

- (7) A large ac signal is generated.
- (8) The transient response is sufficiently rapid to follow flow transients.
- (9) The only connection to the instrument is an electrical cable.
- (10) The calibration is completely independent of any properties of ferromagnetic materials.

b. Disadvantages

- (1) The calibration may be sensitive to the sodium-velocity profile.
- (2) Electrical resistivity of the sodium and flow tube may alter the calibration with temperature.
- (3) Complex electronics are required to convert the ac signal to a dc level proportional to the sodium velocity.

Of these disadvantages, items (1) and (2) are only uncertainties that could prove to be unimportant. An extension of the theoretical analysis of the velocity-profile calibration effects, along with an experimental program, should provide the answers.

4. Theoretical Design Considerations

The proposed flowmeter would feature a central coil (primary) and two balanced end coils (secondary), all wound on the outside of a flow tube.

Several computer programs are available at ANL to calculate the effect of operating frequency and velocity profile on signal output level for various flow-tube diameters. Exploratory calculations show that the total signal and the out-of-phase component are most sensitive to fluid velocity near the tube wall. However, the region of maximum sensitivity can be moved inward from the wall to at least the one-half-area point by considering the in-phase component and selecting an appropriate operating frequency.

Determination of the optimum frequency for a given flow-tube inside diameter requires combining the typical velocity profiles expected with flowmeter performance data. Listed below are several tube diameters and the corresponding optimum frequencies needed to make the in-phase signal most sensitive to 1200°F sodium velocities in the region of the 5/8-area point (0.791 of the tube radius).

Tube ID, in.	Frequency, Hz	Tube ID, in.	Frequency, Hz
1.0	1130.0	4.0	70.0
1.6	400.0	6.4	27.5
2.5	180.0		

The high signal levels potentially attainable from an eddy-current flowmeter are best illustrated when the unit is designed to fit in the same space as the PM concept of Popper and Glass.¹⁵ With reasonable power input (<200 W) to the primary coil, signals of the order of 0.3 mV per turn can be expected at maximum flow. Thus with secondary-coil windings of a few hundred turns, signal levels well up into the millivolt range are possible.

Generation of large ac signals, elimination of ferromagnetic materials and their bothersome temperature-nuclear radiation effects, and inherent ruggedness are characteristics that strongly support further development of the eddy-current flowmeter.

D. Electromagnetic (EM) Flowmeter

The EM flowmeter that uses a driven coil to produce the magnetic flux was rejected mainly because: (1) a large amount of power and current is needed to produce a modest flux; (2) the power is not easily transmitted to the meter through 0.125-in.-OD, sheath-type leads; and (3) the relatively large coils required cannot be fabricated to fit within the dimensional constraints of the expected FFTF fuel subassemblies.

Of the many EM flowmeter concepts considered, the most attractive was the so-called "saddle" coil meter that uses dc excitation.⁵¹ This meter operates on the orthodox PM principle, except that the magnetic field is supplied by rectangular spiral windings that are curved to conform with a cylindrical surface. Two windings installed on opposite sides of the flow tube (hence the term "saddle") generate a very nearly homogeneous magnetic field within the enclosed flow volume.

The calibration can be predicted to better than $\pm 5\%$ of the flow rate by using the uniform field strength, which can be calculated, and the flow-tube dimensions.

E. Thermal Flowmeter

In the thermal flowmeter, a small amount of sodium flows through an electrically heated channel in the center of the meter. Here, the sodium temperature is increased by the power (<200 W) supplied to the heater elements. At constant heater power, the rise in sodium temperature, as

signaled by thermocouples at either end of the flow channel, provides a measure of the sodium flow rate. This type flowmeter, as designed for in-core use, is best suited to measure local velocity, and the calibration is sensitive to the position of the device in the core coolant channel.

Figure 3 shows a thermal flowmeter designed at ANL and fabricated commercially for use in FARET fuel subassemblies.¹⁶ It features a heater power input of 150 W and two Chromel-Alumel thermocouples. Preparations for water calibration tests of this configuration were under way when the FARET project terminated.

Fig. 3. Thermal-flowmeter Configuration for Measuring Flow in FARET Fuel Subassembly (dimensions are in inches)

A total-calorimetric-type flowmeter was also considered but was rejected because of the need to increase the temperature of the total bulk through a fuel subassembly. Moreover, the large amount of electrical power required would be almost impossible to accomplish.

F. Transit-time Flowmeter

Thermal noise is inherent in flow systems because of temperature fluctuations incurred by changing heat-transfer conditions. Accordingly, the typical transit-time flowmeter uses two thermocouples, spaced a known distance apart, to generate signals of the noise pattern. These signals can be cross-correlated, and the coolant velocity may be deduced from the measured transit time of the noise pattern. The disadvantage of this concept is that a long measurement time of microvolt-level signals is required.

The transit-time flowmeter has been investigated theoretically and experimentally.^{54,55} In the latter case, preliminary tests of a unit using in-stream thermocouples in the Sodium Reactor Experiment indicated that random thermal fluctuations propagate 2 ft or more downstream or last at least 0.5 sec before diffusing. Other tests performed in NaK loops indicated that a matrix of thermocouples could be used to map velocity profiles and flow patterns.

With respect to accurately measuring sodium flow rates in FFTF fuel subassemblies, the transit-time flowmeter could be used only if it were calibrated in a simulated, counterpart flow system. An alternative use would be to check the calibration of other types of flowmeters on a relative basis.

G. Ultrasonic Flowmeter

Use of ultrasonics is an alternative approach to the problem of measuring liquid flow through a closed system. Although several ultrasonic-flowmeter configurations have been proposed, the principle of operation of each is the same.

For example, one configuration uses three transducers mounted equidistantly apart inside a flow tube. In operation, the center transducer is energized by an electronic oscillator so that it emits a wave signal. This signal ultimately impinges on the upstream and downstream transducers, which serve as receivers. The liquid flow rate is then deduced from measurements of the time required for the signal to reach each receiver.

One ultrasonic flowmeter is commercially available. However, the Curie point of the ceramic transducers employed in this unit limits its maximum use temperature to about 165°F.

On the basis of reported research on the ultrasonic-flowmeter concept,⁵⁶ considerable development work will be required before a practical in-core device is evolved.

III. CONCLUSIONS

At present, the PM flowmeter is the leading candidate for service in the FFTF core, since it appears to be the most reliable, most easily developed, and most successfully applied sodium-flowmeter concept considered. However, its successful operation in the FFTF core depends upon the availability of magnets stabilized to produce invariant magnetic fields for 1200 hr at temperatures as high as 1200°F in a fast-neutron flux of 2×10^{14} nv.

Of the three Alnico magnets (V, VI, and VIII) investigated, the best-defined magnet-stabilization procedures have been developed for Alnico V. It can be stabilized for use up to 1000°F, and preliminary results indicate the range may be extended up to at least 1200°F. Independent in-pile test results also support Alnico V magnets as first choice, at least for 1000 hr of operation in the FFTF environment. Alnico VIII shows promise, but fulfillment of this promise depends upon development of more definitive

stabilization and fabrication techniques. Further testing of both alloys to larger integrated neutron exposures is necessary if extended meter lifetime and improved performance are desired.

The relationship between reversible and irreversible magnetic-flux losses and magnet L/D ratios remains to be more clearly defined. On the basis of the limited data available, Alnico VIII probably will suffer the least reversible loss, followed by Alnico V and VI. Irreversible loss varies with maximum exposure temperature and L/D ratio. With proper heat treatment, this loss can be minimized in all three Alnico alloys.

Both metallurgical and irreversible flux changes incurred up to at least 1300°F remain to be determined for Alnico V, VI, and VIII magnets of various L/D ratios. If these types of instabilities can be eliminated by appropriate heat treatment, then stabilized magnets producing an essentially constant magnetic flux can be realized for FFTF in-core flowmeters. This stabilizing treatment removes only the irreversible flux loss; it does not affect the reversible portion of the remanence change with temperature.

Ultimate selection of the PM flowmeter also depends upon magnet performance when subjected to thermal shock and/or mechanical vibrations. Lead wires must be selected to minimize radiation-induced ionization effects, thermoelectric effects, and temperature effects. Additional testing of transmission cables, particularly in transient nuclear-radiation environments, is necessary.

There are no apparent insuperable obstacles to the candidacy of the turbine-type flowmeter. Flowmeter body-turbine assemblies are commercially available in the specified size range. However, reliable long-term operation depends upon development of high-temperature, nuclear-radiation-tolerant bearing materials and designs, and miniature sensing coils.

Finally, a more detailed study and some experimental testing of the eddy-current flowmeter are recommended, since elimination of all ferromagnetic materials and generation of large ac signals without moving parts make this meter particularly attractive for use in the FFTF environment.

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