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TRANSIT TIME FLOWMETER
EMPLOYING NOISE-ANALYSIS TECHNIQUES
PART 2 - 2-in. SODIUM-LOOP TESTS

AEC Research and Development Report

Atomics International
North American Rockwell

P.O. Box 309
Canoga Park, California 91304

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PART 2 - 2-in. SODIUM-LOOP TESTS**

By

R. L. RANDALL

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ABSTRACT

This report describes Part 2 of a program to develop a Transit Time Flowmeter using noise-analysis techniques. Part 2 of the program consists of development and demonstration tests of a 2-in.-diam Transit Time Flowmeter in 80°F water at flow-rates to 15 ft/sec and in sodium at operating temperatures up to 1200°F and flowrates to 10 ft/sec. The previously completed Part 1 of the program included the development of the first model of the Transit Time Flowmeter and related components, and the first tests of this concept using 1-1/2- and 2-in.-diam flow sections with water as the working fluid.

The Transit Time Flowmeter uses sheathed thermocouples with matched-time response installed on replaceable fin-like sensors at two axial positions in a flow channel, to detect in the moving fluid random-temperature fluctuations in the range of 0.01 to 1.0°F peak-to-peak. A Transit Time Computer instrument system has been developed to provide a continuous readout of the time for fluid transport between sensors.

The Transit Time Flowmeter has applications in accurate measurements of flowrate (velocity) in large sodium loops as a flow-calibration technique and in measurements of flow from individual fuel-element assemblies in sodium-cooled and other types of reactors.

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I. INTRODUCTION

The Transit Time Flowmeter (TTF) employing noise-analysis techniques, has been proposed for use in high-temperature sodium systems as a standard against which other types of sodium flowmeters can be calibrated. The reason for this approach is that volume/time calibration methods are not expected to be readily available for use in large sodium systems. The transit-time method is considered to be potentially capable of this service as a fundamental measurement of volumetric flow velocity. The technique provides accurate volumetric flow determination based on measurements of channel size, distance between sensors, and transit time of temperature patterns which are either already present or intentionally introduced into the fluid. Tests made in a water loop⁽¹⁾ with prototype thermocouple (TC) fin assemblies demonstrated an accuracy level better than 1%.

The basic characteristics and components for the TTF system were developed under Part 1 of the program, and are described in Reference 1. The functional parts of the TTF, as shown in Figure 1, include: two or more in-stream detectors, a cross-correlation computer; and a system for converting the cross-correlation function to transit time or rate. Temperature patterns within the fluid on the order of a few hundredths of a degree Fahrenheit pass from the first to the second of two detectors with an average transit time related to the velocity of the fluid. By cross-correlation of the random signal patterns appearing at the detector stations, one obtains a peak in the cross-correlation function which corresponds to the average time for the temperature patterns to pass from one detector to the next. The Transit Time Computer (TTC) electronically determines the position of the peak, and provides an output voltage proportional to transit time. If desired, an output signal with a frequency proportional to velocity can be provided.

As shown in Figure 2 the sensors used to detect thermal eddies are a number of sheathed TC's located along the leading edge of a fin which is extended across the diameter of the circular flow channel. The fin assemblies, or TC rakes, are placed one behind the other at a known spacing.

Two techniques of transit-time flow measurement were investigated. One, called the signal-summation technique, involves the use of resistive summation

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Figure 1. Transit-Time Flow by Correlation of Thermal Fluctuations

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Figure 2. Thermocouple Fin Assembly

networks to combine the signals from the 14 TC's on each TC fin sensor. Measurements of the average transport delay time, between the summation signals from any two of these sensors with known spacing, are used to estimate average flowrate. The second, called velocity profile integration, involves measurement of the transport delay times relating signals from individual TC's at the same radial position on two TC fin sensors. Estimates of average flowrate are obtained by averaging the transit time or velocity samples at the various radial positions.

Temperature patterns or thermal eddies moving down a flow channel are distorted by the instantaneous spatial distribution of velocities across the channel. There are a number of techniques for radial placement of sensors along a flow channel to obtain an optimum sample of an arbitrary velocity profile. The summation of signals from selected sensor locations represents a sample of the instantaneous temperature profile which tends to be independent of velocity-profile radial variations or distortions which occur as a function of such parameters as flow and geometry. Techniques for selection of sensor position and for fabrication and installation of fast-response TC's are discussed in Reference 1.

The basic measurement technique involves detecting temperature patterns passing two points in a flowing stream. The two signals are cross-correlated with a variable delay time. The delay time which gives maximum correlation is used to represent the transit time of the fluid between sensors.

The Signal Correlator used to obtain basic autocorrelation or cross-correlation measurements and the Transit Time Computer (TTC), which automatically converts the output of the Signal Correlator to direct-analog indications of peak cross-correlation, peak correlation coefficient (degree of correlation), peak autocorrelation, decay time, transit-delay time, and width of cross-correlation function at a selected fraction of peak amplitude are shown in Figure 3. A detailed description of the circuitry and operation of the transit-time readout system is included in Reference 1.

Machine accuracy for the transit-time readout is around $\pm 0.2\%$ of range. Although the system is capable of providing on-line measurements, tape-recorded data have been used in this test program. In this off-line application a digital recording system is used to sequentially sample peak correlation, delay

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Figure 3. Signal Correlator and Transit Time Computer

or decay times, width of the correlation function at a selected fraction of the peak, rms amplitude of input signals, and the code signal from the flow-test programmer. The same signals are recorded on a multichannel chart recorder for reference. Figure 4 is a sample chart recording of the time-dependence of measured parameters. Data signals are processed on a one-pass basis at up to 16 times recording speed, permitting one operator to process large quantities of data with high resolution in a relatively short time.

The material in Reference 1 includes a mathematical description of the correlation method, as well as detailed descriptions of the instrumentation and test methods applicable to the present test series. Also, included is a description of a prototype TC fin assembly and the test results obtained with that type of sensor.

Figures 5, 6, 7, 8, and 9, taken from Reference 1, illustrate the characteristics of summation signals from the prototype sensors and provide data for comparison with results of the present tests. Summation signals from two prototype fin assemblies with 36-in. separation are shown in Figure 5. Signals from temperature patterns are compared with background noise for 3-flow conditions. Distances from injection point to sensors are 60- and 96-in. respectively. Results shown in Figure 6 indicate the amplitude of the summation signals from prototype TC fin assemblies decreased as a function of the reciprocal of the distance from the injection point to the sensor, independent of flowrate. Results in Figure 7 indicate the decay-time constant of the summation signals from prototype TC fin assemblies increased (bandwidth decreased) as a function of the average fluid-transit time from the injection point to the sensor. For this particular test configuration the decay-time constant (measured as the $1/e$ point in the autocorrelation function) was $\sim 0.083t + 0.025$ sec, where t is the average fluid-transit time from the injection point to the sensor. The variation of the shape of the autocorrelation function of sensor signals with distance from the injection point is illustrated in Figure 8. The variation in the shape of the autocorrelation function of a detector signal with flow is illustrated in Figure 9.

The techniques and components developed in the Part 1 program were modified and extended in Part 2 to provide a TTF system which could be used in sodium. This required significant improvement of the fin-like sensors to make them suitable for use in sodium at 1200°F.

(a) TRANSIT TIME

(b) PEAK CORRELATION

(c) WIDTH OF CORRELATION FUNCTION AT 90% OF PEAK

(d) TEMPERATURE SIGNALS

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Figure 4. Sample Chart Recording of: (a) Transit Time, (b) Peak Correlation, (c) Width of Correlation Function, and (d) Temperature Signals

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TYPICAL SENSOR SIGNALS

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Figure 5. Comparison of Signals and Noise for Two Thermocouple Fin Assemblies 36-in.-Apart

Figure 6. Normalized and Averaged Signal Amplitude vs Sensor Position

Figure 7. Decay Time Constant of Signals From Thermocouple Fin Assemblies vs Average Fluid Transit Time From Injection Point

Figure 8. Comparison of Autocorrelation Functions of Temperature Fluctuations at Three Detector Positions

Figure 9. Comparison of Normalized Autocorrelation Functions of Temperature Fluctuations at an In-Stream Detector for Five Flow Conditions

During the Part I program (Reference 1) it was shown that temperature patterns could be detected as variations in the electrical conductivity of the fluid (water, in these tests). If a similar technique could be used in sodium the possibility exists that conductivity sensors mounted outside the flow channel could be used to detect the passage of temperature patterns and measure flow velocity in sodium without the use of instream sensors. During the sodium tests unsuccessful attempts were made to detect changes in sodium conductivity resulting from passage of temperature patterns by passing currents (in the range of 100 to 400 amp) through the pipe wall and monitoring voltage changes (in the order of 0.1 to 10 μ v peak-to-peak) on the surface of the pipe wall. Results of this feasibility study are described in Section III-G.

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II. TEST PROGRAM

The major objectives of the test program include:

- 1) The experimental demonstration of the TTF technique to flow measurement in liquid sodium at temperatures up to 1200°F.
- 2) Obtain comparative performance data of a TTF of fixed design in sodium and water; and
- 3) Obtain experimental data relating the potential accuracy of the technique to the number and position of instream sensors, amount and type of heat injection, and operational and measurement techniques.

The basic goal of the test program was to obtain sufficient experimental data to permit design of sensor configurations for a TTF for tests in sodium loops of 6- to 10-in. diam. This information will be used for evaluation of the method and preliminary designs of flowmeters for FFTF, SPTF, and other applications.

The first phase of the test program involved water-loop tests at flowrates up to 15 ft/sec to check the functional characteristics of each sensor and to check the accuracy of the TTF flow measurements for various sensor configurations against volumetric/time measurements.

The second phase of the test program involved sodium-loop tests of the same test section and sensors at flowrates up to 10 ft/sec and sodium temperatures of 500, 900, and 1200°F. Flow measurements for various TTF sensor configurations were compared with measurements from two electromagnetic (EM) flowmeters.

The operation of the TTF depends upon the existence of thermal disturbances in the fluid stream. With the currently available detectors and signal-processing equipment, peak-to-peak signal amplitudes of the order of 0.1 °F are required. Adequate thermal signal sources will be inherent in selected locations in many loops where there are significant heat-transfer processes and/or mixing of fluid streams. For the TTF tests, determination of the required source strength is one of the experimental objectives and potential inherent sources are slight; therefore, specific thermal-source provisions were designed into both the water- and sodium-test assemblies. These are discussed later.

A. SENSORS

Thermocouple fin sensors of the type developed under the Part 1 program⁽¹⁾ were designed for use in H_2O . These prototype TC fin assemblies used thirteen 20-mil-diam sheathed thermocouples radially positioned along the fin to sample equal cross-sectional areas of the flow channel. This technique for radial sampling is called the method of centroids of equal area. The differences in dimensions and performance between the prototype sensors and the TC fin assemblies used in the present tests are discussed below.

The TC fin sensors for the Part 2 program were designed for use in sodium at temperatures to 1200°F and with a sufficient number of the TC's placed in selected radial locations to map the velocity profile in considerable detail. The TC's were required to have uniform and short response times, and to be capable of operation at 1200°F and velocities of 30 ft/sec or more. The finned sensors were also required to be leaktight in sodium under the most severe flow and temperature conditions described above. Sensors to meet the requirements outlined were fabricated in the configuration shown in Figure 10. The arrangement of the TC's is shown by the x-ray (positive) shown in Figure 11, and their location was determined by the method of Chebyshev as described in Reference 2. The TC spacing is designed to minimize the error in determining average velocity. The method also purports to minimize the error in indicated average velocity due to inaccuracies in TC location. The choice of seven on opposite radii was to provide a complete velocity profile in some detail, and to allow flexibility for tests with fewer TC's in selected radial locations to determine the reduction in accuracy resulting from loss of one or more. The dimensions of the sensor components and their locations are shown in Figure 12.

Originally it was planned to fabricate three sensors; with allowance for losses, 66 grounded-junction TC's were prepared. These were 40-mil (sheath OD) chromel-alumel couples with magnesium oxide insulation and a Type 304 stainless-steel sheath. After x-raying, those having sound uniform junctions were ground back until a response time of 45 msec was achieved as determined by the thermal comparator described in Reference 1. Of the original thermocouples, 66 survived this process and were accepted with response times of 46 ± 2 msec. These were bent at right angles near the junctions, as shown in Figure 10, and were arranged in the designed sequence outside the predrilled fin

Figure 10. Fin-Type Sensor With 14 Thermocouples

Figure 11. X-Ray of Thermocouple Fin

body with the junctions positioned in the holes. The TC's were strapped together in the resulting locations then placed inside the flattened tube with the junctions protruding outward. Brazing-alloy powder G.E. J8100 was applied at the points of penetration, and the assembly was heated to $2150 \pm 50^\circ\text{F}$ in vacuum by the heater element shown in Figure 13. The temperature along the length was monitored near the center and at each end-TC position by control TC's tack-welded to the sensor body. The configuration of the heater element (shown in Figure 14) and the use of three control TC's were established after finding that the center of the fin was overheated when the heater element was uniformly spaced from the fin. In developing this brazing process, several TC's were overheated on one fin assembly, and the body of another was melted due to failure of a control TC. Of the three sensor assemblies started, one good one was completed and found to be helium leaktight. The process was then repeated to prepare three additional sensors.

To complete the sensors a plug was heliarc-welded into the flattened end, and a bulkhead was brazed with Nicrobraz 50 at $1800 \pm 50^\circ\text{F}$ at the outer end. The bulkhead brazes being circular in cross-section were made by induction-heating in vacuum without incident. The finished sensor assembly is closed at both ends with an internal helium pressure of 9 psia at room temperature; this was calculated to provide an internal pressure of 25 psia when the sensor is in the test section at 1200°F . The loop pressure is expected to vary between 20 and 35 psia depending upon flowrate; therefore, the external pressure differential on the sensor will be between +17 and -5 psi. An open-junction TC is located in the helium-filled space as shown in Figure 11 to provide a means of detecting in-leakage of sodium.

B. FLOW SECTION

A 2-in. test section as shown in Figure 15 was fabricated for use in the water loop and sodium loops. Flanges for mounting the sensors across the flow-section diameters were located at 0-, 6-, 12-, 36-, and 60-in. positions in one plane and at positions 24- and 48-in. apart in a second plane normal to the first. The flow section was fabricated with flanges at its ends so that it could be bolted into the water loop. When the water tests were completed the flanges were removed and the flow section was dried and welded into the sodium loop. During installation,

Figure 13. Setup for Vacuum-Brazing Thermocouple Sensors

Figure 14. Shaped Heater Element for Brazing Thermocouple Fin

-01 ASSEMBLY
SCALE: $\frac{1}{4}$

-02 ASSEMBLY 4
SCALE: $\frac{1}{4}$

Figure 15. Transit Time Flowmeter, 2-in.-diam Test Section

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after the sensor nozzles were welded in place, it was found that the ID of the flow section was reduced by up to 0.030 in. due to post-welding shrinkage. The flow section was reamed and honed to a uniform diameter of 2.070 ± 0.004 in. to correct this condition.

The test section is designed to be bolted into the existing water loop during calibration. Test positions are provided with flanges and O-ring seals for ease of probe installation during water tests. While operating in the sodium-supply system, the pipe caps, flanges, and flow sensors were welded in place. Initially, use of Conoseal flanges was considered; however, this was decided against because of the delivery time and cost for the required 1-1/4-in. assemblies. For industrial applications Conoseal fittings would be desirable.

C. TEST INSTALLATION

1. Water Loop

The water loop shown in Figure 16 has a pumping capability up to about 160 gpm which provides velocities up to about 15 fps in the 2-in.-diam flow section.

The system is equipped with high-speed solenoid valves which permit flow from the test section to be diverted to a calibrated dump-tank system during the flow tests in order to achieve accurate flow determinations. The loop is also provided with a hot-water injection line, injection-line heaters, storage-tank heaters, and a pneumatic control valve. The hot-water injection line is used to induce thermal disturbances into the test sections. A control panel called the flow-test programmer is used to operate the storage and dump tank solenoids and the tape recorder during flow tests.

2. Sodium Loop

The 2-in. TTF sodium loop was designed to be connected into the AI-FBR sodium-supply system shown in Figure 17 as indicated in the flow diagram Figure 18. The configuration of the loop is shown in Figure 19. Sodium pumped by one or both of the 60-gpm supply-system pumps is circulated into the TTF loop, through the EM flowmeter to a tee, where part of the flow is passed through a heater at a rate controlled by use of a 1-1/2-in. angle valve. Flow passing through the heater is mixed with the other sodium stream just before entering the flow section described in the preceding section. From the flow section the sodium is returned to the sodium-supply system.

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Figure 16. Transit Time Flowmeter Water-Test Loop

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Figure 17. AI-FBR Sodium-Supply System

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Figure 19. Transit Time Flowmeter Test Loop

The TTF loop was installed in front of the AI-FBR system as shown in Figure 20. The flowmeter test section is accessible from three of the four sides.

The TTF loop construction followed the specification used for the high-temperature sodium-supply system.

The sodium-containing piping is seamless Schedule-40 Type 304 stainless steel with 0.04% carbon content minimum. All fittings and piping are Schedule 40 with butt-welded ends. The welds were visually inspected for uniformity and faults. Liquid dye-penetrant tests were required for both root pass and completed welds on sodium-containing pipe. All of the circumferential butt-welds were 100% radiographed.

Tubular heaters were installed on all sodium-containing piping. The valves have cartridge heaters. The heaters are designed to maintain system preheat to 1200°F. Thermocouples were welded onto the pipe surface to facilitate monitoring of the preheat temperatures.

A 15-kw immersion heater is located in one inlet line to the flowmeter test section. The heater input can be controlled to keep constant the temperature of the sodium flowing back to the main system from the TTF test loop. For this purpose a power controller and surface-mounted TC installed on the return piping are used (see Figure 21).

Removable high-temperature insulation suitable for 1200°F operation was installed around the sodium piping and attached electric heaters.

Figure 22 shows the test section with the conductivity electrodes and line heater installed. Figure 23 shows the completed installation during one of the test runs.

3. Test Instrumentation

Figure 24 is a photograph taken during one of the sodium-loop tests showing the instrumentation system used for acquisition and reduction of test data for both the water-loop and sodium-loop tests.

Wires from 14 TC's on each of four sensors are brought to the switch panel (setting on the instrument cart next to the tape recorder). Signals from individual TC's or the summation of selected combinations of them are amplified and

Figure 20. Transit Time Flow-meter Installation

PIPE HEATER & TC INSTALLATION
SCALE - 1" = 1'-0"

HEATER NUMBER	HEATER		VOLTAGE		WATTAGE		TC SEL. SWITCH POINT	THERMOCOUPLE DESIGNATION
	TOTAL	HEATER	COLD END	RATED	OPER.	RATED		
H501-1	15'-6"	11'-0"	6"	208	240	1160	TS-100-1	TC501-1
H501-2	11'-0"	11'-0"	0"	120	240	770	TS-100-2	TC501-2
H501-3	12'-0"	11'-0"	1"	120	240	770	TS-100-3	TC501-3
H501-4	4'-0"	3'-0"	1"	120	240	275	TS-100-4	TC501-4
H501-5	7'-0"	6'-0"	1"	120	240	365	TS-100-5	TC501-5
H501-6	4'-0"	3'-0"	1"	120	240	210	TS-100-6	TC501-6
H501-7	7'-0"	6'-0"	1"	120	240	480	TS-100-7	TC501-7
VH501-1	2'-0"	1'-0"	1"	60	120	19	TS-100-8	TCV501-1
VH501-2	2'-0"	1'-0"	1"	60	120	19	TS-100-9	TCV501-2
VH501-3	2'-0"	1'-0"	1"	60	120	19	TS-100-10	TCV501-3
VH501-4	2'-0"	1'-0"	1"	60	120	19	TS-100-11	TCV501-4
VH501-5	2'-0"	1'-0"	1"	60	120	19	TS-100-12	TCV501-5

DETAIL A
① ANGLE VALVE HEATER & TC INSTALLATION

Figure 21. Heater and Thermocouple Instrument Power and Control

Figure 22. Test Section With
Insulation Removed

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Figure 23. Completed
Installation

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Figure 24. Instrumentation System Used for Acquisition and Reduction of Test Data

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filtered before recording to optimize signal-to-noise ratios. Filters are passive RC circuits that are specially phase-matched to assure uniform response on all channels. Band-pass response extends from 0.1 to 30 Hz. (This was changed to 0.025 to 30 Hz for sodium tests.) Amplifiers (Dynamics, model 6631) are shown below the (C. E. C. VR 3300) tape-recording system. Also included in the same cart are: the digital clock (Anadex Scaler CF-200R) that provides precise 0.1 to 10 hz time signals; the Flow Test Programmer, for controlling the dump system and recorder during water-loop tests; the band-pass filters (described above); and the demodulator for use with the conductivity electrodes.

During the flow tests, signals from selected sensors are displayed on the multichannel chart recorder (Brush, model 260). Direct-current levels from two EM flowmeters, selected loop thermocouples, a run identification signal, and the outputs from the transit time computer are sequentially scanned and recorded in digital form by the (DYMEC, model DY-2010B) data-acquisition system.

Included in the instrument cart at the right, are: the Signal Correlator (PAR, model 101), the Transit Time Computer; the (Anadex-CF100) decade scaler and oscillator (time base reference for the Signal Correlator); dc power supply (Harrison Lab, 802B); and the ac-to-dc converters (DYMEC-2410B).

D. TEST METHODS

Following is a general description of the test-program procedure. The test section with particular sensor configuration was installed and recording instrumentation set up and checked out. The desired loop-flow conditions were set up by using the cathode-ray tube (CRT) display of the signal-correlator output as a flowmeter. Signals from two sensors, 1 ft apart, were correlated, and the transit time relating them was determined from the CRT display. Sensor signals were recorded on magnetic tape, with and without electrical power to the injector-line heater used to generate a thermal tracer.

Basic measurements from the TC sensors were made OFF-line from the FM tape recordings. These include rms level, peak correlation, transit delay time, and width of correlation peak. They are used to study propagation, deterioration, size, and velocity of temperature patterns in relation to sensor positions and hydraulic parameters.

The water-loop tests included velocities ranging from 1.4 to 15 ft/sec in the 2-in.-diam test section. The distance between sensors varied from 6 in. to 5 ft. Temperature patterns were induced by injecting a stream of hot water into the flow channel approximately 18-in. upstream of the first sensor. The injection flowrate was 1 gpm. Injection temperature ranged from 6 to 18°F above stream temperature. The loop volumetric flowrate was determined for each test by using an electrically operated dump-tank system. The time-base reference for all tests was a crystal-controlled 100-kHz oscillator accurate to a few ppm. The output of the oscillator scaled to 10 and 0.1 Hz respectively was recorded on magnetic tape during each test, along with sensor signals and logic signals from the flow-test programmer that operates the dump-tank solenoids.

The sodium-loop tests included velocities ranging from about 1.3 to 9.6 ft/sec and nominal operating temperatures of 500, 900, and 1200°F. A thermal tracer was injected into the flow channel approximately 9 in. upstream of the first sensor. Injection temperature with heater power on and injection-line valve wide-open, ranged from 5 to 52°F above stream temperature, depending on heater power and flowrate. At each flow and temperature condition, flow indications from 2 EM flowmeters were compared with transit-time measurements relating the six combinations of the recorded signals from the four TC fin sensors.

E. TEST DESCRIPTION

1. Water-Loop Tests

After installation and checkout of the sensors and completion of the 2-in.-flow section a preliminary calibration was run at a flow velocity of approximately 10 ft/sec to establish that the system was operating properly. This test indicated that good agreement existed between the flowrate indicated by the TTF and that measured by the dump-tank system. Following this a series of tests was run with the sensors located in the 18-, 53-, and 78-in. positions (with respect to injection point). With a flow velocity of approximately 10 ft/sec, the 54- and 78-in. position sensors were used to obtain reference average flow while the velocity profile was measured by signals from individual TC pairs.

Another series of tests was run with the sensors in the same position to obtain calibration for velocities of 1.4, 2.5, 4, 6, 10, and 15 ft/sec with averaged

signals from each sensor. These data provide comparisons of indicated flowrate from six combinations of sensors, i.e. six different sensor spacings.

The 78-in. position sensor was moved to the 24-in. position and at flow velocities of 6 and 10 ft/sec, data were obtained with this sensor shimmed out 0, 30, 60, and 90 mils from the nominal centered position. The objective of this effort was the evaluation of the effect on accuracy of radially mislocating the fin and TC's.

Finally, the sensor from the 24-in. position was moved to the 42-in. position which placed it perpendicular to the other sensors; velocity measurements were obtained from all sensor combinations for average velocities of 10 and 6 ft/sec.

The total series included 15 water-loop tests, listed in Table 1.

2. Sodium-Loop Tests

The sensors were installed at the 9-, 21-, 45-, and 69-in. positions (from injection point). With a maximum flow velocity of approximately 9.6 ft/sec and loop temperature of 500°F, signals were recorded from individual TC's and from summation of selected combinations of them on each sensor (from 2 to 14). Next, a series of five flow tests were run at nominal flowrates of approximately 10, 6, 4, 2.5, and 1.4 ft/sec.

Similar tests were run at nominal loop temperatures of 900 and 1200°F. Including flow, background, sensor configuration, and flow partition tests a total of 138 recordings was made for the series of 50 test runs listed in Table 2.

TABLE 1
TEST CONDITIONS FOR WATER-LOOP TESTS

Date	Run	Velocity (ft/sec)	Flowrate (gpm)	Loop Temper- ature (°F)	Injection Temper- ature (°F)	Notes
6/27/69	201	10.32	108.4	90	107	Loop checkout
7/7/69	202	10.29	108.1	90	107	Velocity-profile study
7/8/69	203	10.21	107.2	80	97	Calibration test
	204	5.956	62.52	84	94	
	205	4.087	42.91	85	93	
	206	2.451	25.73	86	92	
	207	1.412	14.82	87	96	
7/9/69	208	14.67	154.0	84	104	
	209	6.230	65.40	85	95	Axial-fin change
	210	9.570	100.5	86	103	Axial-fin change
	211	9.605	100.8	87	104	Radial-fin change
	212	9.625	101.0	88	105	
	213	9.571	100.5	89	106	
	214	9.970	104.7	90	108	Axial-fin change, 90°
	215	6.226	65.36	90	98	Axial-fin change, 90°

TABLE 2
TEST CONDITIONS FOR SODIUM-LOOP TESTS

Date	Run	Nominal Flow (ft/sec)	Loop Temperature (°F)	Injection ΔT (°F)	Notes
10-1-69	501-1 to 14	9.57	508	5	Velocity profile study
	502	9.63	502	5	14 TC summation
	503	9.59	502	5	12 TC summation
	504	9.61	502	5	10 TC summation
	505	9.60	502	5	8 TC summation
	506	9.59	502	5	8 TC summation
	507	9.57	506	5	6 TC summation
	508	9.58	504	5	6 TC summation
	509	9.62	504	5	4 TC summation
	510	9.58	504	5	2 TC summation
	511	9.62	506	5	14 TC summation
10-2-69	512	9.57	502	5	Flow test
	513	6.15	482	8	Flow test
	514	3.89	500	13	Flow test
	515	2.51	522	20	Flow test
	516	1.32	510	35	Flow test
10-3-69	901	8.82	829	8	Flow test
	902	6.11	837	11	Flow test
	903	4.07	842	17	Flow test
	904	2.51	844	27	Flow test
	905	1.36	835	52	Flow test
10-7-69	906-1 to 14	9.11	827	8	Velocity-profile study
	907	8.87	888	9	Velocity-profile study
	908-1 to 14	4.29	878	16	Velocity-profile study
	909	4.26	900	17	Velocity-profile study
10-29-69	1001	9.2	941	10	Flow portion study, valve open
	1002	9.2	939	87	Flow portion study, closed 1 turn
	1003	9.2	990	135	Flow portion study, closed 2 turns
	1004	9.2	956	242	Flow portion study, closed 3 turns
	1005	9.2	958	308	Flow portion study, closed 4 turns
10-30-69	1201	2.23	1167	45	Flow test
	1202	3.32	1171	30	Flow test
	1203	5.73	1154	17	Flow test
	1204	6.64	1135	15	Flow test
	1205	8.99	1100	11	Flow test
11-22-69	1206	7.83	1178	9	Flow portion study
	1207	7.69	1179	80	Flow portion, closed 1 turn
	1208-1 to 14	7.76	1186	9	Velocity-profile study
	1209	7.76	1188	9	14 TC summation
	1210	7.73	1189	9	12 TC summation
	1211	7.76	1190	9	10 TC summation
	1212	7.73	1190	9	8 TC summation
	1213	7.77	1191	9	6 TC summation
	1214	7.80	1191	9	4 TC summation
	1215	7.82	1192	9	2 TC summation
	1216	7.77	1192	9	14 TC summation
11-23-69	1217	3.35	1208	21	Flow portion study
	1218	3.35	1207	160	Flow portion study, closed 1 turn
	1219-1 to 14	3.36	1208	21	Velocity-profile study
	1220	3.36	1206	21	Velocity-profile study

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III. TEST RESULTS

The test program is designed to accomplish the following objectives: (1) demonstrate the Transit Time Flowmeter technique to flow measurement in liquid sodium at temperatures up to 1200°F; (2) obtain comparative performance data of a TTF of fixed design in water and sodium; and (3) obtain experimental data relating the potential accuracy of the technique to the number and position of instream sensors, amount and type of heat injection, operational and measurement techniques. This information is intended for use in evaluation of the method and design of sensor configurations for future tests and applications.

This section summarizes the major test results beginning with a study of the propagation of temperature patterns in water and sodium. Measurements and empirical models are given relating the amplitude and bandwidth of sensor signals as functions of sensor position, flowrate, and heat-input rate. Measured flowrate as determined by transit-time measurements relating each of six combinations of four sensors is compared with a reference flowrate (volumetric/time measurements, for the water-loop tests) as functions of (1) mean distance of the sensor pair from the injection point, (2) the mean fluid transit time from the injection point to the sensors, (3) radial-sensor displacement, (4) angular-sensor misalignment, (5) instrumentation bandwidth, (6) the number and radial position of TC's on each fin, and (7) the method for combining temperature signals or measurements from sets of temperature signals for determining average flowrate. The results show methods for detecting and correcting systematic errors in transit-time flow measurements related to the above parameters, and indicate how such errors can be reduced or eliminated in future flowmeter installations.

Sodium-velocity measurements by the transit-time method are compared with relative velocity indications from 2 EM flowmeters. Attempts to detect temperature patterns in sodium by use of conductivity sensors are also discussed.

A. LENGTH OF TEMPERATURE PATTERNS

Turbulent mixing of the main and injection flowstreams tends to create random-temperature fields or temperature patterns that propagate along the

flow channel and are detected at the sensors as time-varying temperature signals. Information on the size (length) of these patterns at various sensor positions and flowrates may be obtained by measuring the average time interval between the "zero" crossings of the sensor signals. The Transit Time Computer is designed to provide a measurement of this quantity, which is equivalent to the decay time constant of the sensor signals (time for the normalized autocorrelation function to decay to a value of $1/e$). See Figures 8 and 9 as examples of the effects of time, distance, and flow on the autocorrelation function of sensor signals.

Measurements of the decay time constants of the signals from the four sensors (in water) for various flow conditions are plotted in Figure 25 as a function of the fluid-transport time from the injection point to the sensor. Results shown in the figure indicate the decay time constant of the summation signals from TC fin assemblies increased (bandwidth decreased) as a function of the average fluid-transport time from the injection point to the sensor. For this particular test configuration the decay time constant was approximately $0.1t + 0.05$ sec, where t is the average fluid-transport time from the injection point to the sensor. The 0.05-sec offset is related to the initial size of temperature patterns at the injection point and the total lag time of the TC's and associated instrumentation.

If we assume that Δt is the average time for temperature patterns propagating at a velocity to pass a sensor at a distance (x) from the injection point, then the average length of the temperature patterns (L) is given by:

$$L = v\Delta t = \frac{x}{t} \Delta t = \frac{\Delta t}{t} x .$$

Thus the average length (or average increase in length from the injection point) of temperature patterns passing a sensor is directly proportional to the distance from the injection point. In the example mentioned above $\Delta t/t$ is 0.1; therefore, for each 10-unit length from the injection point the average length of temperature patterns will increase by 1-unit length.

Figure 26 shows measurements of the decay time constant of signals from the same sensors, in the same relative positions in the same flow section, but with sodium flowing at approximately 1200°F. By comparing Figures 25 and 26 it may be noted that for fluid-transport times up to about 1 sec the difference

Figure 25. Measurements of the Decay Time Constants of
 Sensor Signals in Water vs Average Fluid-Transport
 Time From Injection Point to Sensor

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Figure 26. Measurements of Decay Time Constants of Sensor Signals in Sodium vs Average Fluid-Transport Time From Injection Point to Sensor (sodium at 1200°F)

in the growth rates of temperature patterns in sodium and water is not significant. The observed differences at fluid-transport times above about 1.5 sec are due at least in part, to the use of filters with a lower ac cutoff frequency in the sodium tests. Approximately the same sampling time (about 5 min) was used in both cases. The existence of the lower-frequency components in the signals from the sodium tests tended to make the autocorrelation measurements less stationary at low flowrates and the determination of the $1/e$ decay time less precise than corresponding measurements from water tests.

Another factor that could affect the above relationship is the difference in the size and geometry of the injection lines at the injection point. For the water tests the injection line was a 0.25-in.-diam tube in a 2-in. channel. For the sodium tests the injection line was a 1.25-in.-diam pipe in a 3.5-in.-diam mixing tee (see detail "C" in Figure 20). This would tend to affect the initial average size of the temperature patterns at the injection point. In a later section it will be shown that the difference in geometry and injection rates for the water and the sodium tests had a significant effect on the acceleration and dispersion of the thermal tracer.

B. AMPLITUDE OF TEMPERATURE SIGNALS

Previous studies⁽¹⁾ of the propagation and deterioration of temperature patterns in water were limited to sensor positions ranging from 57 to 96 in. from the injection point. Results indicated that signal amplitude from a TE fin sensor decays inversely proportional to the distance from the injection point (see Figure 6).

The present water-loop test data include amplitude measurements for sensor positions from 18 to 78 in. Figure 27 shows the observed decay of signal amplitude as a function of sensor distance from the injection point. The normalized measurements in Figure 27 indicate that signal amplitude is proportional to $1/(1 + 0.13x)$ where x is the distance from the injection point in inches.

Results from these and previous studies of the length and amplitude of temperature patterns led to the conclusion that temperature patterns in water are elongated as a function of distance by the radial variation in stream velocity. Thus if the velocity difference between two concentric annular regions in a flow-stream is 1 ft/sec a temperature pattern common to the two regions would be

Figure 27. Amplitude of Summation Signals From Thermocouple Fin Assemblies in Water Tests

spread by 1 ft each second. This stretching effect, with the help of turbulent mixing, tends to dilute or diminish the concentration of the thermal tracer. For example, consider a 1-ft-long cylindrical volume of the thermal tracer at an average temperature of 10°F above stream temperature. At some distance downstream of that point the cylindrical volume will have lengthened by 1 ft, occupy twice the original volume, and have an average temperature of about 0.5°F above stream temperature. The average length increases linearly with distance and the average-concentration (average-temperature difference) decreases proportionally.

Typical signal levels for these tests were on the order of $0.25\text{ }\mu\text{volt rms}$ or 0.01°F rms at the second sensor, or about 0.1°F peak-to-peak at the first sensor. The peak-to-peak signal amplitude at the first sensor (six times the rms level) was approximately equal to the ratio of injection flow to total flow times the temperature difference between the injection and main flows.

Measurements of signal amplitude ($\mu\text{volt rms}$) for the sodium tests (Runs 1201 to 1205) are shown in Figure 28. Figure 29 shows the same measurements (at five flow conditions) scaled to peak-to-peak ($^{\circ}\text{F}$) and divided by the temperature difference between the injection and inlet-flow lines.

The similarity of the results shown in Figures 6, 27, and 29 implies that the decay of temperature patterns in a flow channel is related to mechanical or geometrical factors rather than to differences in the thermal properties of the fluids.

The measurements of signal amplitude described above were obtained by measuring rms signal levels, both with and without heat injection. The values shown above represent the square root of the difference in the squares of the measured rms levels, with and without heat injection. For the case of the water tests there were virtually no detectable temperature patterns without heat injection. Since the entire water-test loop was at approximately room temperature, no heat transfer at any point in the loop could create significant temperature patterns. However, in the 1200°F sodium tests the signal levels at the second and following sensors were 60 to 100% of the net levels obtained with a 12-kw heat input in the injection line, because of heat-transfer (heat losses) at the preceding uninsulated-sensor nozzles. Background signal levels at the four sensor positions for Runs 1201 through 1205 are shown in Figure 30.

Figure 28. Amplitude of Signals Created by Injection of Thermal Tracer in 1200°F Sodium Tests

Figure 29. Relative Signal Amplitude at Five Flow Conditions; Sensor- ΔT /Source- ΔT

The test loop (see Figure 23) is well insulated except at points corresponding to the injection-line valve, injection-line heater, and sensor installation nozzles. Note in Figure 30 that the signal levels at the first (9-in.) sensor position are, without heat injection, an order of magnitude less than the corresponding signal levels in Figure 28 with heat injection.

Summation signals from each of the four thermocouple fin sensors for two flow conditions, both with and without power to the injection-line heater, are similar to Figure 5. Note the effects described above. It is also possible to see some correlations between sensor signals and observe the respective signal transport delays.

C. VELOCITY OF TEMPERATURE PATTERNS

Recorded signals were reproduced at eight times recording speed; measurements of transit time, peak correlation, width of the correlation function, and rms levels were recorded as functions of time for selected signal pairs in analog form on a multichannel chart recorder and in digital form using a line printer. Digital measurements of transit time were recorded in effective real-time increments of 30 sec. Ten consecutive samples were averaged to represent "measured" flow velocity for each of six sensor pairs for each test run. For the water tests, "average" flow values were determined by using the dump-tank system.

Figure 31 is a plot of measured velocity of temperature patterns in water (using the signal summation method) as a function of the mean axial distance from the injection point to the sensors for average flowrates from 1.41 to 14.7 ft/sec. These results indicate the presence of systematic errors in measured velocity of temperature patterns at high flow velocities.

The TTF is based on the assumption that inherent or induced temperature disturbances in a flowing stream are propagating at the average velocity of the fluid. Previous tests in water verified that this assumption was valid for cases where the average fluid-transport time from the injection or source point in a 2-in.-diam flow channel to the TC sensors was at least 0.393 sec.*

*At maximum velocity 14 ft/sec and minimum average sensor distance from injection point of 5.5 ft

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Figure 30. Rms Amplitude of Inherent Background Signals Observed in 1200°F Sodium Tests, With No Power on Injection-Line Heater

Figure 31. Measured Velocity in Water vs Mean Axial Position of Sensor Pair

The present water-test data include measurements of the velocity of temperature patterns where the average fluid-transport time from the injection point to the sensors is as small as 0.136 sec. Figure 32 shows the ratio of the measured velocity of temperature patterns to the average flow velocity using the TTF method; this was determined using the dump-tank system, as a function of the average fluid-transport time from the injection point to the sensors. These results indicate an apparent discrepancy between the measured velocity of temperature patterns and the average fluid velocity for cases where the average fluid-transport time, t , from the injection point to the sensors is less than 0.35 sec. The observed fractional discrepancy, E , may be approximated by the following empirical relation.

$$E = \frac{2^{-10t}}{5} \quad \dots (1)$$

Figure 33 shows the data in Figure 32 corrected using Equation 1.

Measured-to-average flow ratios averaged over all axial positions both with and without correction factors are given in Table 3 as a function of flowrate.

The nature of the observed discrepancy between measured velocity of temperature patterns and average fluid velocity for short fluid-transport times is indicated by the shape of the measured velocity profile in Figure 34. The non-symmetrical pattern indicates a poorly developed profile. Apparently a minimum

TABLE 3
MEASURED/AVERAGE FLOW RATIO vs FLOWRATE

Run	Average Flow (ft/sec)	Axial Average of Measured/Average Flow	Axial Average with Correction for End Effects
208	14.67	0.967	1.002
202	10.29	0.981	1.001
204	5.96	0.996	1.001
205	4.09	0.999	1.001
206	2.45	1.022	1.022
207	1.41	1.015	1.015

Figure 32. Measured/Average Flow Ratio vs Average Fluid-Transport Time From Injection Point

Figure 33. Data From Figure 32 Corrected for End Effects

Figure 34. Measured Velocity Profile in Water Showing Nonsymmetrical Flow Distribution Near Injection Point

of about 0.35 sec is required for the heated injection fluid to achieve symmetrical dispersion across the channel and accelerate to the average stream velocity. This is discussed in more detail in Section III-D, Velocity-Profile Integration.

Test results described in a later section will show that time measurements due to variations in the radial or angular alignment of sensors diminish as the distance between sensors increases. Errors related to the dispersion and acceleration of the thermal tracer were smallest for sensors located far (in time) from the injection point. Table 4 is a summary of the results obtained using sensor combinations with maximum separation (5 and 4 ft). Note that for flow velocities up to 10 ft/sec all measurements with these sensor combinations are within 2% of the average flow. With corrections for end effects the measurements at flowrates above 4 ft/sec are within a band of $\pm 1.5\%$ of average flow.

In the sodium tests there was no means for obtaining volume/time measurements of average flow. Therefore an average of the measured flow with these two sensor combinations is used as the reference flowrate in the sodium tests.

Figure 35 is a plot of measured velocity of temperature patterns in 1200°F sodium (using the signal-summation method) as a function of the mean axial distance from the injection point to the sensors. These measurements indicate the presence of errors in measured velocity of temperature patterns which relate to specific axial positions.

To investigate the axial variations in measured flowrates the ratios of measured to reference flow were computed for all sodium tests involving summation of 14 TC's (see Table 2). Figure 36 is a plot showing the mean (± 3 std error) of the ratios at the various axial positions for all flow conditions above 2 ft/sec.

Results from the water tests indicate the radial dispersion and acceleration of the thermal tracer to the average stream velocity was a function of time, (the ratio of distance and flowrate). Results of sodium tests indicate that these effects are a function of distance along the flow channel, independent of flowrate. The difference is apparently related only to the test configurations, not fluid properties. In the sodium tests the injection rate was proportional to total flowrate; in the water tests, injection flowrate was held constant, independent of flowrate.

TABLE 4

FLOW MEASUREMENTS OBTAINED USING SENSOR PAIRS 5- AND 4-ft APART

Run	Average Flow (ft/sec)*	Sensor Pair (in.)	Measured Flow (ft/sec)†	Ratio Measured/ Average Flow	Measurement/ Average Flow Ratio with Correction for End Effects
208	14.67 ± 0.08	18 and 78	14.19 ± 0.10	0.967	0.995
	14.67 ± 0.08	30 and 78	14.56 ± 0.10	0.986	1.000
202	10.29 ± 0.05	18 and 78	10.12 ± 0.06	0.983	0.999
	10.29 ± 0.05	30 and 78	10.19 ± 0.04	0.990	1.003
204	5.96 ± 0.03	18 and 78	5.88 ± 0.03	0.987	0.989
	5.96 ± 0.03	30 and 78	5.99 ± 0.03	1.006	1.005
205	4.09 ± 0.02	18 and 78	4.09 ± 0.02	1.000	1.000
	4.09 ± 0.02	30 and 78	4.09 ± 0.02	1.000	1.000
206	2.45 ± 0.01	18 and 78	2.49 ± 0.03	1.014	1.014
	2.45 ± 0.01	30 and 78	2.50 ± 0.01	1.020	1.020
207	1.412 ± 0.01	18 and 78	1.425 ± 0.008	1.009	1.009
	1.412 ± 0.01	30 and 78	1.434 ± 0.004	1.016	1.016

*Volume/time measurement (±3 std error)

†Average of 10 transit-time samples (±3 std error)

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Figure 35. Measured Velocity in 1200°F Sodium vs Mean Axial Position of Sensor Pair

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Figure 36. Measured/Reference Flow Ratio vs Mean Axial Position of Sensor Pair

For the water tests the corrections to be applied to the transit-time measurements for the acceleration of the thermal tracer were dependent on transit from the injection point (a function of distance and flowrate). For the configuration used in the sodium tests the correction term is independent of flowrate. The advantage of this latter configuration for future applications is obvious.

Figure 37 is a plot of the data in Figure 35 with corrections for the acceleration of the thermal tracer (end effects).

The use of four instream sensors makes it possible to obtain transit time or velocity measurements for six sensor-pair combinations. An average of the six measurements corrected for end effects should provide an optimum estimate of average flow velocity. However as indicated in Figure 36 and a discussion of measurement errors in another section of this report, velocity measurements for certain sensor combinations have lower probable error than other combinations. The optimum weighting factor⁽³⁾ for averaging samples with different probable error is inversely proportional to the square of the standard deviation of those samples. Therefore to compute the "axial mean" flow velocity for each test in water and sodium the corrected measurements for each of six axial positions were weighted by the reciprocal of the square of their respective probable errors (including that of the correction factor). Table 5 provides a summary of the flow measurements in water and sodium (with identical sensor configurations). Note the close relation of Average Flow, Reference Flow and Axial Mean Flow for the tests in water, and the corresponding relation between Reference Flow and Axial Mean Flow in sodium.

Note the close relationship of flow measurements with various numbers of TC's (Runs 502 to 511 and 1209 to 1216). The measurements were consistent within 1% for 2, 4, 6, 8, 10, 12, or 14 TC's per sensor.

It should be noted that the weighting factors used to compute axial mean flow had an effect of only a few tenths of a percent as compared to the unweighted mean. These weighting factors were observed to be essentially proportional to the distance between sensors. Therefore, in future TTF applications estimates of axial mean velocity, V_{AM} , will be computed directly from individual transit-time measurements, T_i , and the distances between sensors, X_i , by $V_{AM} = \sum X_i / \sum T_i$. This function is far simpler to compute than the weighted axial mean described above, and yet based on empirical observations it is essentially equivalent to the weighted axial mean.

TABLE 5
COMPARISON OF FLOW MEASUREMENTS IN WATER WITH THOSE IN SODIUM

Run	Fluid	Average Flow (ft/sec)	Reference Flow (ft/sec)	Ratio Ref/Avg Flow	Weighted Axial Mean Flow (ft/sec)	Ratio Axial Mean Average Flow	Ratio Axial Mean Ref Flow	Notes
201	Water (80°F)	10.32 ± 0.08	10.35 ± 0.04	1.003	10.35 ± 0.02	1.003	1.000	Loop checkout
202		10.29 ± 0.05	10.30 ± 0.04	1.001	10.30 ± 0.05	1.001	1.000	Calibration test
204		5.96 ± 0.03	5.94 ± 0.03	0.997	6.00 ± 0.03	1.007	1.010	Calibration test
205		4.09 ± 0.02	4.09 ± 0.02	1.000	4.09 ± 0.02	1.000	1.000	Calibration test
206		2.45 ± 0.01	2.49 ± 0.02	1.016	2.49 ± 0.02	1.016	1.000	Calibration test
207		1.412 ± 0.01	1.429 ± 0.005	1.012	1.433 ± 0.010	1.015	1.003	Calibration test
208		14.67 ± 0.08	14.64 ± 0.10	0.998	14.78 ± 0.10	1.007	1.010	Calibration test
501-1 to 14	Sodium (500°F)		9.62 ± 0.08		9.61 ± 0.02		0.999	Velocity profile study
502			9.68 ± 0.03		9.65 ± 0.02		0.997	14 TC summation
503			9.63 ± 0.03		9.62 ± 0.03		0.999	12 TC summation
504			9.66 ± 0.03		9.64 ± 0.03		0.998	10 TC summation
505			9.65 ± 0.03		9.65 ± 0.03		0.998	8 TC summation
506			9.61 ± 0.03		9.62 ± 0.02		1.001	8 TC summation
507			9.63 ± 0.04		9.63 ± 0.02		1.000	6 TC summation
508			9.63 ± 0.04		9.64 ± 0.03		1.001	6 TC summation
509			9.67 ± 0.04		9.68 ± 0.03		1.001	4 TC summation
510			9.62 ± 0.04		9.61 ± 0.03		0.999	2 TC summation
511			9.67 ± 0.03		9.66 ± 0.02		0.999	14 TC summation
512			9.62 ± 0.03		9.60 ± 0.02		0.998	Flow test
513			6.18 ± 0.03		6.18 ± 0.03		1.000	Flow test
514			3.91 ± 0.02		3.94 ± 0.01		1.008	Flow test
515	Sodium (900°F)		2.569 ± 0.010		2.569 ± 0.013		1.000	Flow test
516			1.281 ± 0.010		1.323 ± 0.011		1.033	Flow test
901			8.87 ± 0.03		8.84 ± 0.01		0.997	Flow test
902			6.13 ± 0.02		6.12 ± 0.01		0.998	Flow test
903			4.09 ± 0.02		4.09 ± 0.01		1.000	Flow test
904			2.513 ± 0.014		2.542 ± 0.003		1.012	Flow test
905			1.367 ± 0.011		1.380 ± 0.010		1.010	Flow test
906-1 to 14			9.16 ± 0.03		9.15 ± 0.02		0.999	Velocity profile study
907			8.92 ± 0.03		8.92 ± 0.02		1.000	14 TC summation
908-1 to 14			4.31 ± 0.02		4.31 ± 0.01		1.000	Velocity profile study
909			4.28 ± 0.02		4.27 ± 0.01		0.998	14 TC summation
1201	Sodium (1200°F)		2.26 ± 0.01		2.26 ± 0.01		1.000	Flow test
1202			3.37 ± 0.01		3.37 ± 0.01		1.000	Flow test
1203			5.82 ± 0.02		5.82 ± 0.02		1.000	Flow test
1204			6.74 ± 0.02		6.74 ± 0.02		1.000	Flow test
1205			9.18 ± 0.03		9.15 ± 0.02		0.997	Flow test
1206			7.87 ± 0.03		7.85 ± 0.02		0.997	Flow portion study
1207			7.73 ± 0.02		7.73 ± 0.02		1.000	Valve closed 1 turn
1208-1 to 14			7.80 ± 0.03		7.79 ± 0.02		0.999	Velocity profile study
1209			7.79 ± 0.03		7.80 ± 0.02		1.001	14 TC summation
1210			7.77 ± 0.03		7.76 ± 0.02		0.999	12 TC summation
1211			7.81 ± 0.03		7.80 ± 0.02		0.999	10 TC summation
1212			7.78 ± 0.02		7.78 ± 0.02		1.000	8 TC summation
1213			7.81 ± 0.03		7.82 ± 0.02		1.001	6 TC summation
1214			7.85 ± 0.03		7.85 ± 0.02		1.000	4 TC summation
1215			7.86 ± 0.03		7.90 ± 0.02		1.005	2 TC summation
1216			7.81 ± 0.03		7.81 ± 0.02		1.000	14 TC summation
1217			3.37 ± 0.01		3.37 ± 0.01		1.000	Flow portion test
1218			3.36 ± 0.01		3.36 ± 0.01		1.000	Valve closed 1 turn
1219-1 to 14			3.38 ± 0.01		3.39 ± 0.01		1.003	Velocity profile study
1220			3.38 ± 0.01		3.38 ± 0.01		1.000	14 TC summation

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Figure 37. Measured Velocity in 1200°F Sodium
(with corrections for end effects) vs
Mean Axial Position of Sensor Pair

D. VELOCITY-PROFILE INTEGRATION

The detailed analysis of the test data up to this point has been centered around the evaluation of the signal-summation technique for transit-time flow measurement. This signal-summation technique involves the use of resistive summation networks to combine the signals from the 14 TC's on each TC fin sensor. Measurements of the average transport delay time between the summation signals from any two TC fin sensors with known spacing are used to estimate average flowrate.

A second method called velocity-profile integration involves measurement of the transport-delay times relating signals from individual TC's at the same radial positions on two TC fin sensors. Estimates of average flowrate are obtained by averaging the transit time or velocity samples at the various radial positions.

To illustrate this method let us begin with the data in Figure 34, the measurements being listed in Table 6. This particular example involves an extreme case of radial asymmetry related to the injection of the thermal tracer. As indicated in a previous section, in cases where the average fluid-transport time from the injection point to the sensors is greater than 0.35 sec a more symmetrical velocity profile is expected. This is illustrated by comparison of the data in Figures 38 and 34, the measurements in Figure 38 being listed in Table 7.

Figures 39 and 40 show velocity profiles measured in sodium at 1200°F which correspond to the same sensor combinations as the measurements in Figures 34 and 38, respectively. Table 8 is a listing of the velocity measurements in Figures 39 and 40 respectively.

One basic reason for using as many as 14 TC's on the fin sensors was to permit flexibility in choosing the number of velocity samples to be averaged to obtain an estimate of average flow in the test section. Table 9 indicates the optimum combination of the 14 available velocity samples to be averaged for even numbers of samples from 2 to 14 where the selection of radial samples to be averaged is based on the Chebyshev sampling method.

Table 10 is a listing of averages for even numbers of radial-velocity samples from 2 to 14 for two sensor-pair combinations, for both water and sodium.

TABLE 6
VELOCITY MEASUREMENTS IN WATER AT 14 RADIAL
POSITIONS BETWEEN THERMOCOUPLE FIN
ASSEMBLIES AT 18- AND 30-in. POSITIONS

Thermocouple No.	Radial Position* of Thermocouples (in.)	Measured Velocity† (ft/sec)
1	1.00	9.72 ± 0.029
2	0.90	10.16 ± 0.053
3	0.84	10.64 ± 0.032
4	0.73	10.17 ± 0.047
5	0.60	10.26 ± 0.015
6	0.50	10.22 ± 0.052
7	0.25	10.51 ± 0.050
8	0.25	10.71 ± 0.028
9	0.50	10.13 ± 0.014
10	0.60	10.14 ± 0.025
11	0.73	9.72 ± 0.017
12	0.84	7.83 ± 0.046
13	0.90	7.11 ± 0.087
14	1.00	7.21 ± 0.043

*Nominal pipe radius = 1.035 in.

†± std error of mean of 10 transit-time samples

Figure 38. Measured Velocity Profile in Water Showing
Partially Developed Flow Distribution
54 in. From Injection Point

TABLE 7
VELOCITY MEASUREMENTS IN WATER AT
14 RADIAL POSITIONS BETWEEN THERMO-
COUPLE FIN ASSEMBLIES AT 30- AND
78-in. POSITIONS

Thermocouple No.	Measured Velocity* (ft/sec)
1	10.43 $\pm$ 0.106
2	10.34 $\pm$ 0.085
3	10.37 $\pm$ 0.085
4	10.36 $\pm$ 0.042
5	10.41 $\pm$ 0.085
6	10.28 $\pm$ 0.026
7	10.40 $\pm$ 0.060
8	10.10 $\pm$ 0.093
9	9.73 $\pm$ 0.056
10	9.62 $\pm$ 0.068
11	9.40 $\pm$ 0.156
12	9.88 $\pm$ 0.086
13	10.13 $\pm$ 0.183
14	10.39 $\pm$ 0.261

* $\pm$ std error of mean of 10 transit-time
samples

Figure 39. Measured Velocity Profile in Sodium Showing Nonsymmetrical Flow Distribution Near Injection Point

Figure 40. Measured Velocity Profile in Sodium Showing Partially Developed Flow Distribution 45 in. From Injection Point

TABLE 8
VELOCITY MEASUREMENTS IN 1200°F SODIUM AT 14 RADIAL
POSITIONS FOR TWO SENSOR-PAIR COMBINATIONS

Thermocouple No.	Measured Velocity for Sensors (ft/sec)*	
	9- and 21-in. Positions	21- and 69-in. Positions
1	7.87 ± 0.062	8.01 ± 0.046
2	8.01 ± 0.064	8.03 ± 0.053
3	8.36 ± 0.066	8.04 ± 0.018
4	7.70 ± 0.066	7.86 ± 0.029
5	7.32 ± 0.058	7.76 ± 0.035
6	7.19 ± 0.074	7.84 ± 0.064
7	7.02 ± 0.093	7.90 ± 0.022
8	6.89 ± 0.047	7.84 ± 0.036
9	7.07 ± 0.031	7.89 ± 0.029
10	7.42 ± 0.071	7.64 ± 0.055
11	8.48 ± 0.060	7.49 ± 0.026
12	9.52 ± 0.116	7.43 ± 0.040
13	8.72 ± 0.136	7.53 ± 0.049
14	7.50 ± 0.088	7.55 ± 0.047

*± Std error of mean of 10 transit-time samples

TABLE 9
THERMOCOUPLE SELECTIONS FOR
RADIAL AVERAGING

Thermocouple No.	Number of Radial Samples Included Average						
	14	12	10	8	6	4	2
1	x	x	x				
2	x	x		x	x	x	
3	x	x	x	x			
4	x		x		x		x
5	x	x	x	x			
6	x	x		x	x	x	
7	x	x	x				
8	x	x	x				
9	x	x		x	x	x	
10	x	x	x	x			
11	x		x		x		x
12	x	x	x	x			
13	x	x		x	x	x	
14	x	x	x				

TABLE 10

COMPARISON OF FLOW MEASUREMENTS USING SUMMATION METHOD AND
VELOCITY-PROFILE INTEGRATION METHOD

Reference Flow Measurement (ft/sec)	Number of Radial Samples per Sensor	Flow Measurements (ft/sec)			
		Between 1st and 2nd Sensor Position		Between 2nd and 4th Sensor Position	
		Velocity-Profile Integration Method	Summation Method	Velocity-Profile Integration Method	Summation Method
10.30 ± 0.05 (Water) Run 202	14	9.61 ± 0.33	9.79 ± 0.05	10.13 ± 0.09	10.19 ± 0.04
	12	9.55 ± 0.39	-	10.17 ± 0.08	-
	10	9.69 ± 0.38	-	10.14 ± 0.12	-
	8	9.56 ± 0.47	-	10.10 ± 0.11	-
	6	9.59 ± 0.50	-	10.04 ± 0.16	-
	4	9.41 ± 0.77	-	10.12 ± 0.14	-
	2	9.95 ± 0.23	-	9.88 ± 0.48	-
7.80 ± 0.03 (1200°F Sodium) Runs 1208 to 1215	14	7.79 ± 0.20	7.37 ± 0.07	7.77 ± 0.06	7.78 ± 0.04
	12	7.74 ± 0.23	7.36 ± 0.05	7.79 ± 0.06	7.72 ± 0.05
	10	7.81 ± 0.25	7.25 ± 0.07	7.75 ± 0.07	7.78 ± 0.04
	8	7.95 ± 0.31	7.27 ± 0.06	7.77 ± 0.08	7.73 ± 0.04
	6	7.86 ± 0.27	7.45 ± 0.06	7.77 ± 0.09	7.76 ± 0.03
	4	7.75 ± 0.39	7.42 ± 0.05	7.82 ± 0.11	7.78 ± 0.04
	2	8.09 ± 0.39	7.70 ± 0.05	7.68 ± 0.19	7.78 ± 0.04

tests. Velocity measurements using the summation method (without corrections for end effects) are also listed for 14 radial samples per sensor in the water tests and for all even numbers of radial samples per sensor from 2 to 14 in the sodium tests. Reference flow measurements (from Table 5) are also included in Table 10.

Note that for velocity measurements between sensors 4-ft apart (the second and fourth sensor positions) the number of samples per sensor has some effect on probable error but very little (approximately 1 to 2%) on measured flow velocity. Also note the close agreement between the summation and velocity-profile-integration methods for measurements in sodium between sensors 4-ft apart.

E. FACTORS AFFECTING ACCURACY

The following section includes a discussion of errors in transit-time measurements related to instrumentation bandwidth, alignment of temperature sensors, and distorted or marginal correlation functions.

1. Bandwidth of Temperature Signals

As random-temperature patterns pass a given sensor, temperature signals are created with frequency components (depending in the size, shape, and velocity of temperature patterns) extending from essentially zero Hz (or dc) up to the frequency limits of the sensor. The autocorrelation measurements of the decay time constant, T , of temperature signals provide direct measurements of the upper cutoff frequency or half-power bandwidth, f_c , where $f_c = 1/(2\pi T)$.

Results of the autocorrelation studies show that the upper-cutoff frequency of temperature signals is a function of the fluid-transport time from the injection point to the sensor. This is a function of both flowrate and sensor position.

Considerable effort was given to assure that all sensors, amplifiers, and filters had minimum practical time response. Also the response times of all sensors and instruments were matched to minimize errors in transit-time measurements.

At high flowrates and axial positions near the injection point, small or fast-moving temperature patterns cause rapid temperature fluctuations. Since temperature patterns tend to pass center-stream TC's at a faster rate and have

higher frequency components than edge TC's, it is reasonable to assume that in extreme cases of high flow, short fluid-transport times from the injection point, and the use of slow response TC's the low-pass filtering effect of the TC's could change the effective weighting of the signals from the TC's at various radial positions. If the TC's used to obtain radial samples have a time response long compared to the average time for temperature patterns to pass, the slower-moving temperature patterns near the channel wall will result in larger signals than at the center. The transit time measured by cross-correlation of the summation signals from sensors at two axial positions would be dominated by the correlations of signals from TC's in the slower-velocity regions. Measured transit time would tend to be longer, or measured velocity would tend to be lower than average velocity. This limitation may be partially responsible for the observed discrepancies between measured and average flow described in the previous section.

In previous water-loop tests with TC fins smaller TC's with faster response were used (20- vs 40-mil sheath OD). The response of 20-mil TC's is approximately four times as fast as 40-mil. Thus the effects described above would tend to be negligible in previous tests.

The tendency for temperature patterns to pass center-stream TC's at a faster rate and have higher frequency components than edge channel TC's applies at all flowrates. At low flowrates and axial positions far from the injection point the attenuation of low-frequency signals by the ac coupling network in the recording system results in an effect similar but opposite to that described above. Signals from center-channel TC's dominate the correlation function and the measured transit time tends to be shorter, or the measured velocity tends to be higher than average velocity.

The signal from each of the four TC fin assemblies represents the summation of signals from 14 TC's. Before recording, the signal from each resistive summation network is amplified by 1000, passed through an ac coupling filter with a 0.1-Hz high-pass cutoff, and amplified by another factor of 1000. To study the effects of the high-pass filter on measured transit time, simultaneous recordings were made using a high-pass filter with a cutoff at 3 Hz.

These measurements used in Figure 33 (data from Figure 32 with corrections for short fluid-transport times using Equation 1) were made using an ac coupling filter with a 1.59-sec time constant (0.1-Hz high-pass cutoff). Figure 41 is a similar plot of measurements made using an ac coupling filter with a 3-Hz high-pass cutoff. Note that the measured velocity is significantly higher than the average fluid velocity, particularly at lower flowrates (longer fluid-transport times).

In the earlier fin design fewer TC's were used (13 vs 14) and the edge TC's were farther from the wall (50 vs 35 mils). The velocity drops rapidly near the channel wall. The edge TC's in the recent test series clear the wall by only about 15 mils and could be expected to contribute lower-frequency components than were observed by edge TC's in previous tests. Thus the effects described above would tend to be more severe in the recent test series.

In Figure 31 and Table 3 the measurements at 2.45 ft/sec (Run 206) and 1.41 ft/sec (Run 207) were 1 to 3% above average flow. To assure that the accuracy of the flow measurements in sodium at low flowrates and long fluid-transit times would not be affected by the ac coupling filter, the recording system was modified to extend the response of the ac coupling network to lower frequencies (0.025 Hz).

The sensor and instrumentation bandwidth limitations described above apply only to velocity measurements based on the summing method. Velocity-profile measurements made between TC's at similar radial positions should not be subject to these limitations. Summation of individual radial-velocity measurements may be used to cross-check the accuracy of flow measurements using the signal-summation method.

2. Alignment of Temperature Sensors

A series of tests (Runs 210 to 213) were made in water to study the effects of radial-sensor misalignment. With sensors in the 18-, 24-, 30-, and 54-in. positions, signals were recorded with the 24-in.-position sensor installed at radial positions of -30, 0, +30, and +60 mils respectively from the nominal centered position. A comparison of measured-to-average flow ratio for flow measurements between the 24- and 30-in.-position sensors and the 24- and 54-in.-position sensors is made in Table 11.

Figure 41. Measured/Average Flow Ratio vs Average Fluid-Transport Time for Data Recorded Using 3-Hz High-Pass Filter (with corrections for end effects)

TABLE 11
EFFECTS OF RADIAL-SENSOR MISALIGNMENT

Radial Fin Position	Sensor Pair* (in.)	Measured/ Average Flow Ratio	Measured/ Average Flow Ratio With Correction for End Effects
-30 mils	24 and 30	0.927	0.967
Nominal (centered)	24 and 30	0.965	1.005
+30 mils	24 and 30	0.972	1.012
+60 mils	24 and 30	1.006	1.046
-30 mils	24 and 54	0.990	1.007
Nominal (centered)	24 and 54	0.984	1.001
+30 mils	24 and 54	0.986	1.003
+60 mils	24 and 54	0.989	1.006

*Note that sensor alignment has a significantly larger effect for sensors at 6- than at 30-in. apart.

TABLE 12
EFFECTS OF ANGULAR-SENSOR MISALIGNMENT

Flowrate (ft/sec)	Angular Fin Position*	Sensor Pair (in.)	Measured/ Average Flow Ratio†
9.97	0°	18 and 30	1.00
6.23	0°	18 and 30	0.99
9.97	90°	18 and 42	1.01
6.23	90°	18 and 42	1.00
9.97	90°	30 and 42	1.03
6.23	90°	30 and 42	1.04

*Note that angular orientation has a significantly larger effect for sensors at 12- than at 36-in. apart.

†With correction for end effects

Two tests (Runs 214 and 215) were made to study the effects of angular sensor misalignment. One sensor was installed at the 42-in. position at a 90° angle to sensors at the 18-, 30-, and 54-in. positions. A comparison of measured-to-average flow ratio for flow measurements between sensors oriented at 0 and 90° is given in Table 12.

3. Marginal or Distorted Correlation Functions

The cross-correlation function relating signals from two sensors is measured and from this bell-shaped function the transport delay time relating the two signals is measured. Therefore factors which affect the magnitude and general shape of the cross-correlation function can affect the measurement of transport delay time.

The TTC determines transport delay time by the following steps:

- 1) The smoothed correlation function from the Signal Correlator is sampled at a precise fixed rate of 0.5 msec/% full-scale. Thus it takes precisely 50 msec to scan the entire correlation function. (This process is repeated every 60 msec.)
- 2) A peak detector measures and holds the magnitude of the maximum value of the correlation function.
- 3) A logic circuit determines the time (percent of full-scale) where the correlation function reaches a selected fraction (typically 90%) of the previously measured peak correlation value.
- 4) Another logic circuit determines the time (percent of full-scale) where the correlation functions drop below the selected fraction of peak correlation.
- 5) The mean of these two time measurements (corrected for the smoothing time constant) represents an estimate of transport delay time on a scale of 0 to 100%.
- 6) The time average of these estimates (generated every 60 msec) is used to represent a measurement of transport delay time.

The bell-shaped correlation function is also displayed on an oscilloscope and the operator selects a time range on the signal correlator so that the peak correlation value occurs between 40 and 90% of full-scale.

Under ideal conditions the normalized cross-correlation function relating random-temperature signals from two in-line sensors is Gaussian or bell-shaped, with a peak value (near unity) displaced in time by a value equal to the average fluid-transport time. Any change or deterioration of the temperature patterns that take place between the two sensors will result in decreased peak correlation. The TTC automatically compensates for changes in the peak correlation value and provides accurate measurements of signal delay time for correlation values above about 0.05. However, as the correlation drops toward zero the relative stability of the function decreases, and for a given sample time the statistical precision of transit-time estimates decreases, or for a given statistical precision the required sample time increases.

The amplitude of inherent temperature fluctuations (see Figure 30) created by heat loss at the first in-stream sensor installation were sufficient to provide adequate temperature signals for flow measurements between the second sensor, 12-in. downstream, and the fourth sensor, 60-in. downstream. Results listed in Table 13 show that transit-time velocity measurements without heat injection were consistent within 1% of those with. However, because of the low correlation values the statistical precision is lower for the measurements without heat injection.

TABLE 13
FLOW MEASUREMENTS IN SODIUM OBTAINED WITH
SENSOR PAIR 21 TO 69 in.

Run No.	With Injection Heater "ON" (12 kw)		With Injection Heater "OFF"	
	Measured Flow (ft/sec)	Peak Correlation	Measured Flow (ft/sec)	Peak Correlation
1201	2.27 ± 0.02	0.18 ± 0.02	2.28 ± 0.05	0.08 ± 0.03
1202	3.39 ± 0.01	0.22 ± 0.02	3.39 ± 0.04	0.08 ± 0.03
1203	5.80 ± 0.02	0.25 ± 0.01	5.81 ± 0.08	0.12 ± 0.04
1204	6.71 ± 0.03	0.28 ± 0.02	6.70 ± 0.05	0.14 ± 0.04
1205	9.14 ± 0.05	0.21 ± 0.03	9.11 ± 0.12	0.12 ± 0.04

The degree of correlation between two sensors varies with distance and the relative level of uncorrelated disturbances. As the distance between sensors increases, deterioration of the temperature patterns and uncorrelated background noise will eventually cause the peak correlation to approach zero.

Variation in peak correlation as a function of axial distance between sensors and of radial position of individual TC's is illustrated in Figure 42. For the test conditions in Figure 42 the typical peak correlation for summation of 14 TC's on each sensor was 0.68 for sensors 12-in. apart, 0.57 for 36-in. apart, and 0.49 for 60-in.

In the water-loop tests there was only one source or point where temperature patterns were generated. However, as indicated in a previous section, temperature patterns in sodium were generated by heat transfer at each sensor-installation nozzle and by turbulent mixing of two flowstreams at the injection point. Heat transfer to the walls of the flow channel would also tend to create temperature patterns in the boundary flow region near the pipe wall.

It was shown previously (Section III-C, Figure 32) that temperature patterns are accelerated as an exponential function of distance, from their initial velocity to the average stream velocity. Thus the time for temperature patterns to pass from one sensor to the next depends on their point of origin and original velocity.

The effect of the temperature patterns propagating at velocities less than the average stream velocity on measured transit time depends on the relative magnitudes of the temperature patterns from the various sources. The measured cross-correlation function is an average or super-position of the correlation functions of the temperature patterns from each source. There will tend to be a peak in the measured cross-correlation function corresponding to the average transit time of the temperature patterns from each source.

The ratio of the magnitude of temperature patterns originating at the injection point to that generated along the walls of the flow channel decreases with distance from the injection point. Cross-correlation measurements between sensors which are far from the injection point will tend to be distorted by multiple peaks related to the various sources of temperature patterns. The distortion will tend to be greater at low flowrates (long fluid-transport times) and in cases

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Figure 42. Measurements of Peak Correlation Relating Thermocouples on the First Sensor With Those at Similar Radial Positions on the Second, Third, and Fourth

where heat input in the injection line is minimal. In such cases measured transit time will tend to be greater than average fluid-transit time, or measured velocity will tend to be lower than average fluid velocity. This effect is illustrated in Figures 43 and 44 for TTF velocity measurements at low flowrates and sensor combinations far from the injection point.

The measurements in Figures 43 and 44 were corrected for the acceleration of the thermal tracer (end effects). In comparison with the measurements at 1200°F shown in Figure 37, these measurements at lower temperatures resulted in greater errors in velocity measurements. A number of factors may have contributed to the observed improvement. The tests at 500, 900, and 1200°F were run chronologically in that order, and at 500 and 900°F were run without power to the line heaters along the flow section to minimize electrical interference on the conductivity sensors. Those at 500°F were run as shown in Figure 23 with no insulation around the sensor installation nozzles. In subsequent tests at 900°F, additional insulation (similar to that shown in Figure 23 on the injection line heater and valve) was packed around the bases of the sensor installation nozzles to reduce heat losses around the test loop. The amount of insulation was increased again for the 1200-series tests (which were run with full power to the line heaters). Nominal power to the injection-line heater was 6, 9, and 12 kw respectively for the 500, 900, and 1200°F tests.

The use of the line heater and additional insulation to reduce the temperature gradient between the sodium and the pipe wall were probably the most significant factors in eliminating or reducing the effects of extraneous sources of temperature patterns on measured flow velocity.

F. COMPARISON WITH ELECTROMAGNETIC FLOWMETERS

The sodium test loop was not equipped with a means for determining absolute average flow; however, relative flow measurements were obtained during each test run from two EM flowmeters. Signals from the main-loop EM flowmeter, FI-207, and the transit-time flowmeter-loop EM flowmeter, FI-100 (see Figure 18), were sequentially recorded during each test run using an integrating digital voltmeter with line-printer output. The average of 10 samples from each EM flowmeter (1-sec integration time) taken at ~30-sec intervals, is listed in Table 14 for each test run. Scale factors relating millivolt output to flow velocity

Figure 43. Measured Velocity in 500°F Sodium (with corrections for end effects) vs Mean Axial Position of Sensor Pair

Figure 44. Measured Velocity in 900°F Sodium (with corrections for end effects) vs Mean Axial Position of Sensor Pair

TABLE 14
COMPARISON OF MILLIVOLT OUTPUT SIGNALS FROM
TWO ELECTROMAGNETIC FLOWMETERS

Run No.	Temperature (°F)	Flowmeter FI-100 (mv)	Flowmeter FI-207 (mv)	Ratio FI-100/FI-207
501	508	14.70		
502	502	14.76		
503	502	14.78		
504	502	14.79		
505	502	14.81		
506	502	14.80		
507	502	14.78		
508	504	14.77		
509	504	14.81		
510	504	14.74		
511	506	14.75		
512	502	14.76	21.33	0.692
513	482	9.38	13.61	0.689
514	500	6.12	8.68	0.705
515	522	4.00	5.75	0.695
516	510	2.42	3.22	0.752
901	829	13.32	19.20	0.693
902	837	9.07	13.08	0.693
903	842	6.04	8.68	0.695
904	844	3.79	5.44	0.696
905	835	2.10	2.96	0.710
906	827	13.75	19.84	0.692
907	888	13.45	19.46	0.691
908	878	6.42	9.25	0.693
909	880	6.38	9.05	0.705
1201	1167	3.05		
1202	1171	4.57		
1203	1154	7.98		
1204	1134	9.38	13.69	0.685
1205	1100	12.7	18.57	0.685
1206	1172	11.37	16.53	0.687
1207	1180	11.11	16.17	0.687
1208	1174	11.39	16.54	0.688
1209	1189	11.34	16.50	0.687
1210	1190	11.27	16.44	0.685
1211	1190	11.29	16.44	0.686
1212	1190	11.30	16.42	0.688
1213	1190	11.31	16.47	0.687
1214	1190	11.33	16.50	0.686
1215	1190	11.35	16.49	0.688
1216	1190	11.34	16.54	0.686
1217	1208	4.49	6.47	0.694
1218	1208	4.50	6.46	0.697
1219	1208	4.5	6.47	0.694
1220	1208	4.53	6.51	0.696

in ft/sec were computed for various sodium temperatures based on pretest, room temperature, measurements of magnetic flux density, dimensions of pole face, pipe diameter, etc.⁽⁴⁾ The average velocity as computed from the two EM flowmeters, based on pretest flux measurements, differed by ~ 5 to 8% depending on flow and temperature conditions. However, the velocities computed from the EM flowmeter signals were 12 to 20% lower than the velocities measured with the transit-time method.

Post-test measurements of the flux density of the permanent magnet used on the TTF loop showed a decrease from the original pretest measurements by $23.4 \pm 1.5\%$ at room temperature. New scale factors based on the post-test flux measurements were calculated for the EM flowmeter on the TTF loop and used in preparing the following figures and tables.

Figures 45, 46, and 47 compare the average velocity as computed from the two EM flowmeters with the velocities measured with the transit-time method for tests at nominal loop temperatures of 500, 900, and 1200°F respectively. A listing of such measurements for all test runs is included in Table 15.

The scale factors computed for the EM flowmeters vary 5 to 10% with sodium temperatures from 500 to 1200°F. This is due primarily to the change in the field strength of the permanent magnets with magnet temperature. Uncertainty in actual magnet temperature at each sodium-temperature condition and in the temperature-dependence of these particular magnets could readily account for 3 to 5% relative errors in the computed scale factors at the various sodium-temperature conditions. Uncertainty in the actual flux density of these permanent magnets in the operating environment can, as was indicated above, lead to errors in calculated flowrate as high as 20%, or more.

G. CONDUCTIVITY MEASUREMENTS

The electrical resistance of sodium varies $\sim 0.2\%/^{\circ}\text{F}$ at 1200°F. An attempt was made to detect the passing of temperature patterns in the flow channel as variations in resistance across the pipe.

The conductivity electrodes were copper bars $1/4$ by 2 in. which were machined at the ends to match the pipe OD so that they covered an arc of about 90° on opposite sides of the pipe. They were clamped against the pipe at five axial locations.

Figure 45. Comparison of Transit Time Flowmeter Flow-Velocity Measurements (axial mean velocity) in 500°F Sodium With Relative Velocity Indications From Two Electromagnetic Flowmeters

Figure 46. Comparison of Transit Time Flowmeter Flow-Velocity Measurements (axial mean velocity) in 900°F Sodium With Relative Velocity Indications From Two Electromagnetic Flowmeters

Figure 47. Comparison of Transit Time Flowmeter Flow-Velocity Measurements (axial mean velocity) in 1200°F Sodium With Relative Velocity Indications From Two Electromagnetic Flowmeters

TABLE 15
COMPARISON OF TRANSIT TIME FLOWMETER FLOW-VELOCITY MEASURE-
MENTS (axial mean velocity) WITH RELATIVE VELOCITY INDICATIONS
FROM TWO ELECTROMAGNETIC FLOWMETERS

Run No.	Temperature (°F)	Axial Mean TTF Velocity (ft/sec)	Flowmeter FI-100 Measurements (ft/sec)	Flowmeter FI-207 Measurements (ft/sec)
501	508	9.61	9.90	
502	502	9.65	9.94	
503	502	9.62	9.95	
504	502	9.64	9.96	
505	502	9.63	9.97	
506	502	9.62	9.97	
507	502	9.63	9.95	
508	504	9.64	9.95	
509	504	9.68	9.98	
510	504	9.61	9.93	
511	506	9.66	9.94	
512	502	9.6	9.94	8.43
513	482	6.18	6.31	5.37
514	500	3.94	4.12	3.43
515	522	2.569	2.70	2.27
516	510	1.323	1.63	1.27
901	829	8.84	9.32	7.74
902	837	6.12	6.35	5.28
903	842	4.09	4.23	3.50
904	844	2.542	2.66	2.20
905	835	1.38	1.47	1.19
906	827	9.15	9.62	8.00
907	888	8.92	9.48	7.90
908	878	4.31	4.51	3.75
909	880	4.27	4.49	3.67
1201	1167	2.26	2.22	
1202	1171	3.37	3.33	
1203	1154	5.82	5.79	
1204	1134	6.74	6.80	5.73
1205	1100	9.15	9.20	7.74
1206	1172	7.85	8.28	6.95
1207	1180	7.73	8.09	6.80
1208	1174	7.79	8.29	6.96
1209	1189	7.8	8.27	6.95
1210	1190	7.76	8.22	6.93
1211	1190	7.8	8.24	6.93
1212	1190	7.78	8.24	6.92
1213	1190	7.82	8.25	6.94
1214	1190	7.85	8.27	6.95
1215	1190	7.9	8.28	6.95
1216	1190	7.81	8.28	6.97
1217	1208	3.37	3.28	2.73
1218	1208	3.36	3.29	2.73
1219	1208	3.39	3.29	2.73
1220	1208	3.38	3.31	2.75

Since the resistance across the 2-in. flow channel was on the order of 10^{-5} ohms (including the pipe wall) it was necessary to use carrier currents of several-hundred amps to produce a detectable voltage drop. At 300-amp a signal level of the order of $6 \mu\text{volts}/^\circ\text{F}$ was expected in 1200°F sodium. Signal levels expected from the thermal changes in electrical resistance due to passage of temperature patterns are in the range from 0.1 to $10 \mu\text{volts}$ peak-to-peak.

Tests in a 2-in.-diam nonflowing test rig using liquid Woods metal to simulate sodium indicated the instrumentation system could detect conductivity variations of $<10 \text{ ppm}$ at 10^{-4} ohms.

Attempts were made to detect temperature changes in flowing sodium, using a variety of carrier frequencies and detection systems. Attempts to use a 400-Hz carrier were unsatisfactory due to limited penetration of sodium because of eddy-current "skin effects." The observed electron impedance across the pipe ($\sim 5 \times 10^{-5} \Omega$) was sensitive to the slightest change of stress due to static loading or vibration of the test section.

Attempts to use a lower-frequency carrier, 60 Hz, or dc current were limited by background noise signals due to axial currents flowing in the pipe, induced by the EM pumps. These signals which were similar to those observed on an EM flowmeter had the same spectral characteristics as temperature patterns but did not correlate with observed signals from TC fin sensors. The observed background noise signals were one to three orders of magnitude larger than the signals expected from the thermal changes in electrical resistivity due to passage of temperature patterns. By attaching signal leads at various axial positions along the test section it was observed that the background signals were in-phase at all axial positions, and it was concluded they were related to axial currents along the test sections, which were proportional to the power to the EM pumps.

Efforts to improve sensitivity by using in-stream electrodes were stopped by a scheduled shutdown in loop operation to make loop modifications.

The technique may be usable in systems using mechanical rather than electromagnetic pumps, and further investigation of this system should be made in the future.

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IV. DISCUSSION AND CONCLUSIONS

Water-loop tests and analytical studies in an earlier phase of the program indicated that the TTF method, which is based on the detection and correlation of temperature patterns at two axial positions in a flow channel, would perform satisfactorily in sodium at flowrates above 1 ft/sec.

Tests of a 2-in.-diam Transit Time Flowmeter in sodium and water described in this report provide the following experimental evidence that the TTF method is applicable to accurate flow measurement in high-temperature sodium.

- 1) The sodium tests demonstrated that inherent or induced temperature patterns are readily detectable at two or more axially spaced in-stream sensors and that these signals are suitable for measuring flow velocity. Random-temperature patterns, generated by injection of a thermal tracer, were detected at all four in-stream sensor positions, and transit-time measurements were obtained relating the six sensor-pair combinations for all flow and temperature conditions. Typical signal levels ranged from 0.01 to 1.0°F peak-to-peak, depending on heater power, flowrate, and sensor position. Test results for flow velocities from ~1.4 to 10 ft/sec indicate temperature patterns decay at approximately the same rates in sodium and water. This is in agreement with the studies in Reference 1 which indicated that hydrodynamic effects, not thermal diffusion, dominate the deterioration of temperature patterns.
- 2) Transit-time flow-velocity measurements obtained by two different methods were compared for a multiplicity of sensor configurations to demonstrate the high consistency of the measurements. One method, Signal Summation Technique, involved the use of resistive summation networks to combine the signals from up to 14 TC's on each of their fin sensors. Measurements of the average transport delay time between the summation signals from any two TC fin sensors with known spacing were used to estimate average flowrate. The second method, velocity-profile integration, involved the measurement of the transport delay times relating signals from individual TC's at the same

radial positions on two fin sensors. Estimates of average flow velocity were obtained by averaging the transit time or velocity samples at the various radial positions.

Transit-time flow-velocity measurements at 1200°F between the sensors at 21- and 69-in. positions (4-ft separation) were consistent within $\pm 1\%$ for measurements obtained by cross-correlation of signals from the summation of 14, 12, 10, 8, 6, 4, or 2 TC's per sensor. Estimates of average flow velocity obtained by averaging velocity measurements relating individual TC's at the same radial position also were consistent with $\pm 1\%$ for the average of velocity measurements at 14, 12, 10, 8, 6, 4, or 2 radial positions. The above 14 estimates of average flowrate (after a +0.7% correction for the acceleration of the thermal-tracer end effects) were also consistent within $\pm 1\%$ with the average of velocity measurements relating the six sensor-pair combinations (axial mean velocity) obtained using the summation method with 14, 12, 10, 8, 6, or 4 radial samples per sensor. (Measurements with two radial samples per sensor were consistent with the above measurements within a band of $\pm 1.2\%$.)

- 3) Because of the lower density and heat capacity of sodium, temperature patterns of detectable magnitude are more readily generated in sodium than in water. For the sodium tests the principal temperature patterns were generated by turbulent mixing of two flowstreams, one of which (the injection-line) was heated by an immersion heater. Secondary temperature patterns were produced by heat loss from the sensor nozzles and at 1200°F the signals from these were 60 to 100% as large as the net signals created by operating the electrical injection-line heater at 12 kw. TTF velocity measurements relating sensors 4-ft apart during 1200°F operation without heat injection were consistent within 1% with the velocity measurements using heat injection.
- 4) Studies of the acceleration and dispersion of the injected thermal tracer (end effects) in tests with sodium and water show that the velocity of the thermal tracer approaches the stream velocity in a consistent and predictable manner and that the effect of this error source can be eliminated in the velocity calculation.

In the water tests where injection flow was constant for all flow conditions the velocity of the thermal tracer was accelerated as an exponential function of time (independent of flowrate) from the initial-injection velocity to the average stream velocity. By making measurements at various flow conditions and plotting measured to average flow vs mean fluid-transport time from the injection point, the exponential velocity relation was readily observed. In the sodium tests where injection flow was proportional to total flow the velocity of the thermal tracer was an exponential function of mean distance of the sensor from the injection point (independent of flowrate).

Identification of the coefficients of the exponential function made it possible to apply second-order corrections to velocity measurements for the various sensor combinations for both water and sodium tests. The axial mean velocity computed from the six sensor-pair combination in the water tests was within 1% of the average flow (determined by volume/time measurements) for all flow conditions above 4 ft/sec, and within 1.6% for flowrates down to 1.4 ft/sec. The "larger" consistent errors at low flowrates were attributed to the use of a 0.1-Hz high-pass filter in the signal-conditioning system, and the response was extended to 0.025 Hz for the sodium tests. The behavior of temperature patterns in sodium was essentially identical to their behavior in water, which indicated that the "mean axial velocity" measured in 1200°F sodium was equal or very close to the true average velocity. Assuming that the temperature patterns created in sodium at the injection point accelerate to the average stream velocity as they were observed to do in the water tests, the measured axial mean velocity appears to be within 1% of the average stream velocity for the 1200°F sodium tests having flowrates above 4 ft/sec.

- 5) Sodium-velocity measurements by the transit-time method were compared with velocity indications from two EM flowmeters. These results show the expected linear proportionality relationship; however, 15 to 17.5% discrepancies were observed between the two EM flowmeters. The measured velocities using the transit-time method were consistent within 5% with the computed flow velocities measured by the EM flowmeter on the TTF loop. The indicated EM-flowmeter data were based on post-test room-temperature measurements of the field

strength of the permanent magnet. The prediction of actual field strength at temperature is expected to be within 5% of the values predicted from the measurements at room temperature.

- 6) The TTF sensors and flow section were successfully operated over the temperature range from room temperature (water tests) to 1200°F (sodium tests) which demonstrated one of the unique advantages of the TTF over other methods. The useful temperature range is limited only by the temperature limitations of the sensor materials and the TC's. Except for changes in the distance between sensors by thermal expansion (on the order of a few tenths of a percent), flow-velocity measurements by the transit-time method are unaffected by temperature. These factors make the TTF a leading contender for use in calibration measurements of flow velocity in large sodium loops, where volume/time calibration methods are not practical.

Test results confirmed the predicted characteristics of the TTF in that the measurement accuracy and precision tend to improve with distance between sensors. Although the degree of correlation decreases with distance between sensors, and the absolute width of the correlation function increases with time from the injection point, the bell-shaped cross-correlation function becomes more sharply defined and the relative precision of transit-time estimates improves with distance between sensors. If the sensors are placed too close together the width of the correlation function may be greater than the transit time relating the signals; thus, small statistical variations in the shape of the correlation function tend to produce statistical variations in transit-time estimates that represent a relatively large fraction of the desired measurement. For sensors far apart the width of the cross-correlation function (although wider in absolute magnitude) tends to represent a relatively small fraction of the transit time; therefore, statistical variations in the shape of the correlation function tend to produce relatively small statistical variations in the transit-time estimates.

Measurement errors due to most other factors tend to diminish as the distance between sensors increases. This observation applies to factors which affect measurement accuracy such as variations in time response of TC's or

instrumentation, variations in the number and/or the radial positions of TC's on each sensor, variations in sensor alignment due to rotational flow patterns or errors in angular sensor position, and asymmetric undeveloped flow profiles and velocity variations (end effects) created near the injection point.

Measurement precision is affected also by the correlator averaging time. The accuracy of the transit-time measurement for a constant-flow condition increases with averaging time; however, increasing the averaging time reduces the response time of the TTF. The system used for these tests was limited by the use of only 10 transit-time samples at about 30-sec intervals; i.e. the averaging time constant in the signal correlator was 30 sec. Test results indicated that measurement precision varied from ~ 0.2 to 2%, depending on flow stability at the various radial and axial sensor positions and the degree of correlation-relating sensor signals. In future applications where flowrate is steady and accuracy is of primary importance, measurement precision may be increased by increasing the averaging time constants and sample time. Time response of the existing Transit Time Computer system is nominally 8 sec for on-line operation, using analog averaging circuits. By selecting the appropriate averaging time constant the desired statistical precision may be achieved. In future models of the TTC, more flexible digital-integration methods will be used to eliminate drift, settling time, etc.

The continued recent improvement and reduction in cost of commercially available cross-correlation measurement equipment indicates that such equipment will soon be competitive for widespread industrial application of the transit-time flow measurement method. Correlation systems which required several racks of equipment a few years ago now require a single-rack module. By the time LMFBR's are in operation the electronics package for a TTF with 0.1% accuracy should require no more than three or four circuit cards. Simpler versions with 1% accuracy are also foreseen for use as in-core flowmeters.

The following are recommendations or guidelines for the design and operation of future transit-time flowmeters:

- 1) Temperature patterns may be generated by injection of a thermal tracer or by conductive heat removal or addition. To minimize errors related to the acceleration of the thermal tracer when using

the injection method, the injection flow should be proportional to total flow and the injection velocity should be close to the average stream velocity. To minimize the effects of extraneous sources of temperature patterns on measured flow velocity, insulation and line heaters along the flow section and around the sensor installation nozzles should be designed to minimize temperature gradients along the flow section, from the desired injection or source point to the last (downstream) sensor position.

- 2) Temperature patterns may be detected by two or more in-stream sensors, with two or more fast-response TC's per sensor. To detect systematic errors due to acceleration of the thermal tracer and velocity-profile distortion, sensors should be placed at three or more axial positions with four or more radial samples/sensor. Five sensors with ten radial samples/sensors are suggested for tests and study of a 6-in.-diam TTF for operation to 30 ft/sec.
- 3) Axial position of the sensors may range from the injection or source point to as far as 35-pipe diameters downstream (based on signal levels observed in 1200°F sodium). Axial-sensor positions used for the 2-in. flow-section sodium tests were 4.5-, 10.5-, 22.5-, and 34.5-pipe diameters. A similar configuration is planned for the 6-in.-diam flow section for operation to 30 ft/sec.
- 4) Radial positions of TC's along the fin sensor may be selected using any of the four methods listed in Reference 2; i.e. Chebyshev; Centroids of Equal Area; Gauss; and Newton-Cotes. Both the Chebyshev and Centroids of Equal Area methods have been successfully applied to transit-time flow measurements. The Chebyshev method was used for selecting radial samples for the sodium tests. Tests involving only 2, 4, 6, 8, 10, or 12 of the available 14 radial samples showed an effect of only about 1% on measured flowrate. No more than ten radial samples are planned for future test sensors, and four radial samples appear to be sufficient for most applications.

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