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ANCR-1188

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ERROR ANALYSIS FOR
1-1/2-LOOP SEMISCALE SYSTEM
ISOTHERMAL TEST DATA

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Printed in the United States of America
Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
Price: Printed Copy \$5.45; Microfiche \$2.25

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ANCR-1188

Light Water Reactor Safety and Technology --
System Interactions and Effects
TID-4500

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AEROJET NUCLEAR COMPANY
IDAHO FALLS, IDAHO

Date Published - May 1975

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ACKNOWLEDGMENTS

The authors wish to express their appreciation to the personnel of the Fluids Laboratory Division for their professional and technical contributions, to R. L. Crumley for his assistance in identifying and quantifying errors associated with the density measurement system, to LOFT personnel for their assistance in the preparation of the pump torque and pump speed sections, and to S. H. VanHaverbeke for his work in adapting computer programs for the graphical presentation of test data with uncertainty limits.

ABSTRACT

An error analysis was performed on the measurements made during the isothermal portion of the Semiscale Blowdown and Emergency Core Cooling (ECC) Project. This report on that analysis includes a brief description of the measurement techniques employed, identification of potential sources of errors, and quantification of the errors associated with data as presented in the isothermal data reports. The purpose of this report is to present error limits enabling those concerned with analysis of the published data to make further analysis and comparisons among the data.

SUMMARY

The error analysis was performed to supply confidence limits on data published for the isothermal portion of the Semiscale Blowdown and Emergency Core Cooling (ECC) Project conducted by Aerojet Nuclear Company (ANC) for the United States Energy Research and Development Administration (ERDA).

The analysis method uses standard statistical treatment of independent error components to establish total maximum and total probable errors. Each error component used in the determination of the total error was obtained using one or more of the following: physical information, mathematical techniques, or professional experience and judgement. Each error component was assumed to be independent, to be normally distributed, to have known variance, and to have a 95% certainty. Also, homogeneous flow conditions were assumed for the determination of certain error components for the flowmeter and densitometer measurement systems.

The total maximum error was obtained by adding the individual error components. The total probable error was obtained by the root-sum-square technique of adding the individual error components.

The errors associated with the data acquisition and processing system were considered separately and used as an individual error component when the error associated with the total measurement system was analyzed. The general total maximum and total probable errors determined for the data acquisition and processing system are $\pm 1.05\%$ system full scale and $\pm 0.91\%$ system full scale, respectively.

To establish single values or ranges of values which accurately represent errors associated with each individual measurement system within a group is difficult because of the many variables within each total measurement system. The following error values and ranges of error values are considered to be typical of, or average for, each type of total measurement system.

PRESSURE

Total maximum	$\pm 1.4\%$ transducer full scale
Total probable	$\pm 1.0\%$ transducer full scale

DIFFERENTIAL PRESSURE

Total maximum	$\pm 2.4\%$ transducer full scale
Total probable	$\pm 1.3\%$ transducer full scale

FLUID TEMPERATURE

Total maximum	$\pm 10^{\circ}\text{F}$
Total probable	$\pm 5^{\circ}\text{F}$

METAL TEMPERATURE

Total maximum	$\pm 15^{\circ}\text{F}$
Total probable	$\pm 7^{\circ}\text{F}$

DENSITY

Total maximum	$\pm 1.9 \text{ lb/ft}^3$
Total probable	$\pm 0.9 \text{ lb/ft}^3$

VOLUMETRIC FLOW

Total maximum	± 1.1 to ± 21 gpm, depending on transducer range
Total probable	± 0.6 to ± 10.2 gpm, depending on transducer range

FLOW VELOCITY

Total maximum	$\pm 0.7 \text{ ft/sec}$
Total probable	$\pm 0.5 \text{ ft/sec}$

MOMENTUM FLUX

Total maximum	± 640 to $\pm 1930 \text{ lb/ft-sec}^2$, depending on transducer range
Total probable	± 320 to $\pm 920 \text{ lb/ft-sec}^2$, depending on transducer range

MASS FLOW RATE

Total maximum ^[a]	± 4.5 to $\pm 13\%$ of reading, depending on transducer range
Total probable	

[a] Explicit values for the total maximum errors were not determined.

PUMP SPEED

Total maximum	± 58 rpm
Total probable	± 36 rpm

PUMP POWER

Total maximum	± 0.50 kW
Total probable	± 0.35 kW

PUMP TORQUE

Total maximum	± 7.0 in.-lb
Total probable	± 4.5 in.-lb

LIQUID LEVEL

Total maximum	± 3 in.
Total probable	± 1 in.

Within the framework of the analysis techniques and assumptions used to determine measurement errors, the errors determined for the measurement systems realistically reflect state-of-the-art capabilities of equipment and methods used to measure complex thermal-hydraulic processes.

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ERROR ANALYSIS FOR 1-1/2-LOOP SEMISCALE SYSTEM ISOTHERMAL TEST DATA

I. INTRODUCTION

An error analysis was performed to establish error bands on the data obtained and published for the isothermal test program^[1-8]. The isothermal test program is part of the Semiscale Blowdown and Emergency Core Cooling (ECC) Project conducted by Aerojet Nuclear Company. The project is part of an overall Energy Research and Development Administration-sponsored research and development program directed at: (a) quantifying the physical processes controlling system behavior during a postulated loss-of-coolant accident (LOCA) in a pressurized water reactor (PWR), and (b) providing an experimental data base for assessing reactor safety evaluation models. The data reports of the 1-1/2-loop semiscale system isothermal tests presented data as obtained from the instrumentation and processed by computer^[1-7]. No error bands or confidence limits for the data were included in those reports. Accuracies previously reported^[8] in conjunction with the isothermal tests were based on manufacturers' specifications and engineering estimates only. The purpose of this analysis is to provide confidence limits for the data presented for the 1-1/2-loop semiscale system isothermal tests. Due to continuing improvement in obtaining measurements, this analysis applies only to the 1-1/2-loop semiscale system isothermal tests and not to previous or future tests in the isothermal test program.

The analysis performed is based on the assumption that inputs to the total probable and total maximum errors are independent and normally distributed with known variance. An additional assumption was made for the analysis performed on the turbine flowmeter, drag disc flowmeter, and densitometer measurement systems. This assumption is that the transducer outputs are a result of homogeneous conditions. The homogeneous flow assumption is based on semiscale isothermal test data which indicate the bulk of the system mass was expelled under homogeneous flow conditions. Homogeneous flow conditions are considered to have existed throughout the subcooled portion of blowdown and during the first part of the saturated portion of blowdown. Nonhomogeneous flows which might noticeably affect the calibrated performance of the flowmeters and densitometers are considered to have been absent until 8 to 10 seconds after rupture.

An analysis of the system and components associated with each measurement was performed. The contributing sources of errors for each measurement analyzed are examined in this report, and a description is given of the instrumentation, installation techniques, physical conditions, and experimental procedures to enable the reader to understand the systems and the sources of errors. Because the data obtained in the semiscale tests were primarily of a single-sample nature, many of the error components were obtained from instrument specification sheets provided by manufacturers, established standards, and professional judgement. When all sources of error were identified, the errors were quantified and combined according to an outlined analysis procedure to obtain a total maximum error and a total probable error. The error data were then presented in graphical or tabular form. The error data as presented are considered to be typical of all data obtained similarly unless otherwise indicated.

II. GENERAL ANALYSIS PROCEDURES AND TECHNIQUES

An abbreviated Taylor series expansion may be used to obtain a first order approximation of the variance (σ_y^2) for y in terms of the variance ($\sigma_{z_i}^2$) for the components of y, z_i :

$$\sigma_y^2 = \sum_{i=1}^N \left(\frac{\partial y}{\partial z_i} \right)^2 \sigma_{z_i}^2 \quad (1)$$

Higher order terms will not appear in the expression if the components are uncorrelated (independent)^[9]. The definition of the total differential of y is

$$dy = \sum_{i=1}^N \frac{\partial y}{\partial z_i} dz_i \quad (2)$$

where the dependent variable y is a function of the independent variables z_i . In order to compute the probable error, as presented here, the individual terms in the total differential expression were squared and added in a manner similar to Equation (1); that is,

$$dy' = \sum_{i=1}^N \left(\frac{\partial y}{\partial z_i} \right)^2 (dz_i)^2 \quad (3)$$

The similarity between Equations (1) and (3) evidences that dy' is related to σ_y^2 in the same way dz_i is related to σ_{z_i} . Since the individual error components (dz_i) represent 95% confidence limits, $\sqrt{dy'}$, the probable error, must also represent 95% confidence limits.

The error computed by the preceding method is referred to as the total probable error. In addition to the total probable error, a total maximum error was computed. The total maximum error is defined as the error that would result if all the instruments which combine to yield the data as presented read in such a way that the total error is the sum of the individual inaccuracies. Mathematically stated:

$$\left. \frac{dy}{y} \right|_{\max} = \sum \left| \frac{\partial y}{\partial z_i} \frac{dz_i}{y} \right| \quad (4)$$

Probable and maximum errors have been developed as relative errors and sometimes as absolute errors. The choice between expressing the errors absolutely or relatively was made for mathematical simplicity and convenience. The final results of error analysis computations are based on the following assumptions:

- (1) Each component of the total probable error and the total maximum error is normally distributed and represents 95% confidence limits
- (2) The components of the total probable error or total maximum error are independent.

The data collected in the 1-1/2-loop semiscale system isothermal tests and follow-on hot wall tests are treated here as single-sample data. Single-sample data are those which are not repeated or those in which some uncertainties may not be discovered by repetition. The term experimental uncertainty is somewhat more descriptive than experimental error relative to determining the reliability of data collected from single-sample tests. The experimental uncertainty could then be defined as the possible value the error may have. The individual error components were, in general, estimated on the basis of knowledge and experience concerning the test procedure, instrumentation, calibration, installation, and data acquisition and processing. In all cases, the methods used to determine the magnitude of individual error components are described.

III. ANALYSIS OF DATA ERRORS RESULTING FROM DATA ACQUISITION AND PROCESSING SYSTEM

The data acquisition and processing system was set up to process most of the data channels in a similar manner. The errors associated with the measurement systems are, therefore, similar and inherent in all the data acquired and processed through the system. Errors for data acquired using other special acquisition and processing techniques are developed separately for those particular data measurements.

The errors identified and quantified in this section are general and, where appropriate, are included in the summation of errors for each data measurement.

The function of the data acquisition and processing system includes all the processing of the data from the transducer output through recording of the output on analog and digital tapes. As shown in Figure 1, the process begins with the output signal from the transducer. This signal is fed through a low-level amplifier and then split to provide data input for analog data recording or data digitization. Filtering of the data provides 50-Hz data for digitization and 10-kHz data for analog recording. The digitization process can accommodate up to 200 channels of input and the analog process can accommodate 158 channels. The sampling rate of the digitization process, which is variable, can be as large as 24,000 samples per second. Data are related to real time throughout the process by a time clock which provides real time data inputs to both the digitization and analog tape processes at 100- μ sec intervals. The analog data were digitized to obtain the digital data presented in the isothermal test data reports. This process produced 2000 data points per data plot. The data were also filtered to remove frequencies greater than 5 Hz prior to digitization from the analog tapes.

Fig. 1 Data acquisition and processing system schematic.

The errors or sources of errors considered to be associated with the data acquisition and processing and affecting the data as reported are: (a) electrostatic and electromagnetic noise, (b) system electronic nonlinearity and instability, (c) digitization, (d) timing signals, and (e) calibration signals.

1. ELECTRONIC NOISE

Electronic noise pickup is approximately $\pm 0.1\%$ of full scale^[a]. This value is based upon observation and related professional experience.

2. ELECTRONIC NONLINEARITY AND INSTABILITY

Use of precision electrical equipment and feedback controls maintained a small contribution (0.05% of full scale) to the error in the data due to the electronic system.

3. DIGITIZATION

The data were recorded in analog form and digitized to produce 100-second plots. The digital data used to produce the data plots were obtained by a digitization process which filtered the analog data and then sampled it at increments equally spaced in time. The time interval between samples of the analog data is referred to as the sampling interval. Errors may result from the digitization due to the sampling interval used. The sampling interval is a direct function of the time interval for which digitization is performed because the number of sampled data points for any time interval duration is 2000. Smaller sampling intervals used during digitization result in smaller deviations from the continuous analog data. During the digitization process, the data are filtered. A 5-Hz low pass filter was used during the digitization of analog data. The filtering performed on the analog data is also dependent on the time interval over which the digitization is performed. Filtering allowing higher cutoff frequencies is possible with shorter digitization time intervals.

4. TIMING SIGNALS

Because of the use of a system timing signal and the recording of the time at 100- μ sec intervals, the time correlation throughout the data acquisition and processing is maintained to within $\pm 50 \mu$ sec. This source of error is not significant for the data plots presented. The errors resulting from this process are primarily dependent upon the frequency of the data and the rate of change of the data. Frequencies higher than those accepted by the filters or beyond the reproducibility inherent in the digitization sampling interval are essentially

[a] All errors referred to as percent of full scale in this section are referenced to the electronic full scale range of the acquisition and processing system.

displayed as a trace connecting the midpoints of the transient data. Figure 2 compares the effects of the sampling interval and filtering used during the digitization of the same analog data for different time intervals (100 seconds and 1 second). A higher cutoff frequency, greater than 5 Hz, was used for the 1-second time interval digitization process. As depicted in Figure 2, high rates of change of the data such as associated with step changes are represented by a slower response rate for data digitized for 100-second time intervals. Errors due to data transients can be large for data not digitized for short time intervals. However, these errors are not consistent throughout a particular data plot and are not general within any group of data. To quantify such errors, each set of data would have to be examined individually; therefore, these sources of errors have not been included in the general total maximum or total probable errors established for the data. Emphasis is placed on the fact that the previously mentioned errors only occur during severe transients.

Fig. 2 Comparison of 1-second and 100-second plots.

5. CALIBRATION SIGNALS

A set of calibration steps was recorded with the data just prior to blowdown and just following blowdown. The calibration steps were obtained from known preset values with an error of $\pm 0.005\%$ of full scale. This calibration was used to correct for gain, nonlinearity, and zero offset. The gain corrections are as accurate as the calibration electronics, within

$\pm 0.05\%$ of full scale. However, the nonlinearity and zero offsets which occurred were corrected for by linear interpolation with respect to time. This correction method is subject to an error of the same magnitude as the correction because the time the nonlinearity or zero shift occurs is not known. This error source is random in occurrence and magnitude; however, $\pm 0.9\%$ of full scale is considered to contain 95% of the errors resulting.

6. SUMMARY OF ERRORS ASSOCIATED WITH GENERAL DATA ACQUISITION AND PROCESSING

The following are the error components identified as affecting the general data due to the data acquisition and processing:

(1)	Electronic pickup noise	$\pm 0.1\%$ of full scale
(2)	General electronic system	$\pm 0.05\%$ of full scale
(3)	Calibration and correction	$\pm 0.9\%$ of full scale

From these error components, the total probable and total maximum errors are found to be:

(1)	Total maximum error for data acquisition and processing.	$\pm 1.05\%$ of full scale
(2)	Total probable error for data acquisition and processing.	$\pm 0.91\%$ of full scale

IV. ERRORS RESULTING FROM THE TOTAL MEASUREMENT SYSTEMS

Each kind of data published for the isothermal test portion of the Semiscale Blowdown and Emergency Core Cooling Project was obtained from information obtained from one or more types of detectors. The errors associated with each type of detector measurement system have been determined in this section.

The general errors quantified for the data acquisition and processing system have been added as an individual error component along with the other individual error components determined for each detector measurement system.

Mass flow rate data were obtained using information from two detector measurement systems. Errors determined for the combined data were obtained by summation of the errors associated with each detector measurement system using the statistical methods described in the general analysis procedures and techniques section of this report.

The errors for each system have been presented in as concise a form as possible. Full scale, as it is used in this section, refers to the detector full scale range unless otherwise stated.

1. PRESSURE MEASUREMENTS

Pressure measurements were made with 0- to 3000-psig-range Norwood (Precise Sensors, Inc.) strain gage pressure transducers. The sources of errors in the pressure data were in the following areas: (a) transducer installation, (b) transducer calibration, (c) transducer temperature sensitivity, and (d) data acquisition and processing.

1.1 Installation

The pressure transducers were installed in standoffs to minimize transducer thermal drift. The standoffs, which are lines connected to the system to allow the system pressure to be transmitted to the transducer, were water cooled for the first 12 to 18 inches from the system. The pressure transducer standoffs were flush mounted to minimize deviations resulting from disturbances in the flow caused by projections into the flow regime. The error associated with dynamic flow and the typical entrance effects due to the transducer installation is $\pm 0.3\%$ ^[10].

A ringing effect sometimes occurs in the pressure data for subcooled blowdown as a result of the pressure transducers being located in standoffs. A pressure measurement at the pressure transducer may not exactly represent the true pressure in the vessel due to the transmission characteristics of the standoff. The resulting error is a function of the frequency response and resonance characteristics of the standoffs. Analysis performed on

previous semiscale tests provided information showing the variation in transducer response between a transducer mounted in a water-cooled standoff and one flush mounted. Figure 3 shows the typical ringing behavior occurring when a sudden depressurization reaches the transducer during the subcooled decompression portion of a blowdown test. Because of the close agreement between the results from the two transducers, no error from this source was included in the total maximum or total probable errors. The effects of the ringing on the output from the transducer is not visibly noticeable on the scale on which the data are presented (100-second plots).

Fig. 3 Comparison of response of flush- and standoff-mounted pressure transducers.

During installation, torque applied to the transducer housing affected the calibrated output of the transducer. This error was observed to be as much as $\pm 1.0\%$ of transducer full scale. However, this error was nullified in those tests in which an in-place static pressure calibration was performed. The static in-place calibration was performed on all 0- to 3000-psig-range transducers for tests other than Tests 1001, 1002, and 1003.

1.2 Calibration

A dead-weight tester was used to calibrate all pressure transducers. The uncertainty resulting from hysteresis and nonlinearity for the transducers calibrated was determined to be $\pm 0.2\%$ of transducer full scale. The accuracy of the dead-weight tester is within $\pm 0.5\%$ of reading. Pressure transducers in the vessel were calibrated in place prior to all tests except Tests 1001, 1002, and 1003. This calibration was made at static system flow conditions through use of a precision pressure gauge (Heise gauge). The Heise gauge was mounted in the vessel head and had a range of 0 to 5000 psig with an accuracy to within $\pm 0.1\%$ of

transducer full scale. The Norwood transducers, when calibrated with the Heise gauge, had the same variance as the Heise gauge plus the variance due to the hysteresis and nonlinearity. The pressure transducers were found to have a general uncertainty of $\pm 0.2\%$ of full scale. The calibration error for this technique is determined by noting that the uncertainty contributed by the Heise gauge is ± 5 psi and that the contribution due to the hysteresis and nonlinearity of a 3000-psig Norwood transducer is ± 6 psi. The total possible error is ± 11 psi, which for a 0- to 3000-psig-range transducer is equivalent to an accuracy to within $\pm 0.37\%$ of transducer full scale.

1.3 Temperature Sensitivity

Pressure transducers are not only sensitive to pressure but also to temperature. Dead-weight calibrations were performed at various temperatures to determine the thermal sensitivity of the transducers. During the isothermal test series, the pressure transducers were located in standoffs which were water cooled for the first 12 to 18 inches from the system. Measurements indicated that the fluid temperature at the pressure transducers was essentially the ambient air temperature of the test cell and remained constant during the test. The ambient air temperature of the test cell varied a maximum of $+40^{\circ}\text{F}$, about the ambient temperature at which the transducers were calibrated.

Transducer output remained linear for any constant temperature within the test environment. The temperature sensitivity in a typical test environment was $3.3 \times 10^{-3}\%$ full scale per $^{\circ}\text{F}$ temperature change.

1.4 Data Acquisition and Processing

As is the case with other strain gage devices, the pressure transducer is sensitive to the excitation voltage applied during data acquisition. The power dissipation in the strain gage circuit is 0.07 watt for an excitation voltage of 5 volts. The thermal effects due to electrical power dissipation within the transducer were negligible due to heat transfer within the transducer and to the environment of the transducer.

The excitation voltage is electronically regulated at $5 \text{ V} \pm 0.2 \text{ mV}$. Therefore, the errors resulting from excitation voltage variations are small and considered negligible.

1.5 Summary of Errors Associated with Pressure Data

The following are the error components identified as affecting the pressure data:

(1) Installation errors

Entrance effects: $\pm 0.3\%$ full scale^[a]

Torque effect (applicable only to transducers calibrated outside of the system): $\pm 1\%$ full scale^[a].

[a] Full scale = 3000 psig.

- (2) Calibration errors (applicable to transducers calibrated with only the dead-weight tester)

$$\text{Maximum error: } \pm 0.2 + 0.5 R/FS^{[a]}$$

$$\text{Probable error: } \pm 0.5\% \text{ full scale}^{[a]}$$

where

$$R = \text{Transducer reading (psig)}$$

$$FS = \text{Transducer range full scale, 3000 psig.}$$

- (3) Calibration errors (applicable only to transducers calibrated in system using Heise gauge)

$$\text{Maximum error: } \pm AH \left(\frac{5000}{FS} \right) + 0.2 = \pm 0.37\% \text{ full scale}^{[a]}$$

$$\text{Probable error: } \pm \sqrt{\left[AH \left(\frac{5000}{FS} \right) \right]^2 + (0.2)^2} = \pm 0.26\% \text{ full scale}^{[a]}$$

where

$$AH = \text{Accuracy of Heise gauge, } \pm 0.1\% \text{ full scale}^{[b]}$$

$$FS = \text{Transducer range full scale, 3000 psig.}$$

- (4) Temperature sensitivity error: $\pm 0.13\% \text{ full scale}^{[a]}$.

- (5) General data acquisition and processing errors

$$\text{Maximum error: } \pm 1.5\% \text{ full scale}^{[a]}$$

$$\text{Probable error: } \pm 0.91\% \text{ full scale}^{[a]}.$$

From these error components, the total maximum and total probable errors are:

- (1) Total maximum error

Transducers calibrated using the dead-weight tester only:

$$\pm 2.7\% + 0.5 R/FS \text{ full scale}^{[a]}$$

[a] Full scale = 3000 psig.

[b] Full scale = 5000 psig.

Transducers calibrated in the system using the Heise gauge:

$$\pm \left[AH \frac{5000}{FS} + 1.7 \right] = \pm 1.8\% \text{ full scale}^{[a]}$$

where

R = Transducer reading (psig)

FS = Transducer range full scale, 3000 psig

AH = Accuracy of Heise gauge, $\pm 0.1\%$ full scale^[b].

(2) Total probable error

Transducers calibrated using the dead-weight tester only:

$$\pm \sqrt{(1.4)^2 + (0.5 R/FS)^2} \text{ full scale}^{[a]}$$

Transducers calibrated in the system using the Heise gauge:

$$\pm \sqrt{\left[AH \frac{5000}{FS} \right]^2 + (1.0)^2} = \pm 1.0\% \text{ full scale}^{[a]}$$

Sample pressure data with total probable error bands are presented in Appendix A, Figures A-1 through A-4.

[a] Full scale = 3000 psig.

[b] Full scale = 5000 psig.

2. DIFFERENTIAL PRESSURE MEASUREMENTS

Differential pressure measurements were taken using Baldwin Lima Hamilton (BLH) strain gauge diaphragm transducers. High line, low, medium, and high differential types were used.

Potential sources of errors in the differential pressure data were in the following areas: (a) transducer installation, (b) transducer calibration, (c) transducer temperature sensitivity, (d) transducer pressure sensitivity, (e) data acquisition and processing, (f) air entrapment, and (g) blowdown of transducer connecting lines.

2.1 Installation

Lines connecting the pressure transducer to the system were tapped into the system flush with the side of the vessel at the desired point of measurement. The error associated with dynamic flow and this installation method is $\pm 0.3\%$ of full scale. The connecting lines were orientated to minimize errors resulting from line drainage, variation in density of the fluid between the connection lines, and air entrapment in the lines. All transducers were located at or below the elevation of the lower tap.

2.2 Calibration

The differential pressure transducer calibrations were made outside of the system using a dead-weight tester. The accuracy of the dead-weight tester is within $\pm 0.5\%$ of reading. The repeatability of the BLH differential pressure transducers is within $\pm 0.1\%$ of full scale. The hysteresis for the transducers is:

Transducers range full scale (psid)	Hysteresis ^[a] (% of full scale)
<u>+0.72</u> , <u>+1.8</u> , <u>+3.6</u> , <u>+10.8</u> , <u>+18</u> , <u>+28.9</u>	<u>+0.2</u>
<u>+50</u> , <u>+100</u> , <u>+500</u>	<u>+0.15</u>
<u>+1000</u> , <u>+1500</u>	<u>+0.1</u>

[a] Specifications obtained from "Pressure Transducers", September 1973, Bulletin 402-404, BLH Electronics, Inc. 42 Fourth Ave., Waltham, Mass.

The calibration errors are:

Transducer Range Full Scale (psid)	Maximum Error (% of full scale)	Probable Error (% of full scale)
$\pm 0.72, \pm 1.8, \pm 3.6,$ $\pm 10.8, \pm 18, \pm 28.9$	$\pm [0.3 + (0.5 R/FS)]$	$\pm [(0.05) + (0.5 R/FS)^2]^{1/2}$
$\pm 50, \pm 100, \pm 500$	$\pm [0.25 + (0.5 R/FS)]$	$\pm [(0.03) + (0.5 R/FS)^2]^{1/2}$
$\pm 1000, \pm 1500$	$\pm [0.2 + (0.5 R/FS)]$	$\pm [(0.02) + (0.5 R/FS)^2]^{1/2}$

where

R = Transducer reading (psid)

FS = Transducer range full scale (psid).

2.3 Temperature Sensitivity

The temperature sensitivity for the differential pressure transducers is 1.0% full scale/100°F. Because the transducers were located away from the vessel and system piping, they underwent only a small temperature change ($\Delta T \cong 50^\circ\text{F}$) from their calibration temperature.

Temperature variations in fluid transmission lines caused the fluid density, and thus the static head experienced by the transducer, to vary. The temperature variations in the transmission lines were small and the error contribution was considered negligible. However, care must be used in the interpretation of differential pressure data from transducers having an elevation difference between pressure tap locations because of the static head variations between taps resulting from temperature changes, liquid voiding, and decompression within the experimental system itself.

2.4 Pressure Sensitivity

The BLH differential pressure transducers used in the semiscale isothermal tests are pressure sensitive. Pressure sensitivity is the term applying to the situation in which pressure exerted on the transducer case causes a differential pressure output from the transducer when zero pressure differential exists. This deviation from the true differential output is caused by deformation of the transducer casing. The deformation is a result of pressure forces within the transducer and becomes greater for greater system pressures. For example, a differential pressure transducer may indicate a zero differential pressure output when 10 psi is applied to both inputs; but when 1000 psi is applied to both inputs, the transducer may indicate .10 psid. The pressure sensitivity was established over the useful range of each transducer, and the differential pressure data were corrected for this systematic error before presentation.

Care must be used in the interpretation of differential pressure data from transducers having an elevation difference between pressure tap locations. Similar to temperature effects on the static head between taps, large pressure changes also affect the static head between taps. Such effects are not considered errors in the differential pressure measurement but part of the physical system being measured.

2.5 Data Acquisition and Processing

As is the case with other strain gage devices, a possible source of data error may result from the thermal effect on the transducer. This error is due to the power dissipation of the applied excitation voltage during data acquisition. The power dissipation in the circuit is 0.07 watt for the 5-volt electronically regulated excitation voltage used. The thermal effects due to electrical power dissipation within the transducer were negligible. Heat transfer within the transducer and to the environment of the transducer was more than adequate to dissipate any heat generation without significant temperature variation within the strain gage bridge.

2.6 Air Entrapment

Prior to the tests, entrapped air was bled at low pressure from lines connecting the transducer to the system. This action greatly reduced this source of error in the data. The error resulting from air entrapment is ± 0.01 psid.

2.7 Blowdown of Transducer Connecting Line

The lines connecting the differential pressure transducers to the system were cooled to below saturation temperature within a few inches distance from the entrance tap. This cooling prevented blowdown of the liquid in the lines during the system blowdown.

2.8 Summary of Errors Associated with Differential Pressure Data

The following are the error components identified as affecting the differential pressure data.

(1) Installation error: $\pm 0.3\%$ full scale

(2) The calibration errors are:

<u>Transducer Range</u> <u>Full Scale (psid)</u>	<u>Maximum Error</u> <u>(% of full scale)</u>	<u>Probable Error</u> <u>(% of full scale)</u>
$\pm 0.72, \pm 1.8, \pm 3.6,$ $\pm 10.8, \pm 18, \pm 28.9$	$\pm [0.3 + (0.5 R/FS)]$	$\pm [(0.05) + (0.5 R/FS)^2]^{1/2}$
$\pm 50, \pm 100, \pm 500$	$\pm [0.25 + (0.5 R/FS)]$	$\pm [(0.03) + (0.5 R/FS)^2]^{1/2}$
$\pm 1000, \pm 1500$	$\pm [0.2 + (0.5 R/FS)]$	$\pm [(0.02) + (0.5 R/FS)^2]^{1/2}$

where

R = Transducer reading (psid)

FS = Transducer range full scale (psid)

(3) Temperature sensitivity errors

Strain gage bridge: $\pm 0.5\%$ full scale

(4) Pressure sensitivity errors: Corrected for

(5) General data acquisition and processing error

Maximum error: $\pm 1.05\%$ full scale

Probable error: $\pm 0.91\%$ full scale

(6) Air entrapment error: ± 0.01 psid

(7) Transmission line blowdown: Negligible.

From the previous error components, the total maximum and total probable errors are:

(1) Total maximum error:

<u>Transducer Range Full Scale (psid)</u>	<u>Total Probable Error (% full scale)</u>
<u>+0.72, +1.8, +3.6,</u> <u>+10.8, +18, +28.9</u>	$\pm(2.15 + 0.5 R/FS + \frac{0.01}{FS} \times 100)$
<u>+50, +100, +500</u>	$\pm(2.1 + 0.5 R/FS + \frac{0.01}{FS} \times 100)$
<u>+1000, +1500</u>	$\pm(2.05 + 0.5 R/FS + \frac{0.01}{FS} \times 100)$

(2) Total probable error:

<u>Transducer Range Full Scale (psid)</u>	<u>Total Probable Error (% full scale)</u>
$\pm 0.72, \pm 1.8, \pm 3.6,$ $\pm 10.8, \pm 18, \pm 28.9$	$\pm [1.22 + (0.5 \frac{R}{FS})^2 + (\frac{0.01}{FS} \times 100^2)^{1/2}]$
$\pm 50, \pm 100, \pm 500$	$\pm [1.20 + (0.5 \frac{R}{FS})^2 + (\frac{0.01}{FS}) \times 100^2]^{1/2}$
$\pm 1000, \pm 1500$	$\pm [1.19 + (0.5 \frac{R}{FS})^2 + (\frac{0.01}{FS} \times 100^2)^{1/2}]$

where

R = Transducer reading (psid)

FS = Transducer range full scale (psid).

Sample differential pressure data with total probable error bands are presented in Appendix A, Figures A-5 through A-10.

3. FLUID AND METAL TEMPERATURE MEASUREMENTS

Fluid and metal temperatures were measured through use of Chromel-Alumel^[a] thermocouples. Sources of errors affecting the accuracy of the temperature data were analyzed to determine the overall accuracy of the data. Those sources of error considered were: (a) installation, (b) calibration, (c) data acquisition and processing, and (d) aging effects.

3.1 Installation

The accuracy of a thermocouple temperature detector is highly dependent on the technique by which the thermocouple was installed because the manner in which the detector is installed influences the capability of the transducer to detect and follow the temperature of the designated substance. Special precautions must be taken to minimize the undesirable thermal influence of heat transfer from other environmental sources. Also, care in the fabrication of the thermocouple junction and in the installation of the thermocouple is necessary to assure required transducer response time. To correct for poor installation by computing correction factors is usually difficult because of lack of available data. Such correction factors can result in greater error than those effects that are being rectified^[11].

Installation procedures and techniques used for measuring metal and fluid temperatures varied during the 1-1/2-loop semiscale system isothermal tests. Those errors generally associated with both measurements are examined first, and then errors unique to one or the other of the measurements are examined separately.

3.1.1 Errors Common to Fluid and Metal Temperature Measurements. Errors resulting from installation procedures and techniques common to the fluid and metal temperature measurements are caused by parasitic thermoelectric electromagnetic forces (emf), parasitic voltaic emfs, junction configuration, and reference junction temperature.

(1) Parasitic Thermoelectric Emfs. Parasitic thermoelectric emfs are a source of error associated with thermocouple installation. This type of error results from inhomogeneities in the thermocouple metals. The error is proportional to the temperature gradient existing between the measuring junction and the reference junction. Manufacturers of thermocouples provide wire with the degree of homogeneity conforming within a particular tolerance of standard tables for thermoelectric emfs. However, during installation, bending and other physical working of the wire may cause inhomogeneities to occur. The inhomogeneities which result from cold working are primarily due to reductions in cross-sectional area of the wire. The magnitude of an error resulting from inhomogeneity is directly proportional to the portion of the overall temperature variation between the reference and measuring junctions occurring in regions of inhomogeneity. If the temperatures are the same at the effective junctions created by a change in the thermoelectric

[a] Chromel-P was the specific Chromel alloy used.

properties of a section of the thermocouple wire, then no effect on the net emf of the circuit results. The effect of no net emf generation between two junctions at the same temperature is a consequence of the Law of Intermediate Metals^[12].

During the 1-1/2-loop semiscale system isothermal tests, a maximum of 25% of the total temperature difference existing between the measuring junction and the reference junction occurred in a region where cold working of the thermocouple wire had occurred. An average of 10% reduction in area results from the required cold working during installation. From Figure 4, the change in emf due to cold working of Chromel is -0.13 mV and for Alumel the change is -0.07 mV. The combined measurement error thus resulting is -0.20 mV. The maximum error for the combined alloys in the temperature range 32 to 575°F is -8°F. However, the change in emf due to cold working only occurs in the wire experiencing 25% of the total temperature gradient between the reference and measuring junctions. Therefore, only a -2°F error results. For compatibility with the methods used to determine total maximum and total probable errors, the known sign of this error component is ignored.

Fig. 4 Effect of cold work on emf^[13].

(2) Parasitic Voltaic Emfs. Parasitic voltaic emf is also a source of error in some thermocouple temperature measuring systems. The voltaic emf results when two metals of different composition are in electrical communication through an electrolyte. This source of error was avoided in the 1-1/2-loop semiscale isothermal test data because the thermocouple wires were insulated and contained in a stainless steel sheath.

(3) Junction Configuration. A grounded measuring junction of Class 1 type was used. The junction weld was ground to a thickness of 10 mils to improve transfer conditions between the junction and the actual substance whose temperature was being measured. This technique reduced the response time of the thermocouple and thus reduced errors in the measurement of transient temperature data. The maximum measured time constant for the thermocouples was 0.02 second for a step temperature change input.

(4) Reference Junction Temperature. Reference junctions are another source of installation error. Reference ovens were used to maintain the reference junctions at a constant temperature. This technique reduced the error due to reference junction temperature variation to $\pm 0.01^{\circ}\text{F}$. This error is negligible in comparison with other installation errors.

3.1.2 Errors Affecting Only the Fluid Temperature Measurements. Errors resulting from installation procedures and techniques which apply only to the fluid temperature measurements are caused by thermal conduction and thermal radiation.

An installation error affecting only the fluid temperature measurements results when dryout occurs in the region adjacent to the thermocouple. Thermal conduction along the thermocouple sheathing and wires and also thermal radiation from the surrounding vessel walls affect the indicated temperature measurement. Analysis of the data indicates this error to be as large as 50% of reading on occasion. Dryout usually occurs only near the end of blowdown and is easily noticeable by the sharp increase in indicated temperature from the formerly characteristic decreasing saturation fluid temperature. The uncertainty in the data after dryout occurs is probably large but cannot be well established. The uncertainties presented herein for data from thermocouples affected by dryout does not include the error from this source, and therefore, the error analysis is not applicable once dryout behavior is observed.

Some fluid temperature measurements were obtained from thermocouples that had been shielded to minimize errors due to radiation from nearby materials. The shielding consisted of five concentric stainless steel tubes of approximately 1-inch length. The tubes were evenly separated by approximately 1/16 inch and mounted with three pins at each end for support. The overall diameter of the shielding was approximately 5/8 inch and the inside diameter of the center tube was approximately 1/8 inch. As shown in Figure 5, the thermocouple sheathing and wire penetrated all shielding tubes, and the junction was welded to the opposite side of the center tube approximately 1/2 inch from each end of the shielding. The thermocouple protective tubing, approximately 1/4-inch diameter, penetrated all the shielding tubes except the centermost tube. Both shielded and unshielded thermocouples provided data which followed the saturation temperature until dryout occurred in the region adjacent to the junction. Thermal conduction along the protective

Fig. 5 Shielded thermocouples.

tubing and thermocouple sheathing provides the main source of error in the shielded thermocouple reading because, at the temperatures involved, radiation has only a small effect. Therefore, the output from the shielded thermocouple after dryout occurs is in error in a manner similar to the output from the unshielded thermocouple. The uncertainties presented for data from shielded thermocouples do not include the error due to dryout, and therefore, the analysis is not applicable once dryout is observed. All other errors associated with the fluid temperatures as measured by shielded thermocouples are similar to those associated with the temperatures from unshielded thermocouples.

3.1.3 Errors Affecting only Metal Temperature Measurements. Errors resulting from installation procedures and techniques which apply only to the metal temperature measurements are caused by system fluid contact with the thermocouple junction and by uncertainty in radial positioning of the thermocouple junction.

An installation error affecting only certain metal temperature measurements resulted from system fluid coming into contact with the thermocouples. The thermocouples located in the downcomer filler piece were contacted by system fluid in the region where metal temperatures were measured. As a result, the indicated temperature tended to follow the saturation temperature of the fluid rather than the temperature of the metal. Errors as large as 25% of reading resulted. These errors vary with transducer and location. The uncertainty in the data obtained from the downcomer filler piece thermocouples being contacted by the system fluid is probably large but cannot be well established. The uncertainties presented herein for data from these thermocouples do not include this type of error, and therefore, the error analysis is not applicable for metal temperature measurements after the fluid contacts the thermocouple. (Questionable data obtained under these conditions are so noted in the data reports.)

Uncertainty also exists in the radial position of the thermocouples used to measure metal temperatures. For the manufacturing tolerances (± 0.005 inch) and for typical temperature gradients, the resulting uncertainty in temperature at the assumed location is $\pm 50^\circ\text{F}$ [14].

3.2 Calibration

The thermocouple output data obtained during the tests were interpreted by the use of standard thermocouple reference tables. The error associated with the data obtained by this method for Chromel-Alumel thermocouples is generally accepted to be:

<u>Temperature Range (°F)</u>	<u>Error Limits^[12]</u>
32 to 530	$\pm 2^{\circ}\text{F}$
530 to 2300	$\pm 3/8\%$ of reading.

These errors are not calibration errors resulting from a direct calibration of the thermocouples in the system but are the measurement errors which may occur when a certain grade of thermocouple wire is used and reference tables are used to interpret the thermocouple output.

3.3 Data Acquisition and Processing

No unique errors were associated with the acquisition and processing of fluid and metal temperature data. The acquisition and processing errors are the same as those generally associated with the system; that is, a maximum error of $\pm 1.05\%$ full scale and a probable error of $\pm 0.91\%$ full scale.

3.4 Aging Effects

Changes in the emf output of Chromel-Alumel thermocouples may occur after numerous heating cycles. The amount of change in emf is related to the temperatures encountered, length of time in service, and the atmosphere surrounding the thermocouple. Under the conditions existing during the semiscale tests, the uncertainty in measured temperature is $\pm 0.5^{\circ}\text{F}$ ^[15].

3.5 Summary of Errors Associated with Fluid and Metal Temperature Data

The following are the error components identified as affecting the temperature measurement data:

- (1) Error resulting from changes in homogeneity of the thermocouple wire due to cold working. Applicable to both fluid and metal temperature measurements: $\pm 2^{\circ}\text{F}$.
- (2) Errors resulting from reference junctions. Applicable to both fluid and metal temperature measurements: Negligible.
- (3) Thermal conduction and radiation induced error. Variable with time and location. Applicable only to fluid temperature measurements. Results in errors 50% of reading or less after dryout occurs: Not applicable to general data.

- (4) Errors resulting from thermocouples used for metal temperature measurement being contacted by fluid during blowdown. Variable with time and location. Applicable only to downcomer filler piece metal temperature measurements. Can be as large as 25% of reading: Not applicable to general data.
- (5) Errors resulting from uncertainty in thermocouple radial position. Applicable only to metal temperature measurements: $\pm 5^{\circ}\text{F}$.
- (6) Error associated with temperature data obtained from Chromel-P versus Alumel wire and interpreted from standard reference tables^[12]. Applicable to both fluid and metal temperature measurements: $\pm 2^{\circ}\text{F}$.
- (7) General data acquisition and processing error. Applicable to both fluid and metal temperature measurements

Maximum error: $\pm 1.05\%$ full scale^[a]

Probable error: $\pm 0.91\%$ full scale^[a].
- (8) Errors resulting from thermal aging of the thermocouples. Applicable to both fluid and metal temperature measurements: $\pm 0.5^{\circ}\text{F}$.

From the preceding error components, the total maximum and total probable errors are:

- (1) Total maximum error for fluid temperature measurements: $\pm 10^{\circ}\text{F}$ ^[b]
- (2) Total maximum error for metal temperature measurements: $\pm 15^{\circ}\text{F}$ ^[c]
- (3) Total probable error for fluid temperature measurements: $\pm 5^{\circ}\text{F}$ ^[b]
- (4) Total probable error for metal temperature measurements: $\pm 7^{\circ}\text{F}$ ^[c]

Sample fluid and metal temperature data with total probable error bands are presented in Appendix A, Figures A-11 through A-16.

[a] Full scale used for general computation is 500°F , based on a maximum system temperature of 650°F and a reference junction temperature of 150°F .

[b] The error analysis is not applicable once dryout is observed.

[c] The error analysis is not applicable for thermocouples in contact with system fluid.

4. DENSITY MEASUREMENTS

Density measurements were obtained through use of gamma attenuation densitometers. In these devices, the attenuation of a collimated gamma beam is used to measure the average fluid density across the section being monitored. The attenuated radiation is detected by a scintillation crystal, and a photomultiplier tube is used to amplify the output. The output voltage data are then processed using a computer conversion program based on a derived calibration factor.

Sources of errors affecting the accuracy of the density data as obtained from the densitometers were analyzed to determine the overall accuracy of the data. Those errors considered were errors resulting from transducer installation, errors resulting from decaying source strength, errors in calibration, errors from transducer sensitivity to temperature, errors in transducer output voltage, and errors introduced through data acquisition and processing. The general terms used in the error analysis are:

ρ	=	density
V	=	voltage output
V_e	=	voltage output at density of air; $\rho \cong 0$
V_{off}	=	offset voltage
V_h	=	photomultiplier tube supply voltage
i	=	photomultiplier tube anode current
t	=	time
T	=	temperature
A	=	perpendicular area of the channel seen by the detector
Φ	=	radiation through A
Φ_v	=	amount of visible light
x	=	thickness of the material traversed
μ	=	linear absorption coefficient
γ	=	mass absorption coefficient
I	=	intensity of radiation

I_o = initial intensity of radiation

K = constant fraction of generated light falling on the photomultiplier tube

$F_1(T)$ = conversion efficiency of the scintillation crystal

$F_2(T)$ = a value determined by the conversion efficiency of the photomultiplier tube and the units in which voltage is expressed.

The output voltage of the densitometer measuring system may be related to the average density in the region of measurement as follows: The relationship between output voltage and density may be obtained by noting that the output voltage is a function of the photomultiplier tube anode current or

$$V = g(i)$$

where $g(i) = K F_2(T) V_h^7 \Phi_v$

The expression for the voltage output is then

$$V = K F_2(T) V_h^7 \Phi_v$$

Substitution of $F_1(T)\Phi$ for Φ_v and then IA for Φ leads to the output voltage:

$$V = K F_2(T) V_h^7 F_1(T) IA.$$

Substitution of $I = I_o e^{-\gamma \rho x}$ into the output voltage equation gives

$$V = K F_2(T) V_h^7 F_1(T) I_o e^{-\gamma \rho x} A.$$

If $K F_2(T) V_h^7 F_1(T) I_o A = \beta$, then

$$V = \beta e^{-\gamma \rho x}. \quad (5)$$

The density of the empty vessel is considered zero. When $\rho = 0$, the expression for the output voltage becomes $V_e = \beta$, where V_e is the voltage output when the vessel is empty.

The following expression for density may be obtained from Equation (5):

$$\rho = \frac{1}{\gamma x} \ln \frac{V}{\beta}$$

and since $\beta = V_e$, the relationship for the density in terms of the output voltage is

$$\rho = \frac{1}{\gamma x} \ln \frac{V}{V_e}$$

If x and γ are constant and $\frac{1}{\gamma x} = k$, then $\rho = k \ln \frac{V_e}{V}$. An offset voltage is always associated with the measured output voltage and is not part of the voltage resulting from the relationship $I = I_{oe}^{-\mu x}$. Thus, the relationship between density and voltage output from the densitometer becomes

$$\rho = k \ln \frac{V_e - V_{\text{off}}}{V - V_{\text{off}}}$$

The errors obtained using the error analysis techniques are

$$\text{Maximum error} = \pm \left[\frac{1}{(\ln V_{e_1} - \ln V_1)} \frac{dV_1}{V_1} + \frac{1}{(\ln V_{e_1} - \ln V_1)} \frac{dV_{e_1}}{V_{e_1}} \right] \quad (6)$$

$$\text{Probable error} = \pm \sqrt{\frac{1}{(\ln V_{e_1} - \ln V_1)^2} \left(\frac{dV_1}{V_1} \right)^2 + \frac{1}{(\ln V_{e_1} - \ln V_1)^2} \left(\frac{dV_{e_1}}{V_{e_1}} \right)^2} \quad (7)$$

where

$$V_{e_1} = V_e - V_{\text{off}}$$

$$V_1 = V - V_{\text{off}}$$

4.1 Installation

The primary sources of installation errors are alignment of the gamma beam and detector and gamma-source positioning. Because each densitometer was calibrated in the test system, the installation errors which might otherwise have affected the data were nullified.

4.2 Source Strength

Decay of the gamma-source material affects the gamma radiation strength reaching the transducer. However, since the source used (Cs-137) has a half life of 30.2 years, no noticeable change in source strength occurred during the period between detector calibration and the end of a blowdown test.

4.3 Calibration

Graphs of voltage as a function of density were generated using two calibration points for each densitometer. One point was obtained with the measurement region full of water at 60°F and the other was obtained with the measurement region empty. During warmup and

just prior to blowdown, any drift in the system was compensated for by slight changes in the high voltage applied to the photomultiplier tube. The calibration point obtained with cold water is subject to uncertainty because the density is determined from temperature and pressure which cannot be determined with infinite accuracy.

The error in the density due to temperature and pressure uncertainties is $\pm 0.6\%$ full scale where full scale equals 62.4 lb/ft^3 .

4.4 Temperature Sensitivity

The conversion efficiency of the scintillation crystal and the efficiency of the photomultiplier tube are both temperature dependent. The detector housings were maintained at a constant temperature to minimize this effect. Temperature measurements were made under test conditions. No significant temperature variations were observed, and therefore, $F_1(T)$ and $F_2(T)$ were considered constant.

Both the thickness of the material traversed and the area of the channel seen by the detector are temperature dependent, but the variation involved is considered negligible. However, note should be taken that the adjustment of the high voltage to correct for deviations between the calibration curve and the data is a correction for temperature-caused variations in the data output.

4.5 Transducer Output Voltage

The density measured by the densitometer transducer is obtained by use of the previously established relationship:

$$\rho = k \ln \frac{V_e - V_{\text{off}}}{V - V_{\text{off}}}$$

or

$$\rho = k \ln \frac{V_{e1}}{V_1} .$$

From this relationship, the error in ρ is seen to be a function of the errors in V_{e1} and V_1 . In turn, the errors in V_{e1} and V_1 are functions of other random errors resulting from temperature sensitivities, installation, and offset errors. If the errors in V_{e1} and V_1 can be established, maximum and probable errors in density can be obtained from the previously determined equations, Equations (6) and (7). The errors obtained from those equations contain all error components occurring in the measuring system through the output of the densitometer.

The usefulness of Equations (6) and (7) for maximum and probable errors is dependent on whether dV_1 and dV_{e1} can be determined. In order to determine these quantities, a physical relationship must be established for V_{e1} and V_1 in terms of other system parameters. Through use of previously mentioned physical relationships, the following equations were derived:

$$V_{e1} = C V_h^7 - V_{off}$$

$$V_1 = C V_h^7 e^{-\gamma \rho x} - V_{off}$$

where C is a summation of constant terms.

The variability in V_{e1} and V_1 is desired with density held constant. If γ , ρ , and x are assumed constant, then $e^{-\gamma \rho x}$ is a constant and the preceding equations may be written:

$$V_{e1} = C V_h^7 - V_{off}$$

$$V_1 = C_1 V_h^7 - V_{off}$$

If the total derivative of the preceding expressions is taken and if constants C and C_1 are defined as

$$C = \frac{V_{e1} + V_{off}}{V_h^7}$$

and

$$C_1 = \frac{V_1 + V_{off}}{V_h^7}$$

then substitution of the total derivative and the constants into Equations (6) and (7) results in the following:

$$\left. \frac{dV_1}{V_1} \right|_{\text{maximum}} = \frac{7(V_1 + V_{off})}{V_1} \frac{dV_h}{V_h} + \frac{dV_{off}}{V_1}$$

$$\left. \frac{dV_1}{V_1} \right|_{\text{probable}} = \left[\left(\frac{7(V_1 + V_{off})}{V_1} \right)^2 \left(\frac{dV_h}{V_h} \right)^2 + \left(\frac{dV_{off}}{V_1} \right)^2 \right]^{1/2}$$

$$\left. \frac{dV_{e1}}{V_{e1}} \right|_{\text{maximum}} = \frac{7(V_{e1} + V_{off})}{V_{e1}} \frac{dV_h}{V_h} + \frac{dV_{off}}{V_{e1}}$$

$$\left. \frac{dV_{e1}}{V_{e1}} \right|_{\text{probable}} = \left[\left(\frac{7(V_{e1} + V_{off})}{V_{e1}} \right)^2 \left(\frac{dV_h}{V_h} \right)^2 + \left(\frac{dV_{off}}{V_{e1}} \right)^2 \right]^{1/2}$$

The maximum and probable errors in the voltages V_1 and V_{e1} for the Densitometer D-228 are presented in Table I. The error values for the various detectors vary slightly; however, the values presented for Densitometer D-228 are typical.

TABLE I
MAXIMUM AND PROBABLE ERRORS IN DENSITOMETER VOLTAGE OUTPUT^[a]

V_1 (volts)	Maximum % Error in V_1	Probable % Error in V_1	Maximum % Error in V_e	Probable % Error in V_e	V_{e1} (volts)
5.4	2.05	1.86	0.66	0.56	18.0
6.8	1.64	1.48	0.66	0.56	18.0
8.0	1.41	1.26	0.66	0.56	18.0
10.0	1.14	1.01	0.66	0.56	18.0
12.2	0.95	0.83	0.66	0.56	18.0
14.0	0.83	0.71	0.66	0.56	18.0
16.0	0.74	0.64	0.66	0.56	18.0
17.0	0.70	0.60	0.66	0.56	18.0
18.0	0.66	0.56	0.66	0.56	18.0

[a] Values of errors presented were obtained for Densitometer D-228 using

$$V_{\text{off}} = 10 \text{ volts}$$

$$dV_{\text{off}} = \pm 0.1 \text{ volt}$$

$$V_1 = 5.4 \text{ to } 18 \text{ volts}$$

$$V_{e1} = 18 \text{ volts}$$

$$V_h = 800 \text{ volts}$$

$$dV_h = 0.08 \text{ volt.}$$

The total maximum and total probable errors in the density are obtained through use of Equations (6) and (7). The maximum and probable errors shown in Table II and Figure 6 are errors in transducer output only and do not include other sources of error in the final data.

TABLE II
ERRORS IN DENSITOMETER OUTPUT^[a]

V_1 (volts)	Maximum Error in Density (% of reading)	Probable Error in Density (% of reading)	Density (lb/ft ³)
5.4	2.25	1.60	62.3
6.8	2.36	1.61	50.0
8.0	2.55	1.70	41.5
10.0	3.06	1.96	30.0
12.2	4.13	2.57	20.0
14.0	5.93	3.60	13.0
16.0	11.89	7.22	6.0
17.0	23.79	14.36	2.8
18.0	∞	∞	0

[a] Based on data from Densitometer D-228.

4.6 Data Acquisition and Processing

The data processing of the transducer output is similar to that used for all instrumentation and has the same errors associated with it. The source strength is considered constant even though the gamma generation varies over a given period of time. The variance is only a small fraction of the total signal and is masked by the overall general errors resulting from the data acquisition and processing system. During the data processing, an error unique to the density data was introduced. This error results from the inability to obtain the offset voltage value exactly and from the fact that this voltage is not always constant although it was considered such during data processing. The deviation in the offset voltage, V_{off} , is $\pm 1\%$ of the established value.

Fig. 6 Errors in densitometer output.

4.7 Summary of Errors Associated with Density Data

The following are the error components identified as affecting the density data:

(1) Calibration error: $\pm 0.6\%$ full scale^[a]

(2) Transducer output errors^[b]

Maximum error: Table II and Figure 6

Probable error: Table II and Figure 6.

(3) General data acquisition and processing errors

Maximum error: $\pm 1.05\%$ full scale^[a]

Probable error: $\pm 0.91\%$ full scale^[a]

[a] Full scale is the density of water at 60°F (62.4 lb/ft³).

[b] Contains all error components through the densitometer output.

From the preceding error components, the total maximum and total probable errors are:

Total maximum error: Table III and Figure 7

Total probable error: Table IV and Figure 7.

Sample density data with total probable error bands are presented in Appendix A, Figures A-17 through A-22.

TABLE III

TOTAL MAXIMUM ERROR IN DENSITY DATA

Density (lb/ft ³)	ERROR COMPONENTS					
	Transducer Output Error. [a] (% of reading)	Calibration Error		Acquisition and Processing Error		Total Maximum Error (% of reading)
		% full scale	% of reading	% full scale	% of reading	
10	7.4	0.60	3.7	1.05	6.6	17.7
20	4.2	0.60	1.9	1.05	3.3	9.4
30	3.0	0.60	1.2	1.05	2.2	6.5
40	2.6	0.60	0.9	1.05	1.6	5.1
50	2.4	0.60	0.7	1.05	1.3	4.4
60	2.3	0.60	0.6	1.05	1.1	4.0

[a] Data obtained from Figure 6, which is based on data from Densitometer D-228.

Fig. 7 Total maximum and total probable errors for density measurement.

TABLE IV

TOTAL PROBABLE ERROR IN DENSITY DATA

Density (lb/ft ³)	ERROR COMPONENTS					Total Probable Error (% of reading)
	Transducer Output Error [a] (% of reading)	Calibration Error		Acquisition and Processing Error		
		% full scale	% of reading	% full scale	% of reading	
10	4.5	0.60	3.7	0.91	5.7	8.2
20	2.6	0.60	1.9	0.91	2.8	4.3
30	1.9	0.60	1.2	0.91	1.9	2.9
40	1.7	0.60	0.9	0.91	1.4	2.4
50	1.6	0.60	0.7	0.91	1.1	2.1
60	1.6	0.60	0.6	0.91	0.9	1.9

[a] Data obtained from Figure 6, which is based on data from Densitometer D-228.

5. VOLUMETRIC FLOW MEASUREMENTS

Volumetric flow rate measurements were obtained by using full-bore turbine flowmeters manufactured by Flow Technology, Inc.

A turbine flowmeter consists of a housing containing a propeller which is rotated by the fluid flowing through the meter. The rotational speed of the propeller is proportional to the velocity of the fluid and since the cross-sectional flow area is fixed, the rotational speed of the turbine is also proportional to the volume of fluid flowing through the meter.

Support bearings are the only physical connection between the turbine and its housing. The rotation of the turbine is sensed by an external pickoff mounted on the outside surface of the body of the flowmeter. The pickoff electromagnetically senses the passing of the turbine blades and produces a series of electrical pulses. These pulses are then transmitted through acquisition and processing electronics for amplification and conversion into meaningful information. This processing of the electrical pulses requires the application of calibration information relating the pulse frequency to the velocity of the fluid flow.

Installation, calibration, transducer sensitivity to velocity profiles, dead bands, and data acquisition and processing are sources considered to affect the accuracy of volumetric flow rate measurements as obtained from the turbine flowmeters.

5.1 Installation

The turbine flowmeters used to determine volumetric flow rate were full-flow devices. Installation errors resulting from misalignment were, therefore, not applicable. The meters were calibrated in piping systems similar to those in which they were used. Errors arising from velocity profile differences between the calibration system and the measurement system are discussed in the following section.

5.2 Calibration

The turbine flowmeters were calibrated in the Daniel Industries Flow Calibration Facility in Houston, Texas. Instrument reading errors at this facility were $\pm 0.25\%$ of full scale. The accuracy of the calibration standard used was $\pm 0.25\%$ of full scale, traceable to the National Bureau of Standards. The range of the calibration standard was 1250 gpm and the uncertainty was, therefore, ± 3.1 gpm. Flowmeters calibrated against this standard included the 200-, 300-, 500-, and 800-gpm units.

The smaller flowmeters were calibrated against a 100-gpm meter having an accuracy to within $\pm 0.50\%$ of full scale or to within ± 0.50 gpm. They were subject to the same instrument reading error of $\pm 0.25\%$ of full scale. Flowmeters calibrated against this standard included the 20- and 50-gpm units. Table V summarizes calibration errors.

TABLE V
TURBINE FLOWMETER CALIBRATION ERRORS

<u>Full Scale Range (gpm)</u>	<u>Instrument Reading Error (% full scale)</u>	<u>Error Due To Calibration Standard (% full scale)</u>	<u>Maximum Calibration Error (% full scale)</u>	<u>Probable Calibration Error (% full scale)</u>
20	0.25	2.5	2.8	2.5
50	0.25	1.0	1.2	1.0
200	0.25	1.6	1.8	1.6
300	0.25	1.0	1.2	1.0
500	0.25	0.6	0.8	0.6
800	0.25	0.4	0.6	0.5

5.3 Velocity Profiles

Turbine flowmeters were calibrated in piping arrangements similar to those in which they were to be used. Flow reversal in the blowdown environment results in the location of drag discs and other flow disturbers being sometimes upstream of the turbine flowmeter and sometimes downstream. For these reasons, consideration of the effect of velocity profile variations on turbine flowmeter output is important for error analysis.

In order to analyze the sensitivity of the turbine flowmeter to velocity profiles, a mathematical model was developed to express the incremental forces on the flowmeter blades. Several velocity profiles were assumed, and their total effect on the flowmeter blades was obtained by integration of forces on the blades.

The turbine flowmeter model analyzed consisted of a rotor having constant pitch blades as did the turbine flowmeters used in semiscale tests. The driving force on the rotor was assumed to be caused by lift forces produced on the blades by the fluid flowing over them. For simplicity, drag forces were assumed to be zero. An arbitrary blade element at radius r is subjected to forces as indicated by the vectors shown in Figure 8. The incremental lift force dF , on the blade element, is

$$dF = \frac{\rho}{2} C_L U_e^2 l dr \quad (8)$$

- α = Angle of Attack
- β = Blade Angle
- dr = Incremental Element of Blade
- V = Incoming Fluid Axial Velocity
- V_{wr} = Fluid Particle Effective Linear Velocity Relative to the Blade due to Blade Angular Velocity ω at Radius r
- l = Effective Blade Width Perpendicular to Plane of Rotation

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Fig. 8 Turbine blade with acting and resulting forces and vectors.

where

ρ is the fluid density

C_L is the lift coefficient

V_e is the fluid velocity with respect to the blade

U_e is the resultant fluid velocity

l is the effective blade width in the axial plane

dr is the radius of the blade increment.

For angles of attack less than 30° , $C_L = C_\ell \sin \alpha$, where C_ℓ is a lift constant.

The incremental torque, dT , is $dT = r dF$. (9)

Combining Equations (8) and (9) and using $U_e^2 = V^2 + (wr)^2$ results in

$$dT = \frac{\rho}{2} C_\ell \sin \alpha [V^2 + (wr)^2] l r dr . \quad (10)$$

Since $\alpha = \beta - \phi$, as shown in Figure 8, $\sin \alpha$ may be written as $\sin \alpha = \sin \beta \cos \phi - \cos \beta \sin \phi$, and Equation (10) becomes

$$dT = \frac{\rho}{2} (C_\ell \sin \beta \cos \phi - \cos \beta \sin \phi) [V^2 + (wr)^2] l r dr . \quad (11)$$

The blade torque may be obtained by integrating Equation (11) from the turbine rotor hub, H, to the blade tip, R:

$$T = \int_H^R dT.$$

For equilibrium conditions, the torque will be zero, and therefore:

$$\frac{\rho}{2} C_\ell \int_H^R (\sin \beta \cos \phi - \cos \beta \sin \phi) [V^2 + (\omega r)^2] r dr = 0, \quad (12)$$

where ρ is assumed constant.

By the definition of ϕ (Figure 8), $\cos \phi = \frac{V}{\sqrt{V^2 + (\omega r)^2}}$ and

$$\sin \phi = \frac{\omega r}{\sqrt{V^2 + (\omega r)^2}} \quad \text{Substitution of these expressions for } \cos \phi \text{ and } \sin \phi \text{ and simplification}$$

of the resulting expression leads to

$$\sin \beta \int_H^R V [V^2 + (\omega r)^2]^{1/2} r dr - \omega \cos \beta \int_H^R [V^2 + (\omega r)^2]^{1/2} r^2 dr = 0. \quad (13)$$

For simplicity, β is assumed to be 45° , which is a reasonable approximation for semiscale turbine flowmeters and therefore:

$$\sin \beta = \cos \beta = \frac{1}{\sqrt{2}}.$$

Also, for purposes of comparing profiles, the annular flow case is considered where V is a constant, R_2 is the outer radius of the fluid annulus, and R_1 is the inner radius of the fluid annulus. Assume no contribution is assumed outside the fluid region between R_1 and R_2 . Then, Equation (13) becomes

$$\frac{V}{\sqrt{2}} \int_{R_1}^{R_2} A r dr - \frac{\omega}{\sqrt{2}} \int_{R_1}^{R_2} A r^2 dr = 0 \quad (14)$$

where

$$A = [V^2 + (\omega r)^2]^{1/2}.$$

Solutions to Equation (14) can be determined for various velocity profiles represented by constant velocity fluid concentrations (various values of R_1 and R_2). For each solution, a constant value for V was determined by equating the volumetric flow rate within the region

between R_1 and R_2 to the volumetric flow rate, set equal to unity. For a flat velocity profile, $R_1 = 0$ and $R_2 = 1$. This approach makes V a nondimensional quantity and allows its computation from the expression $V = 1/(R_2^2 - R_1^2)$. After R_1 and R_2 are selected from the flow geometry and V is computed, Equation (14) is integrated and solved for ω , which is also dimensionless.

As an example, for the case where $R_1 = 0$ and $R_2 = 1$, $V = 1$ and integration of Equation (14) yields

$$\left. \frac{A^3}{3\omega} - \frac{rA^3}{4} + \frac{rA}{8} + \frac{1}{8\omega} \ln[r\omega + A] \right|_{r=0}^{r=1} = 0 \quad (15)$$

By solution of Equation (15), ω is found to have a value of 1.54 for this flat velocity profile case.

In a manner similar to the preceding, ω was determined for several velocity profiles by considering various limits of integration and solving Equation (14). The resulting values of the nondimensional quantities of V , ω , and ω/V are shown graphically in Figure 9 and numerically in Table VI. The reported solutions cover ranges of fluid velocity concentrations varying from near the center of the pipe (core flow) to near the pipe wall (annular flow).

The preceding information was used to estimate the error due to differences in velocity profiles as follows: A change in velocity profile represented by a 33% increase in the fluid axial velocity changes the rotor angular velocity from 1.54 to 1.69. A 10% change in fluid axial velocity is considered reasonable for an uncertainty estimate. On the basis of the linearity of the curves in Figure 9 in the region of $1.54 \leq \omega \leq 1.69$, a linear interpolation was used to obtain a 0.045 change in ω for a 10% change in velocity profile. This interpolation results in an error of $\pm 2.9\%$ of reading.

5.4 Dead Band

The process of repeated testing resulted in turbine drag or sticking due to bearing wear. The effect of the turbine sticking was to increase the dead band or area of low flow such that proper mechanical or electrical operation did not always occur. Experience with the operation of the flowmeters used in the semiscale system indicates that the aging effects and dead bands of the turbine flowmeters show themselves as zero data at flows below 5% of full scale. When bearing wear caused dead bands larger than 5% of full scale, the bearings were replaced. To account for dead bands, when a turbine flowmeter indicates flow of $\leq 5\%$ of full scale, the error is assumed to be 5% of full scale.

Fig. 9 Turbine flowmeter rotor rotational velocity as a function of fluid velocity profile.

5.5 Data Acquisition and Processing

The volumetric flow data are subject to the general data acquisition and processing errors and additional errors associated with converting the frequency output of the flowmeters to an analog voltage proportional to the rotational velocity of the turbine rotor. Flow Technology, Inc. flow rate monitors, Model PRI-102FR, were used to convert the meter output to an analog voltage output. The manufacturer indicates the maximum error associated with this set of electronics is $\pm 0.25\%$ of full scale.

5.6 Summary of Errors Associated with Volumetric Flow Rate Data

The errors associated with the turbine flowmeters and the volumetric flow rate data obtained from them are presented in Tables VII and VIII. Sample volumetric flow rate data with total probable error bands are presented in Appendix A, Figures A-23 through A-25.

TABLE VI

TURBINE FLOWMETER ROTOR ROTATIONAL VELOCITY
AS A FUNCTION OF FLUID VELOCITY PROFILE

Flow Description	Element Radii		Radial Distance To Center of Fluid Radius ($\frac{R_2 + R_1}{2}$)	Axial Velocity of Entering Fluid (dimensionless)	Rotor Angular Velocity ω (dimensionless)	ω/V (dimensionless)
	Inner R_1 (fraction of pipe radius)	Outer R_2				
Annular	1.0	1.0	1.000	∞	∞	1.00
Annular	0.98	1.0	0.990	25.25	25.51	1.01
Annular	0.95	1.0	0.975	10.26	10.52	1.02
Annular	0.90	1.0	0.950	5.26	5.54	1.05
Annular	0.80	1.0	0.900	2.78	3.08	1.11
Annular	0.75	1.0	0.875	2.29	2.59	1.13
Annular	0.50	1.0	0.750	1.33	1.69	1.27
Annular	0.10	1.0	0.550	1.01	1.56	1.50
Flat	0	1.0	0.500	1.00	1.54	1.54
Core	0	0.95	0.475	1.11	1.71	1.54
Core	0	0.90	0.450	1.23	1.90	1.54
Core	0	0.80	0.400	1.56	2.41	1.54
Core	0	0.70	0.350	2.04	3.14	1.54
Core	0	0.60	0.300	2.78	4.28	1.54
Core	0	0.50	0.250	4.00	6.16	1.54
Core	0	0.40	0.200	6.25	9.62	1.54
Core	0	0.30	0.150	11.11	17.11	1.54
Core	0	0.20	0.100	25.00	38.50	1.54
Core	0	0.10	0.050	100.00	154.00	1.54
Core	0	0	0	∞	∞	1.54

TABLE VII

SUMMARY OF TURBINE FLOWMETER ERRORS

Volumetric flow rate error components							
Flowmeter Range (gpm)	Calibration Errors		Velocity Profile (% of reading)	Frequency To Voltage Conversion (% full scale)	Dead Band ^[a] (% full scale)	Data Acquisition and Processing	
	Instrument Reading (% full scale)	Calibration Standard (% full scale)				Maximum (% full scale)	Probable (% full scale)
20	0.25	2.5	2.9	0.25	5	1.05	0.91
50	0.25	1.0	2.9	0.25	5	1.05	0.91
200	0.25	1.6	2.9	0.25	5	1.05	0.91
300	0.25	1.0	2.9	0.25	5	1.05	0.91
500	0.25	0.6	2.9	0.25	5	1.05	0.91
800	0.25	0.4	2.9	0.25	5	1.05	0.91

[a] Applies to lower 5% of full scale range only.

TABLE VIII

SUMMARY OF VOLUMETRIC FLOW RATE ERRORS

Flowmeter Range (gpm)	Maximum Errors ^[a]	Total Probable Error ^[a]
20	$\pm(4\% \text{ full scale}^{[b]} + 2.9\% \text{ reading})$	$\pm \left[0.29 + (2.9\% \text{ reading})^2 \right]$
50	$\pm(2.6\% \text{ full scale}^{[b]} + 2.9\% \text{ reading})$	$\pm \left[0.49 + (2.9\% \text{ reading})^2 \right]$
200	$\pm(3.2\% \text{ full scale}^{[b]} + 2.9\% \text{ reading})$	$\pm \left[14.1 + (2.9\% \text{ reading})^2 \right]$
300	$\pm(2.5\% \text{ full scale}^{[b]} + 2.9\% \text{ reading})$	$\pm \left[17.6 + (2.9\% \text{ reading})^2 \right]$
500	$\pm(2.1\% \text{ full scale}^{[b]} + 2.9\% \text{ reading})$	$\pm \left[32.8 + (2.9\% \text{ reading})^2 \right]$
800	$\pm(1.9\% \text{ full scale}^{[b]} + 2.9\% \text{ reading})$	$\pm \left[71.2 + (2.9\% \text{ reading})^2 \right]$

[a] Both total probable and total maximum errors are 5% of transducer full scale for readings $\leq$ 5% of full scale.

[b] Transducer full scale range.

6. FLOW VELOCITY MEASUREMENTS

The local fluid velocity was measured at several locations in the vessel downcomer during the isothermal test series through use of turboprobes manufactured by Flow Technology, Inc. Turboprobes are small turbine flowmeters installed in the end of metal cylinders (one-inch diameter) which are inserted into the moving fluid. The turbine flowmeter itself is 3/8 inch in diameter. The manufacturer quotes an overall accuracy for the device of $\pm 0.5\%$ of full scale. Other than the fact that they measure local velocity rather than volumetric flow rate, turboprobes operate exactly like the turbine flowmeters described in the previous section.

Installation, calibration, velocity profile, dead bands, and data acquisition and processing are sources of errors affecting the accuracy of velocity measurements as measured by turboprobes.

6.1 Installation

A certain amount of misalignment is likely when a turboprobe is installed. This misalignment could be on the order of 5° . The errors from this degree of rotation is obtained by: $1 - \cos 5^\circ = 0.004$, or $\pm 0.4\%$ of reading. An axial error in locating the probe would produce approximately the same size error, and therefore, the total installation error is $\pm 0.8\%$ of reading.

6.2 Calibration

The turboprobes used in the isothermal test series were essentially uncalibrated other than by the manufacturer. Because of significant differences between the geometries used for the manufacturer's calibration and that encountered during the semiscale tests, a total calibration error of $\pm 5\%$ of full scale is assumed.

6.3 Velocity Profile

The velocity profile within the downcomer annulus could change markedly prior to and during blowdown. However, since the turboprobe measures a localized velocity, no error contribution other than that included for calibration error is included.

6.4 Dead Bands

Turboprobe dead band errors are identical to those for turbine flowmeters – 5% of full scale for readings less than 5% of full scale.

6.5 Data Acquisition and Processing

The error arising from data acquisition and processing is identical to that for a turbine flowmeter, that is, $\pm 0.25\%$ of full scale for frequency to analog conversion and $\pm 1.05\%$ of full scale maximum error or $\pm 0.91\%$ of full scale probable error for other acquisitions and processing.

6.6 Summary of Velocity Measurement Errors

Total maximum error = $\pm(6.3\% \text{ full scale} + 0.8\% \text{ of reading})$.

Total probable error = $\pm[(0.0508 \times \text{transducer full scale})^2 + (0.8\% \text{ of reading})^2]^{1/2}$.

For readings less than 5% of full scale, both total maximum and total probable errors are $\pm 5\%$ of full scale. Sample flow velocity data with total probable error bands are presented in Appendix A, Figure A-26.

7. MOMENTUM FLUX FLOW MEASUREMENTS

Momentum flux measurements were performed using Ramapo Instrument Company, Mark V drag disc flowmeters. These devices are basically strain-gaged cantilever beams with a flat disc on one end which protrudes into the flow path. The analog output is proportional to the fluid density times fluid velocity squared, or ρv^2 .

Sources of errors affecting the accuracy of the momentum flux data obtained from the drag disc flowmeters were analyzed to determine the overall accuracy of the data. Sources of error considered were installation, calibration, transducer sensitivity to temperature and pressure, and data acquisition and processing.

7.1 Installation

Installation errors caused by misalignment of the drag disc target in the flow path contributed to the error in the transducer output. The most desirable installation of the drag disc target is to have the target centered in the cross-sectional area of the spool piece with the target surface area perpendicular to the fluid flow path. Misalignment due to installation resulted in a target alignment deviation of as much as 5° from the perpendicular to the flow path. This misalignment resulted in an error of $\pm 0.37\%$ of reading. Failure to center the target in the flow path resulted in an additional source of alignment error. However, both of these errors were eliminated by the recalibration correction obtained during data processing and are not included in this error analysis.

The velocity profiles existing at the drag discs may have been different from those occurring during calibration because the test and calibration system configurations were different. The velocity profile and associated errors may also have changed with time during blowdown. The error determined for velocity profile changes in homogeneous flow is $\pm 2.9\%$ of reading.

7.2 Calibration

The drag disc flowmeters used in the 1-1/2-loop semiscale system isothermal tests were calibrated in the Daniel Industries Flow Calibration Facility in Houston, Texas. Attempts were made during calibration to establish environmental conditions similar to those existing in the test system. Instrument spool pieces from the semiscale system were used during the calibration. A turbine flowmeter was present in the same instrument spool piece.

The standard used during the flow calibration was a precision turbine flowmeter. The accuracy of this standard turbine flowmeter was checked periodically with a weigh tank that measured the actual flow over a period of time and was always found to be within $\pm 0.25\%$ of full scale. Full scale for the standard turbine flowmeter was 1250 gpm.

During the calibration, the data collected from the drag disc were in millivolts per volt for flows in both directions. The millivolts per volt value obtained for each measured flow rate was plotted against the corresponding momentum flux value obtained from the calibration standard. These data were processed by the IBM 360 computer and the FORTRAN program, LSPF (Least Squares Polynomial Fit). A best straight-line fit through the calibration data points was thus obtained. This straight-line fit was used as the calibration curve for the drag disc.

An error analysis was performed to determine the error associated with the calibration curve data. Each calibration data point has some σ_x and σ_y associated with it, where x is the electrical output of the transducer and y is the momentum flux determined from velocity and density measurements. The uncertainties in x and y were determined in the following manner.

The contributing sources of errors associated with the electrical output of the transducer are electrical processing, temperature, and pressure. The electrical processing error is $\pm 0.1\%$ full scale. Temperature errors are $\pm 0.5\%$ full scale per 100°F for zero shift error and 0.5% full scale per 100°F for span error. The known sign of the span error component is ignored for compatibility with the methods used to determine maximum and total probable errors. Pressure error is $\pm 0.05\%$ full scale per 100 psig. The sources of these errors are explained in the discussion of errors resulting from drag disc transducer sensitivity to temperature and pressure.

In summary, the components making up the errors in the electrical output of the transducer are:

(1) Electrical processing error for calibration data: $\pm 0.1\%$ full scale

(2) Errors resulting from transducer temperature sensitivity

Zero shift error: $\pm 0.5\%$ full scale/ 100°F ^[a]

Span error: $\pm 0.5\%$ full scale/ 100°F ^[a]

(3) Errors resulting from transducer pressure sensitivity:

$\pm 0.05\%$ full scale/100 psig^[b]

The total maximum and total probable calibration errors for the measured electrical output of the transducer are:

Total maximum error: $\pm 0.22\%$ full scale

Total probable error: $\pm 0.12\%$ full scale.

The contributing errors associated with the measured momentum flux are velocity measurement errors and density determination errors. The uncertainty in y may be determined by considering the definition of momentum flux $y = \rho v^2$, where

y = momentum flux

ρ = density of fluid

v = velocity of fluid.

[a] Temperature variation in the transducer was 10°F .

[b] Pressure variation in the transducer was 10 psig.

Taking the total differential and dividing by y yields

$$\frac{dy}{y} = \frac{d\rho}{\rho} + 2 \frac{dv}{v}$$

and the maximum and probable errors in y may be expressed as

$$\left. \frac{dy}{y} \right|_{\text{maximum}} = \frac{d\rho}{\rho} + 2 \frac{dv}{v}$$

$$\left. \frac{dy}{y} \right|_{\text{probable}} = \sqrt{\left(\frac{d\rho}{\rho} \right)^2 + \left(2 \frac{dv}{v} \right)^2}$$

The following values were determined from the calibration system measurement accuracies for velocity and temperature:

$$dv = 0.185 \text{ ft/sec}$$

$$d\rho = 0.04 \text{ lb/ft}^3$$

Table IX indicates the maximum and probable calibration errors in y obtained using these quantities together with the density of water at calibration conditions, $\rho = 62.4 \text{ lb/ft}^3$.

Error bands expressing the uncertainty associated with the calibration curve can be obtained by applying the errors for x and y to each point along the calibration curve. The application of the errors for x and y to produce error bands was done by combining the errors in x and y to obtain the maximum possible deviations from the calibration curve. Equations used to determine these deviations are:

$$\begin{aligned} \text{Maximum deviations for maximum errors in x and y} &= \left[\left(\left. \frac{dy}{y} \right|_{\text{max}} \right)^2 + \left(\left. \frac{dx}{x} \right|_{\text{max}} \right)^2 \right]^{1/2} \end{aligned} \quad (16)$$

$$\begin{aligned} \text{Maximum deviation for probable errors in x and y} &= \left[\left(\left. \frac{dy}{y} \right|_{\text{prob}} \right)^2 + \left(\left. \frac{dx}{x} \right|_{\text{prob}} \right)^2 \right]^{1/2} \end{aligned} \quad (17)$$

Figure 10 shows the calibration curve with the maximum error bands determined from Equation 16, together with actual calibration data points. The scatter in the data points tends to agree with the error band spacing.

Table X provides maximum and probable calibration errors for the calibration uncertainty. These errors were obtained from the following equations:

$$\text{Maximum error} = \left(\left. \frac{dy}{y} \right|_{\text{max}} \right) (y) + \left(\left. \frac{dx}{x} \right|_{\text{max}} \right) (x)$$

$$\text{Probable error} = \left(\left. \frac{dy}{y} \right|_{\text{prob}} \right) (y) + \left(\left. \frac{dx}{x} \right|_{\text{prob}} \right) (x)$$

TABLE IX

MAXIMUM AND PROBABLE CALIBRATION ERRORS IN MOMENTUM FLUX
DETERMINED FROM DENSITY AND VELOCITY MEASUREMENTS

Determined Momentum Flux, ρv^2 (lb/ft-sec ²)	Measured Velocity (ft/sec)	Error In Density, $\frac{dp}{\rho}$ (%)	Error In Velocity, $\frac{dv}{v}$ (%)	Maximum Error In Momentum Flux $\frac{dy}{y} _{\max}$ (%) [a]	Probable Error In Momentum Flux $\frac{dy}{y} _{\text{prob}}$ (%) [a]
100	1.27	0.06	14.57	29.2	29.1
500	2.83	0.06	6.54	13.1	13.1
1000	4.00	0.06	4.63	9.3	9.3
2000	5.66	0.06	3.27	6.6	6.5
3000	6.93	0.06	2.67	5.4	5.3
4000	8.01	0.06	2.31	4.7	4.6
5000	8.95	0.06	2.07	4.2	4.1
10,000	12.66	0.06	1.46	3.0	2.9
20,000	17.90	0.06	1.03	2.1	2.1
30,000	21.93	0.06	0.84	1.7	1.7
40,000	25.30	0.06	0.73	1.5	1.5
50,000	28.31	0.06	0.65	1.4	1.3
60,000	31.00	0.06	0.60	1.3	1.2

[a] % of determined momentum flux.

where

y = momentum flux

x = transducer full scale.

Due to the dominance of the terms $\frac{dy}{y}|_{\max}$ and $\frac{dy}{y}|_{\text{prob}}$ and their near equality, the maximum and probable errors are only slightly different.

Fig. 10 Maximum error bands for drag disc calibration data.

7.3 Temperature and Pressure Sensitivity

The manufacturer of the drag disc uses a four-active-arm opposite mounted strain gage bridge to help compensate for environmental temperature variations. The transducers used in the semiscale system were constructed for a temperature range of -65 to 650°F and had the following specifications:

Zero shift: $\pm 0.5\%$ full scale per 100°F

Span: 0.5% full scale per 100°F.

The span error refers to temperature associated changes in the modulus of elasticity of the material. The preceding errors are considered maximum errors. Mathematical modeling of some of the temperature sensitive physical parameters of the transducer was performed to determine resultant deviations in the transducer output with variation of temperature. The results of this modeling were in support of the specifications. No attempt was made to establish corresponding errors on the basis of a complete mathematical modeling of the physical transducer system and temperature effects upon the output of the model. The reliability of the specifications was accepted and the specifications were used to establish error limits.

TABLE X

DRAG DISC TRANSDUCER CALIBRATION ERRORS

Momentum Flux (lb/ft-sec ²)	CALIBRATION ERRORS (lb/ft-sec ²)							
	Transducers with Full Scale = $\pm 2 \times 10^4$		Transducers with Full Scale = $\pm 3 \times 10^4$		Transducers with Full Scale = $\pm 5 \times 10^4$		Transducers with Full Scale = $\pm 6 \times 10^4$	
	Maximum	Probable	Maximum	Probable	Maximum	Probable	Maximum	Probable
100	73.0	53.0	95.0	65.0	139.0	89.0	161.0	101.0
500	110.0	90.0	132.0	102.0	176.0	126.0	198.0	138.0
1000	137.0	117.0	159.0	129.0	203.0	153.0	225.0	165.0
2000	176.0	156.0	198.0	168.0	242.0	192.0	264.0	204.0
3000	206.0	186.0	228.0	198.0	272.0	222.0	294.0	234.0
4000	232.0	212.0	254.0	224.0	298.0	248.0	320.0	260.0
5000	254.0	234.0	276.0	246.0	320.0	270.0	342.0	282.0
10,000	344.0	324.0	366.0	336.0	410.0	360.0	432.0	372.0
20,000	464.0	444.0	486.0	456.0	530.0	480.0	552.0	492.0
30,000			576.0	546.0	620.0	570.0	642.0	582.0
40,000					710.0	660.0	732.0	672.0
50,000					810.0	760.0	832.0	772.0
60,000							912.0	852.0

Pressure effects on the transducer output are considered in a manner similar to that for temperature effects. The manufacturer's error due to pressure sensitivity is $\pm 5 \times 10^{-4}\%$ full scale per psig change.

Since the calibrations were made at constant temperature and pressure, the errors from temperature and pressure deviations attributing to the total error in the drag disc flowmeter data output would be:

Zero shift: $\pm 0.5\%$ full scale per 100°F

Span: $\pm 0.5\%$ full scale per 100°F

Pressure: $\pm 0.05\%$ full scale per 100 psi.

These errors were compensated for during data processing. The technique used and the resulting errors are part of the discussion of data acquisition and processing errors as applied to drag disc flowmeter data.

7.4 Data Acquisition and Processing

The drag disc transducers are sensitive to temperature variation due to power dissipation caused by the excitation voltage applied to the strain gage bridge during the data acquisition process. The excitation voltage applied was a regulated 5 volts. The resistance of the transducer strain gage circuit is 120 ohms. The power dissipation under these conditions is 0.21 watt. The drag disc flowmeter housing, upon which the strain gages are mounted, acts as a heat sink for the heat generated and also provides a large surface for convective heat transfer. When the heat capacity of the housing and the heat transfer away from the housing are considered, the heat generation due to the power dissipated in the strain gage circuit is found to be insufficient to cause significant temperature effects in the transducer output.

Data processing errors, unique to drag discs, resulted from use of a data correction technique based on known values of the momentum flux at two times - one at preblowdown conditions and the other at postblowdown conditions. The momentum flux obtained from the transducer output was compared with that known at these two conditions. The discrepancies noted were considered to be errors in the transducer output resulting from temperature, pressure, and alignment deviations from the calibration conditions. Corrections were applied to segments of the data to compensate for the noted discrepancies. The portion of the total discrepancy to be corrected for at the starting and ending times for each data segment was determined by observing actual pressure and temperature data occurring in the system near the drag disc transducer. The amounts of correction applied between the determined correction values at each end of a data segment were obtained using a linear interpolation with respect to time within that particular data segment.

Two errors are associated with this correction process. One results from the uncertainty involved in the known momentum flux calculated using flow measurements and the density from temperature and pressure measurements. The errors in the calculated momentum flux are $\pm 2.6\%$ of reading for the maximum error and $\pm 2.1\%$ of reading for the probable error. The second error results from the method used to apply the corrections to the data. Part of the error is due to uncertainty in the judgements made regarding what period of time noted discrepancies occurred. Also, part of the second error results from the uncertainty in using linear correction factors for periods of time in which the physical conditions contributing to the need for the corrections are not linear. Examination of how the corrections were applied to the data and evaluation of the corrections against the corresponding temperature and pressure data led to an error of $\pm 0.5\%$ full scale being found to result from the method used to apply corrections to the data.

7.5 Summary of Errors Associated with Momentum Flux Data

The following are the error components identified as affecting the momentum flux data:

- (1) Installation and alignment errors: $\pm 2.9\%$ of reading^[a]
- (2) Calibration error: Table X
- (3) Temperature sensitivity error: $\pm 0.5\%$ full scale per 100°F : Corrected for
- (4) Temperature sensitivity span error: $\pm 0.5\%$ full scale per 100°F : Corrected for
- (5) Pressure sensitivity error: $\pm 0.05\%$ full scale per 100 psig: Corrected for
- (6) General data acquisition and processing error

Maximum error: $\pm 1.05\%$ full scale^[b]

Probable error: $\pm 0.91\%$ full scale^[b]

- (7) Data processing errors related to data correction techniques

Errors in magnitude of corrections

Maximum: ± 2.7 of reading^[a]

Probable: ± 2.1 of reading^[a]

Error due to the method used to apply corrections to the data:

$\pm 0.5\%$ full scale^[b]

[a] Reading – measured data in $\text{lb}/\text{ft}\cdot\text{sec}^2$.

[b] Full scale – transducer full scale in $\text{lb}/\text{ft}\cdot\text{sec}^2$.

From the error components, the total maximum error and the total probable error were found to be:

- (1) Total maximum error for momentum flux data:

$$\pm(1.55\% \text{ full scale} + 5.6\% \text{ of reading} + C)$$

where C is the calibration error obtained from Table X for the momentum flux which most closely approximates the momentum flux being measured.

- (2) Total probable error for momentum flux data:

$$\pm[(1.04\% \text{ full scale}]^2 + [(5.0)^2\% \text{ of reading} + C^2]$$

where C is the calibration error obtained from Table X for the momentum flux which most closely approximates the momentum flux being measured.

Sample momentum flux data with total probable error bands are presented in Appendix A, Figures A-27 through A-34.

8. MASS FLOW RATE MEASUREMENTS

Mass flow rate is not measured directly but is computed from any two of the three directly measured quantities: density, volumetric flow rate, and momentum flux. The mass flow rates within the system during the blowdown transient are calculated with a digital computer from either

$$\dot{m} = [\rho (\rho v^2) A^2]^{1/2} \quad (18)$$

or

$$\dot{m} = \rho v A \quad (19)$$

where

$\dot{m}$ = mass flow rate (lb/sec)

ρ = density (lb/ft³).

ρv^2 = momentum flux (lb/sec²-ft)

v = velocity (ft/sec)

A = cross-sectional flow area (ft²).

The errors associated with the mass flow rate data are obtained by the summation of the errors associated with each measured component used in the determination of the mass flow rate. The summation of the errors follows the general techniques used in this report to obtain total maximum and total probable errors.

8.1 Mass Flow Rate Computed from Drag Disc and Densitometer

The uncertainty in the mass flow rate as obtained from the combination of density, momentum flux, and cross-sectional flow area is obtained by substituting $X = \rho$ and $Y = \rho V^2$ into Equation (18) to obtain

$$\dot{m} = X^{1/2} Y^{1/2} A. \quad (20)$$

Application of the error analysis techniques to Equation (20) results in the following uncertainties for the mass flow rates:

$$\begin{aligned} \text{Total maximum error} &= \frac{1}{2} \frac{dX}{X} + \frac{1}{2} \frac{dY}{Y} + \frac{dA}{A} \\ \text{Total probable error} &= \left[\left(\frac{1}{2} \frac{dX}{X} \right)^2 + \left(\frac{1}{2} \frac{dY}{Y} \right)^2 + \left(\frac{dA}{A} \right)^2 \right]^{1/2} \end{aligned}$$

The values for the errors in density and momentum flux, $\frac{dX}{X}$ and $\frac{dY}{Y}$, are obtained from the error analysis for those particular measurements. The error for the change in cross-sectional area, $\frac{dA}{A}$, due to a coefficient of thermal expansion of 10^{-5} inch per $^{\circ}\text{F}$ and an assumed maximum temperature variation of 350°F is $\pm 0.7\%$ of the cross-sectional area. Since the errors in density and momentum flux are dependent on the reading, the actual data curves for density and momentum flux must be used to obtain time correlated errors for $\frac{dX}{X}$ and $\frac{dY}{Y}$. A graphical correlation allowing determination of the mass flow rate uncertainties from momentum flux and density readings is shown in Figures 11 through 14. Sample mass flow rate data with total probable error bands are presented in Appendix A, Figures A-35 through A-43.

8.2 Mass Flow Rate Computed from Turbine Flowmeter and Densitometer

The uncertainty in the mass flow rate as obtained from the combination of density, flow velocity, and cross-sectional flow area was obtained by applying the error analysis techniques to Equation (19). The following are the uncertainties for the mass flow rates:

$$\begin{aligned} \text{Total maximum error} &= \frac{d\rho}{\rho} + \frac{dv}{v} + \frac{dA}{A} \\ \text{Total probable error} &= \left[\left(\frac{d\rho}{\rho} \right)^2 + \left(\frac{dv}{v} \right)^2 + \left(\frac{dA}{A} \right)^2 \right]^{1/2} \end{aligned}$$

Fig. 11 Mass flow rate uncertainty for mass flow rates obtained using drag discs with ranges of $2 \times 10^4 \text{ lb/ft-sec}^2$.

The values for the errors in density and flow velocity, $\frac{d\rho}{\rho}$ and $\frac{dv}{v}$, are obtained from the error analysis for those particular measurements. The error for the change in cross-sectional area, $\frac{dA}{A}$, due to a coefficient of thermal expansion of 10^{-5} inch per $^{\circ}\text{F}$ and an assumed maximum temperature variation of 350°F is $\pm 0.7\%$ of the cross-sectional area. Since the errors for density and flow velocity are dependent on the reading, the actual data curves for density and flow velocity must be used to obtain time correlated values for $\frac{d\rho}{\rho}$ and $\frac{dv}{v}$. Graphical correlations allowing determination of the mass flow rate uncertainties from turbine flowmeter and densitometer readings are shown in Figures 15 and 16. Sample mass flow rate data with total probable error bands are presented in Appendix A, Figures A-44 through A-46.

Fig. 12 Mass flow rate uncertainty for mass flow rates obtained using discs with ranges of $3 \times 10^4 \text{ lb/ft-sec}^2$.

Fig. 13 Mass flow rate uncertainty for mass flow rates obtained using drag discs with ranges of $5 \times 10^4 \text{ lb/ft-sec}^2$.

Fig. 14 Mass flow rate uncertainty for mass flow rates obtained using drag discs with ranges of $6 \times 10^4 \text{ lb/ft-sec}^2$.

Fig. 15 Mass flow rate uncertainty for mass flow rates obtained using turbine flowmeters with ranges from 0 to 20 or 50 gpm.

Fig. 16 Mass flow rate uncertainty for mass flow rates obtained using turbine flowmeters with ranges from 0 to 200 through 800 gpm.

9. PUMP SPEED MEASUREMENTS

The pump speed data were obtained by the use of a gear and sensor pickup coupled with electrical frequency processing. The sensor produces a voltage signal as each gear tooth passes by the sensor. The accuracy of the detecting unit is largely dependent on the sensor at lower frequencies (below 100 rpm) and primarily dependent on the frequency conversion electronics at higher frequencies. Installation, calibration, detector sensitivity, and data acquisition and processing are the sources of error considered in the error analysis.

9.1 Installation

The system was installed and functioned properly with no apparent installation effects on the output data.

9.2 Calibration

The gear and sensor pickup assembly generates a sine wave voltage signal with each positive peak voltage corresponding to the passing of one gear tooth past the magnetic sensing pickup. For rotational speeds greater than 100 rpm, enough voltage is generated by the pickup to assure sufficient signal strength for detection through the electrical frequency processing equipment. The system was calibrated using known frequencies as standards. The error of the frequency standard used for calibration is negligible. The calibration of the signal conversion system indicated the system output to be accurate to within $\pm 0.5\%$ full scale. Full scale was set at 3600 rpm.

9.3 Frequency Sensitivity

The transducer pickup sensor detects the passing of each tooth of the sixty-tooth gear. The pickup does not produce a strong enough output signal for accurate speed measurement for frequencies less than 100 rpm, and the error in data for frequencies less than 100 rpm is completely uncertain. No significant errors result from system insensitivity to frequencies greater than 100 rpm.

9.4 Data Acquisition and Processing

Errors generally associated with the data processing and acquisition system also apply to the pump speed data. Because additional acquisition and processing electronics are used, additional sources of errors result. Electrical noise affects the data beyond the typical amount because the pickup system is subject to electrical noise pickup. The only significant source of electrical noise error during the semiscale isothermal tests was 60-Hz noise. If a 60-Hz signal becomes impressed strongly enough on the sensor signal, a 60-rpm error in the measured frequency would result. This error will only result in a low range, 100 Hz and below, offset. The 60-Hz signal at higher than 100-Hz frequencies will be dominated by the sensor output voltage. The frequency conversion system discriminates between high and low voltage signals and triggers on the highest signal. Therefore, the lower voltage 60-Hz noise signal would not tend to affect the frequency measurement.

9.5 Summary of Errors Associated with Pump Speed Data

The following are the error components identified as affecting the pump speed data:

- (1) Calibration error: $\pm 0.5\%$ full scale^[a]
- (2) Frequency sensitivity error: Negligible above 100 rpm
- (3) General data acquisition and processing error

Maximum error: $\pm 1.05\%$ full scale^[a]

Probable error: $\pm 0.91\%$ full scale^[a]

[a] Full scale = 3600 rpm.

(4) Unique data acquisition error

Electronic 60-Hz noise: Negligible above 100 rpm.

From these error components, the total maximum and total probable errors were found to be:

- (1) Total maximum error: $\pm 1.6\%$ full scale^[a]
- (2) Total probable error: $\pm 1\%$ full scale^[a].

Sample pump speed data with total probable error bands are presented in Appendix A, Figures A-47 and A-48.

10. PUMP POWER MEASUREMENT

Pump power was measured using a halltron. This device measures the current and voltage applied to the pump motor and effectively multiplies them together to produce a voltage output proportional to the power. Sources of errors in the pump power data originated from instrument calibration and data acquisition and processing.

10.1 Calibration

The halltron was calibrated by applying accurately known currents and voltages to be measured by the halltron. The calibration curve obtained for both increasing and decreasing readings is very nearly linear with only $\pm 1\%$ full scale deviation.

10.2 Data Acquisition and Processing

No unique data acquisition and processing errors are associated with the pump power data. The general errors associated with the system apply.

10.3 Summary of Errors Associated with Pump Power Data

The following are the error components identified as affecting the pump power measurement data:

- (1) Calibration error: $\pm 1\%$ full scale^[b]
- (2) General data acquisition and processing error

Maximum error: $\pm 1.05\%$ full scale^[b]

Probable error: $\pm 0.91\%$ full scale^[b].

[a] Full scale = 3600 rpm.

[b] Full scale is 25 kW.

From these error components, the maximum and total probable errors are:

Total maximum error: $\pm 2\%$ full scale^[a]

Total probable error: $\pm 1.4\%$ full scale^[a].

Sample pump power data with total probable error bands are presented in Appendix A, Figures A-49 and A-50.

11. PUMP TORQUE MEASUREMENTS

Torque transmission to the impeller of the circulating pump was metered by a torque transducer manufactured by Lebow Associated, Inc. (Model 1376-104) and mounted in a load cell as shown in Figure 17. The cell is a strain gage device which detects the deflection of a load-carrying member. Both the excitation and output signals were transmitted to and from the load cell by means of a rotating transformer, thereby alleviating the use of slip rings for the shaft-mounted bridge.

Fig. 17 Diagram of pump and motor assembly with load cell.

Installation, calibration, temperature sensitivity, and data acquisition and processing were the sources of error considered in the error analysis.

11.1 Installation

Even an extremely accurate measurement at the detector location does not directly yield torque at the pump impeller. Various torque losses occur between the transducer

[a] Full scale is 25 kW.

location and the pump impeller. The use of the presented data must consider these losses when the desired torque is at locations other than at the transducer. Reference 16 provides useful information for determining frictional torque losses between the torque transducer and the pump impeller.

11.2 Calibration

The entire unit was statically calibrated by the manufacturer. Calibration increments were 50 in.-lb_f from zero to the instrument full scale range of 500 in.-lb_f. The maximum deviation found was $\pm 0.1\%$ full scale.

11.3 Temperature Sensitivity

As is common with strain gage type transducers, the strain gage bridge used as a detector of torque was temperature sensitive. Although the strain gage bridge is temperature compensated over a range of 50 to 150°F, experimental experience with the transducer used indicated that temperature induced zero shifts in the data should be considered. Temperatures at the bridge during testing were within the temperature compensated range of the instrument, but the temperature sensitivity error was determined to be $\pm 0.001\%$ full scale per °F. The manufacturer specified the span temperature sensitivity error to be equal to the zero shift error; therefore, its value was also $\pm 0.001\%$ full scale per °F. A system temperature change of 100°F during testing was estimated for error determinations.

11.4 Data Acquisition and Processing

The general data acquisition and processing errors apply to the torque data. A possible acquisition error source involved the coupling of the electrical signals to and from the strain gage bridge by means of a rotating transformer. The transfer ratio of the transformer is 1.0 over the useful range. Therefore, no error resulted from the transfer ratio. Also, an error may result from the rotation of the transformer, primarily because of nonuniformity of the current induced in the secondary coils. The manufacturer lists the error introduced by these rotational effects as being a maximum of ± 0.005 mV/V, which is negligible.

11.5 Summary of Errors Associated with Pump Torque Data

The following are the error components identified as affecting the pump torque data.

(1) Calibration: $\pm 0.1\%$ full scale^[a]

(2) Temperature sensitivity

Zero shift error: $\pm 0.1\%$ full scale^[a]

Span error: $\pm 0.1\%$ full scale^[a]

[a] Full scale = 500 in.-lb_f.

(3) General data acquisition and processing errors

Maximum: $\pm 1.05\%$ full scale^[a]

Probable: $\pm 0.91\%$ full scale^[a]

From the preceding error components, the total maximum and the total probable errors obtained were:

(1) Total maximum error: $\pm 1.4\%$ full scale^[a]

(2) Total probable error: $\pm 0.3\%$ full scale^[a]

Sample pump torque data with total probable error bands are presented in Appendix A, Figures A-51 and A-52.

12. LIQUID LEVEL MEASUREMENTS

The liquid level data reported in the semiscale isothermal data reports were obtained from a differential pressure detector. The sources of errors typically associated with differential pressure detectors also apply to the liquid level measurements.

The differential pressure cell was installed with one line connected to a standpipe inside the pressure suppression tank and with the other line attached to a port in the bottom of the tank. The standpipe liquid level was maintained constant through the use of a condensate catch basin. Calibration of the system provided data accurate to within ± 0.1 inch of water for operating temperatures as high as 170°F. Because of its location, the measurement system was not subject to the blowdown environment nor to the higher pressures and temperatures associated with the vessel, blowdown loop, and operating loop.

Installation, air entrapment, calibration, temperature and pressure sensitivity, and data acquisition and processing are the sources of errors associated with the liquid level data obtained from the differential pressure transducers.

12.1 Installation

Because almost no dynamic flow condition existed in the pressure suppression tank, the errors associated with entrance effects at the transducer taps are negligible. The standpipe was located inside the pressure suppression tank to minimize temperature effects. A condensate catch basin with overflow was used to assure constant fluid level in the standpipe. The error resulting from installation is negligible.

[a] Full scale = 500 in.-lb_f.

12.2 Air Entrapment

Entrapped air was bled from the transducer connecting lines prior to the tests. This action greatly reduced this source of error in the data. The error resulting from air entrapment is ± 0.01 psid.

12.3 Calibration

The calibration errors are similar to those obtained for differential pressure cells. The calibration errors are:

Transducer range full scale (psid): ± 3.6

Maximum error (% full scale): $\pm [0.3 + (0.5 R/FS)]$

Probable error (% full scale): $\pm [(0.05) + (0.5 R/FS)^2]^{1/2}$

where

R = Transducer reading (psid)

FS = Transducer range full scale (psid).

12.4 Temperature and Pressure Sensitivity

The temperature sensitivity is similar to that discussed for differential pressure transducers, $\pm 1.0\%$ full scale per 100°F . The temperature change from transducer calibration temperature is $\sim 50^\circ\text{F}$ during test conditions. Because both lines of the differential pressure cell are in the same thermal environment, temperature effects are largely nullified. Tests performed at temperatures up to 170°F indicated a maximum error resulting from density variation in the differential pressure cell lines to be ± 0.003 psid.

The maximum pressure sensitivity for the liquid level differential pressure transducer was $\pm 1.75\%$ full scale and was corrected for during data processing.

12.5 Data Acquisition and Processing

The same error sources discussed for the differential pressure cells apply here for the differential pressure cell used for liquid level. Errors resulting from variation in excitation voltage and errors resulting from thermal effects due to electrical power dissipation within the transducer are negligible.

12.6 Summary of Errors Associated with Liquid Level Data

The following are the error components identified as affecting the liquid level measurement data:

- (1) Installation errors: Negligible
- (2) Air entrapment error: $\pm 0.27\%$ full scale^[a]
- (3) Calibration errors

Maximum error: $\pm [0.3 + (0.5 R/FS)] \% \text{ full scale}^{[a]}$

Probable error: $\pm [(0.05) + (0.5 R/FS)^2]^{1/2} \% \text{ full scale}^{[a]}$

- (4) Temperature sensitivity error: $\pm 0.59\%$ full scale^[a]
- (5) Pressure sensitivity error: Corrected for.
- (6) General data acquisition and processing error

Maximum error: $\pm 1.05\%$ full scale^[a]

Probable error: $\pm 0.91\%$ full scale^[a].

From the preceding error components, the total maximum and total probable errors are:

- (1) Total maximum error:

$$\pm (0.3 + 0.5 R/FS + 0.59 + 1.05 + 0.27) \% \text{ full scale}^{[a]}$$

- (2) Total probable errors:

$$\pm [0.05 + (0.5 R/FS)^2 + (0.59)^2 + (0.91)^2 + (0.27)^2]^{1/2} \% \text{ full scale}^{[a]}$$

where

R = Transducer reading (psid)

FS = Transducer range full scale (psid).

Sample liquid level data with total probable error bands are presented in Appendix A, Figures A-53 and A-54.

[a] Full scale is 3.64 psid.

V. DISCUSSION AND CONCLUSIONS

The error limits established by this report for the data obtained during the 1-1/2-loop semiscale system isothermal tests were established using physical information, mathematical techniques, and professional experience and judgement chosen to produce a 95% certainty for known homogeneous flows. Table XI provides a summary of the total probable errors for each type of data reported. For detectors having errors which vary within the measurement range of the detector, values expressing the minimum, maximum, and typical total probable errors are shown.

Periods of nonhomogeneous two-phase flow may increase the uncertainties established for data obtained from densitometers and turbine and drag disc flowmeters. However, during the portion of blowdown in which the majority of the system mass is expelled, until 8 or 10 seconds after rupture, homogeneous flow conditions are considered to prevail, and the errors in Table XI are valid.

Improvements throughout the measurement systems for most measurements made are possible. However, within the framework of the analysis techniques and assumptions used to determine measurement errors, the errors associated with the measurements obtained during the isothermal tests realistically reflect the state of the art in physical measurement capabilities for complex thermal-hydraulic conditions similar to those existing during the 1-1/2-loop semiscale isothermal system loss-of-coolant tests.

TABLE XI

MEASUREMENT SYSTEM TOTAL PROBABLE ERRORS

Measurement	Type	Detector Range	Total Probable Error ^[a]		
			Minimum ^[b]	Maximum ^[c]	Typical ^[d]
Fluid pressure	Diaphragm-bonded strain-gaged pressure transducer	0 to 3000 psig			± 30 psig ^[e] ± 45 psig ^[f]
Differential pressure	Diaphragm-bonded strain gage differential pressure transducer	± 0.72 psid ± 1.8 psid $\pm 3.6, \pm 10.8, \pm 18, \pm 28.9, \pm 50, \pm 100, \pm 500, \pm 1000, \pm 1500$ psid			$\pm 1.8\%$ FS ^[g] $\pm 1.3\%$ FS ^[g] $\pm 1.2\%$ FS ^[g]
Fluid temperature	Chromel-Alumel thermocouples	0 to 2300°F			$\pm 5^\circ\text{F}$
Metal temperature	Chromel-Alumel thermocouples	0 to 2300°F			$\pm 7^\circ\text{F}$
Fluid density	Gamma densitometer	0.01 to 62.4 lb/ft ³	± 0.82 lb/ft ³	± 1.14 lb/ft ³	± 0.87 lb/ft ³
Volumetric flow rate	Turbine flowmeter (full flow)	± 1 to ± 20 gpm ± 2.5 to ± 50 gpm ± 10 to ± 200 gpm ± 15 to ± 300 gpm ± 25 to ± 500 gpm ± 40 to ± 800 gpm	± 0.5 gpm ± 0.7 gpm ± 3.8 gpm ± 4.2 gpm ± 5.8 gpm ± 8.5 gpm	± 0.8 gpm ± 1.6 gpm ± 5.0 gpm ± 9.7 gpm ± 15.6 gpm ± 24.7 gpm	± 0.6 gpm ± 1.6 gpm ± 3.8 gpm ± 4.4 gpm ± 9.2 gpm ± 10.2 gpm

TABLE XI (contd.)

Measurement	Type	Detector Range	Total Probable Error ^[a]		
			Minimum ^[b]	Maximum ^[c]	Typical ^[d]
Fluid velocity	Turbine flowmeter (turboprobes)	1 to 10 ft/sec			± 0.5 ft/sec
Momentum flux	Strain-gaged drag disc	0 to 2×10^4 lb/ft-sec ²	± 220 lb/ft-sec ²	± 630 lb/ft-sec ²	± 320 lb/ft-sec ²
		0 to 3×10^4 lb/ft-sec ²	± 320 lb/ft-sec ²	± 360 lb/ft-sec ²	± 320 lb/ft-sec ²
		0 to 5×10^4 lb/ft-sec ²	± 540 lb/ft-sec ²	± 2320 lb/ft-sec ²	± 900 lb/ft-sec ²
		0 to 6×10^4 lb/ft-sec ²	± 630 lb/ft-sec ²	± 1630 lb/ft-sec ²	± 920 lb/ft-sec ²
Mass flow rate	Turbine flowmeter and gamma densitometer	0 to ± 20 or ± 50 gpm	$\pm 3\%$ R ^[h]	$\pm 9\%$ R ^[h]	$\pm 5.5\%$ R ^[h]
		0.01 to 62.4 lb/ft ³			
		0 to ± 200 to 800 gpm	$\pm 4\%$ R ^[h]	$\pm 12\%$ R ^[h]	$\pm 7.0\%$ R ^[h]
		0.01 to 62.4 lb/ft ³			
	Drag disc flowmeter and gamma densitometer	0 to 2×10^4 lb/ft-sec ²	$\pm 3.5\%$ R ^[h]	$\pm 12\%$ R ^[h]	$\pm 6\%$ R ^[h]
		0.01 to 62.4 lb/ft ³			
		0 to 3×10^4 lb/ft-sec ²	$\pm 3.5\%$ R ^[h]	$\pm 13\%$ R ^[h]	$\pm 13\%$ R ^[h]
		0.01 to 62.4 lb/ft ³			
		0 to 5×10^4 lb/ft-sec ²	$\pm 3.5\%$ R ^[h]	$\pm 13\%$ R ^[h]	$\pm 4.5\%$ R ^[h]
		0.01 to 62.4 lb/ft ³			
		0 to 6×10^4 lb/ft-sec ²	$\pm 3.5\%$ R ^[h]	$\pm 12\%$ R ^[h]	$\pm 4.5\%$ R ^[h]
		0.01 to 62.4 lb/ft ³			
					± 36 rpm
Pump speed	60-tooth gear and magnetic coil	0 to 3600 rpm			

TABLE XI (contd.)

Measurement	Type	Detector Range	Total Probable Error ^[a]		
			Minimum ^[b]	Maximum ^[c]	Typical ^[d]
Pump power	Hall effect multiplier	0 to 25 kW			<u>+0.35 kW</u>
Pump torque	Strain-gaged torque transducer	<u>+500 in.-lb</u>			<u>+4.5 in.-lb</u>
Liquid level	Differential pressure transducer	<u>+3.64 psid</u>			<u>+1.0 in.</u>

[a] The total probable error values were obtained by applying the error information given in this report for each type of detector, detector range, system configuration, and measurement value occurring during the isothermal tests. For cases for which these factors affect the total probable error, minimum, maximum, and typical values are presented. When minimum or maximum error values do not apply or are not significantly different from the typical error value, they are not presented.

[b] The minimum error value was obtained by assuming the best possible conditions typical of the isothermal test data within the reliable range of the detector. This procedure avoided the lower or dead band measurement regions of the detectors and also detector overrange conditions.

[c] The maximum error value was obtained by assuming the worst possible conditions typical of the isothermal test data within the reliable range of the detector. This procedure avoided the lower or dead band measurement regions of the detectors and also detector overrange conditions.

[d] The typical error value was obtained by assuming a mean measurement condition existing within the reliable range of the detector for data from the isothermal tests.

[e] The error value is for detectors calibrated in the system at static flow conditions and applies to all pressure data except those from Tests 1001, 1002, and 1003.

[f] The error value is for detectors only calibrated outside the system to a dead-weight tester and applies to all pressure data from Tests 1001, 1002, and 1003.

[g] % FS = % of detector full range.

[h] % R = % of reading.

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APPENDIX A

SAMPLE DATA WITH ERROR BANDS

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APPENDIX A

SAMPLE DATA WITH ERROR BANDS

Error bands for selected data from isothermal blowdown Tests 1009 and 1011, References A-1 and A-2 are presented in the form of graphs for each type of data reported. The graphs display reported data along with upper and lower error bands determined from the error analysis. Transducer identification and measurement locations may be obtained from Reference A-3.

Fig. A-1 Pressure with total probable error bands -- Test 1009, P-207.

Fig. A-2 Pressure with total probable error bands -- Test 1011, P-207.

Fig. A-3 Pressure with total probable error bands -- Test 1009, P-255.

Fig. A-4 Pressure with total probable error bands -- Test 1011, P-255.

Fig. A-5 Differential pressure with total probable error bands -- Test 1009, DP-19-15.

Fig. A-6 Differential pressure with total probable error bands -- Test 1011, DP-19-15.

Fig. A-7 Differential pressure with total probable error bands -- Test 1009, DP-22-255.

Fig. A-8 Differential pressure with total probable error bands -- Test 1011, DP-22-255.

Fig. A-9 Differential pressure with total probable error bands -- Test 1009, DP-255-207.

Fig. A-10 Differential pressure with total probable error bands -- Test 1011, DP-255-207.

Fig. A-11 Fluid temperature with total probable error bands -- Test 1009, TF-50.

Fig. A-12 Fluid temperature with total probable error bands -- Test 1011, TF-50.

Fig. A-13 Fluid temperature with total probable error bands -- Test 1009, TF-76.

Fig. A-14 Fluid temperature with total probable error bands -- Test 1011, TF-76.

Fig. A-15 Metal temperature with total probable error bands -- Test 1009, TM-78V-0.

Fig. A-16 Metal temperature with total probable error bands -- Test 1011, TM-78V-0.

Fig. A-17 Density with total probable error bands -- Test 1009, D-19V.

Fig. A-18 Density with total probable error bands -- Test 1009, D-50.

Fig. A-19 Density with total probable error bands -- Test 1009, D-1V.

Fig. A-20 Density with total probable error bands -- Test 1009, D-76.

Fig. A-21 Density with total probable error bands -- Test 1009, D-225H.

Fig. A-22 Density with total probable error bands -- Test 1009, D-275V.

Fig. A-23 Volumetric flow rate with total probable error bands -- Test 1009, FT-C-1.

Fig. A-24 Volumetric flow rate with total probable error bands -- Test 1011, FT-C-1.

Fig. A-25 Volumetric flow rate with total probable error bands -- Test 1009, FT-1.

Fig. A-26 Fluid velocity with total probable error bands -- Test 1011, FT-212.

Fig. A-27 Momentum flux with total probable error bands -- Test 1011, FD-1.

Fig. A-28 Momentum flux with total probable error bands -- Test 1009, FD-19.

Fig. A-29 Momentum flux with total probable error bands -- Test 1011, FD-19.

Fig. A-30 Momentum flux with total probable error bands -- Test 1009, FD-50.

Fig. A-31 Momentum flux with total probable error bands -- Test 1011, FD-40.

Fig. A-32 Momentum flux with total probable error bands -- Test 1009, FD-76.

Fig. A-33 Momentum flux with total probable error bands -- Test 1011, FD-76.

Fig. A-34 Momentum flux with total probable error bands -- Test 1009, FD-224.

Fig. A-35 Mass flow rate with total probable error bands -- Test 1009, FD-19 and D-19V.

Fig. A-36 Mass flow rate with total probable error bands -- Test 1011, FD-19 and D-19V.

Fig. A-37 Mass flow rate with total probable error bands -- Test 1009, FD-50 and D-50.

Fig. A-38 Mass flow rate with total probable error bands -- Test 1011, FD-50 and D-50.

Fig. A-39 Mass flow rate with total probable error bands -- Test 1009, FD-76 and D-76.

Fig. A-40 Mass flow rate with total probable error bands -- Test 1011, FD-76 and D-76.

Fig. A-41 Mass flow rate at core barrel inlet with total probable error bands -- Test 1009, FD-224 and D-225H.

Fig. A-42 Mass flow rate at core barrel inlet with total probable error bands -- Test 1011, FD-224 and D-225H.

Fig. A-43 Mass flow rate with total probable error bands -- Test 1011, FD-1 and D-1V.

Fig. A-44 Mass flow rate with total probable error bands -- Test 1009, FT-1 and D-1V.

Fig. A-45 Mass flow rate at core barrel inlet with total probable error bands -- Test 1009, FT-C-1 and D-225H.

Fig. A-46 Mass flow rate at core barrel inlet with total probable error bands -- Test 1011, FT-C-1 and D-225H.

Fig. A-47 Pump speed with total probable error bands -- Test 1009, PS-RPM.

Fig. A-48 Pump speed with total probable error bands -- Test 1011, PS-RPM.

Fig. A-49 Pump power with total probable error bands -- Test 1009, PW-PMP.

Fig. A-50 Pump power with total probable error bands -- Test 1011, PW-PMP.

Fig. A-51 Pump torque with total probable error bands -- Test 1009, T-PMP.

Fig. A-52 Pump torque with total probable error bands -- Test 1011, T-PMP

Fig. A-53 Liquid level with total probable error bands -- Test 1009, LL-PSS.

Fig. A-54 Liquid level with total probable error bands -- Test 1011, LL-PSS.

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