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**SAVANNAH RIVER SITE TMP-SET TESTS
UNCERTAINTY REPORT**

Douglas JN Taylor

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**Idaho National Engineering Laboratory
EG&G Idaho, Inc.
Idaho Falls, Idaho 83415**

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ABSTRACT

This document presents a measurement uncertainty analysis for the instruments used for the Phase I, II and III of the Savannah River One-Fourth Linear Scale, One-Sixth Sector, Tank/Muff/Pump (TMP) Separate Effects Tests (SET) Experiment Series. The Idaho National Engineering Laboratory conducted the tests for the Savannah River Site (SRS). The tests represented a range of hydraulic conditions and geometries that bound anticipated Large Break Loss of Coolant Accidents in the SRS reactors. Important hydraulic phenomena were identified from experiments. In addition, code calculations will be benchmarked from these experiments. The experimental system includes the following measurement groups: coolant density; absolute and differential pressures; turbine flowmeters (liquid phase); thermal flowmeters (gas phase); ultrasonic liquid level meters; temperatures; pump torque; pump speed; moderator tank liquid inventory via a load cells measurement; and relative humidity meters.

This document also analyzes data acquisition system including the pre-sampling filters as it relates to these measurements.

SUMMARY

This document describes the potential error sources and their quantitative contribution to each uncertainty in key measurements made during the Savannah River Laboratory scaled moderator tank/muff/pump Separate Effects Tests (SET) program. The test series were conducted at the Idaho National Engineering Laboratory and were designated as the SET-TMP. The measurements include:

- air and water mass flows,
- liquid level/inventory,
- ambient air relative humidity and temperature,
- fluid temperatures,
- pump torque/rpm,
- absolute and differential pressures, and

An analysis of the Data Acquisition System (DAS) is also included in this document because it contributes to the overall uncertainty of each measurement. Total measurement uncertainty was calculated by the root-sum-square (RSS) method that combines bias (systematic) and precision (random) errors. These uncertainties are reported at the 95% (2σ) confidence level. This summary contains the tabulated measurement uncertainties (U).

Data acquisition system: $U_{DAS} = \pm 0.11\%$ of range

Flow:

$$\begin{aligned} \text{Air: } U_q &= [(0.47 \text{ SLPM})^2 + (.0015R)^2 + (.021q)^2]^{1/2} \text{ (Inlet)} \\ U_q &= [(0.47 \text{ SLPM})^2 + (.0015R)^2 + (.044q)^2]^{1/2} \text{ (Outlet)} \end{aligned}$$

$$\text{Water: } U_q = \pm [(0.24 \text{ l/min})^2 + (0.62\%q)^2 + (.11\%R)^2]^{1/2}$$

where q = volumetric flow reading (SLPM for air,
l/min for water)
and R = Instrument Range

Liquid Inventory:

$$\text{Load Cell: } U_F = \pm 26.2 \text{ N}$$

$$\text{Liquid Level: } U_{ll} = \pm 0.77 \text{ cm}$$

where F = Force and
 ll = Liquid Level

Humidity:

$$U_{RH} = [(.21 \cdot RH)^2 + (.68\%)^2]^{1/2}$$

where RH = Relative Humidity

Temperature:

Fluid Temp (TC): $U_{TC} = \pm\{(3.33 \text{ K})^2 + [0.1\% (T-273) \text{ K}]^2\}^{1/2}$

Ambient Temp (RTD): $U_{RTD} = \pm 0.38 \text{ K}$

Pump Power

Torque: $U_{TM} = \pm[(2.54)^2 + (.434)^2 + (.0008 * \text{Rdg})^2]^{1/2} \text{ N}\cdot\text{m}$

Rotational Vel $U_{RPM} = \pm 0.01 \text{ Rdg (rpm)}$

Absolute Pressure:

(0-172 kPa): $U_p = \pm 0.40 \text{ kPa}$

(0-512 kPa): $U_p = \pm 1.20 \text{ kPa}$

(0-690 kPa): $U_p = \pm 1.60 \text{ kPa}$

(54-108 kPa): $U_p = \pm 0.126 \text{ kPa}$ (electronic barometer)

Differential Pressure

(BLH):

(0-4.97 kPa): $U_{dp} = \pm 0.04 \text{ kPa}$

(0-12.42 kPa): $U_{dp} = \pm 0.1 \text{ kPa}$

(0-24.8 kPa): $U_{dp} = \pm 0.21 \text{ kPa}$

(0-74.6 kPa): $U_{dp} = \pm 0.61 \text{ kPa}$

(0-690 kPa): $U_{dp} = \pm 5.58 \text{ kPa}$

(Sensotec):

(0-6.9 kPa): $U_{dp} = \pm 0.018 \text{ kPa}$

(0-13.8 kPa): $U_{dp} = \pm 0.036 \text{ kPa}$

(0-517 kPa): $U_{dp} = \pm 1.34 \text{ kPa}$

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1. INTRODUCTION

A series of Separate Effects Tests (SET) experiments were conducted to investigate the hydraulic response of a 1/4 linear scaled tank, muff, and pump (TMP) system. These tests supported the Savannah River Site (SRS) requirements for data to investigate the production reactor tank, muff, pump hydraulic response phenomena for large break loss-of-coolant accident (LBLOCA) scenarios.

The test series was divided into three phases: Phase I experiments investigated the hydraulic response phenomena of the 1/4 linear scaled tank, muff, and pump suction piping under gravity flow conditions; Phase II investigated the hydraulic response phenomena of the integral system that included the 1/4 linear scaled tank, muff, pump suction piping, Bingham pump and pump discharge piping; Phase III investigated the two-phase hydraulic response phenomena of the 1/4 linear scale Bingham pump during various modes of operation. A sketch of the SET-TMP test system is shown in Figure 1, and a drawing of the TMP moderator Sector Tank is depicted in Figure 2.

The SET-TMP facility is a 1/4 linear scale (1/4 length and diameter ratio) representation of part of the Savannah River Site (SRS) L-Area heavy water production reactor (L Reactor). This facility was designed and fabricated with no core heat to simulate purely hydraulic phenomena. The SET facility can simulate the following systems: a 1/6 sector of the L Reactor moderator tank (including fuel assemblies); an L Reactor tank muff; an L Reactor tank exit nozzle; an L Reactor pump suction piping; and an L Reactor Bingham Pump.

Experimental data relating to the above phenomena will help in gaining insight and understanding of the hydraulic response for the SET facility. However, instrument uncertainties must be understood and estimated to support data evaluation and analysis.

Instrument uncertainties were estimated through testing activities, manufacturers' specifications, current literature, and engineering judgment. This document details the estimated uncertainties for the measurements made in the Phase I, II, & III test series.

The measurements can be subdivided into the following groupings: coolant density; absolute and differential pressures; turbine flowmeters (liquid phase); thermal flowmeters (gas phase); ultrasonic liquid level meters; temperatures; pump power (pump torque and angular velocity); liquid inventory via a load cell measurement; and relative humidity meters. This document also analyzes the data acquisition system and the pre-sampling filtering system. The estimate of uncertainties is presented at the 95% level of confidence level. This document uses the standardized root-sum-square (RSS) method of combining component uncertainties (bias (systematic) and precision (random) uncertainties).

Figure 1 SET-TMP Test System Diagram

Figure 2 TMP Moderator Sector Tank

2. DETAILED UNCERTAINTY ANALYSIS

2.1 Data Acquisition System

A Megadac 5033A interfaced to an IBM System/2 PC made up the data acquisition system (DAS) used for the SET tests (see Figure 2). The Megadac 5033A, a high-speed data acquisition, signal conditioning, and recording system can sample at a maximum rate of 250,000 times/sec. The Megadac amplifies, multiplexes, and converts the analog data (analog-to-digital conversion) by using expandable modules (up to 256 channels of differential input). Figure 3 illustrates the Megadac 5033A options and accessories for the SET tests. An IBM Personal System 2, Model 70 controls the Megadac. The computer converts the "raw-data" into engineering units and it then calculate the computed parameters from the measurement channels.

2.1.1 Measurement Description

2.1.1.1 Amplifiers

Optim 885D modules amplify and condition the 256 input channels of the DAS. These modules have eight input channels each. Each 885D module has a common mode of ± 10 volts and allows hardware selected gains of 1:1, 1:2, 1:5, 1:10, 1:20, 1:50, 1:100, 1:200, or, 1:500. The 885D modules support all measurements connected to the input.

2.1.1.2 Multiplexer

The Megadac 5033A contains an Optim ADC5516 Multiplexer/Analog-to-Digital converter. The analog signals are first multiplexed and then digitally converted by the 5516 module (A/D). The estimated uncertainty of the multiplexer is accounted for in the specifications for each type of control module.

2.1.1.3 Analog-to-Digital Converter

An analog-to-digital converter module (ADC5516) provides a post-amp gain, multiplexing (depending on the control module used), and conversion of the analog signal to a digital reading. This module provides 16-bit resolution (15 bits plus sign,) and has a dynamic range of $\pm 32,768$ counts (90 Db dynamic Range) (calibrated to $\pm 32,000$ counts) with a full-scale voltage range of ± 10 volts (.3 mv quantization error). Digital readings are transferred to the Megadac memory and to the Small Computer System Interface (SCSI) controlled hard disc during the data recording. During data downloading the digital readings are transferred by an interface (IEEE 488 standard) to an IBM System/2 Model 70 PC for engineering unit conversion and primary storage to a Bernoulli disk.

Figure 3 Megadac 5033A Data System Configuration

2.1.1.4 Excitation Voltage

Excitation voltage for strain gage instruments (absolute/differential pressure measurements and load cells) is provided by a power supply within the Megadac 5033A. Three constant voltage signal conditioning modules (SCV-484) with eight channels each provide a 0, 2, 4, 6, 8, 10, or 12 volt dc output. Each channel consists of a precision constant voltage and a four-wire system (two excitation leads, and two sense leads). Excitation of 10 volts were used.

2.1.1.5 Engineering Unit Conversion

Data from the Megadac are transferred by an IEEE 488 interface to an IBM System/2 Model 70 PC for conversion from counts into engineering units. Calibration coefficients are derived from the calibration of the various instruments and used in the conversion process. A transformation equation is applied to each type of measurement to convert counts into engineering units.

Figure 4 Megadac 5033A Data System Configuration

2.1.1.6 Filtering

The system generally acquired the data at a rate of five samples per second (F_s). Butterworth 4-pole low-pass anti-aliasing filters processed the analog signal prior to digitization. The cutoff frequency ranged between 3-5 Hz because of hardware limitation. The filter attenuated unwanted noise power (frequency > 10 Hz) by at least 20 Db, and by 70 Db at 60 Hz. Although the cutoff frequency is higher than the Nyquist ($F_s/2 = 2.5$ Hz), inferential evidence suggest that there was negligible noise power in the frequency interval of 2.5 and 10 Hz. Hence unwanted signals/noise were not aliased.

2.1.2 Calibration

Prior to shipment, the vendor checked-out each input module and A/D converter. All DAS channels were calibrated "on-site" using multipoint calibration by a DAS engineer. A reference voltage of zero and full-scale for the transducer were applied to each channel to verify the channel output. Also each channel is balanced by applying a zero reference voltage, and the Megadac's software then automatically adjusts the offset. The uncertainty in

this process is included in the general uncertainty of the data system. The Dial-a-Source instrument used to provide the zero-level and full-scale voltages has an accuracy of $\pm 0.005\%$ of the voltage setting.

2.1.3 Specific Uncertainties

The total uncertainty reported for the DAS typically includes the uncertainties for the amplifier/multiplexer modules and the analog-to-digital convertor. The uncertainties associated with the excitation voltage and the engineering unit conversion will be reported with the overall transducer uncertainties. See the specific section for each instrument type for these uncertainties.

2.1.3.1 Amplifier and Multiplexer Uncertainty

The 885D differential input module has the following published manufacturer's specifications:

Accuracy	$\pm 0.05\%$ of full scale
Linearity	$\pm 0.02\%$ of full scale
Noise	± 0.116 microvolt rms
Temperature coefficient	$+0.25$ microvolt per $^{\circ}\text{C}$ $= 0.25$ microvolt per K

2.1.3.2 Analog-to-Digital Converter

The manufacturer's specifications for the analog-to-digital converter are as follows:

Quantization error	$\pm 0.0015\%$ of full scale
Linearity	$\pm 0.01\%$ of full scale
Gain drift	$\pm 0.0015\%$ of full scale
Offset drift	$\pm 0.0005\%$ of full scale
Noise	± 1.0 microvolt rms
Temperature coefficient	200 ppm

2.1.4 Total Uncertainty

The estimated uncertainties for the data acquisition system combine for a precision error of $\pm 0.11\%$ of range and a bias error of $\pm 0.0026\%$ of range. The various DAS uncertainties are summarized in Table 1.

TABLE 1. SUMMARY OF DATA ACQUISITION SYSTEM UNCERTAINTIES *

Parameter	Uncertainty *	
	Precision, S	Bias, B
Input Module		
885D	±0.054% of range	±0.55 ppm
Analog-to-digital converter		
ADC 5516 module	±0.01% of range	±255 ppm
RSS Totals:	±0.055% of range	±0.0026% of range
Uncertainty _{95%} *, $U_{DAS} = [B^2 + (t_{95} S)^2]^{1/2} = \pm 0.11\%$ of range		

* The uncertainty in all tables throughout this report includes both precision and bias errors reported at the two sigma (95% confidence level).

2.2 Flow

2.2.1 Measurement Description

2.2.1.1 Air Flow

Thermal mass flowmeters measured air flow at various locations in the system. The so-called linear, thermal flowmeter internally shunts part of the gas flow into a capillary tube, which is uniformly heated by a transformer⁴. At zero flow the temperature distribution is symmetrical about the midpoint of the tube, and two external thermocouples at symmetrical positions develop an equal but opposite output. When there is flow through the capillary tube, heat is transferred from the tube to the gas and back again, creating an asymmetric temperature distribution. For a constant power input (into the sensing element), the differential thermocouple output (δT) depends on the mass flow rate and the heat capacity of the gas. Because the heat capacity of the gas is relatively constant over wide ranges of temperature and pressure, the flowmeter may be calibrated directly in mass flow units. Changes in gas composition require only a simple multiplier to the air calibration to account for the difference in heat capacity, making the flowmeter useful for a variety of gases. Low, Medium and High Ranges of flow can be measured with such meters by dividing the flow with a fixed ratio shunting (properly sized for sensitivity) array. The sensor needs to heat only a small portion of the total gas, resulting in low power requirements while retaining its mass-flow measuring characteristics.

2.2.1.2 Water Flow

Water flows in the system were measured with turbine flowmeters. The turbine flowmeter is a miniature turbine wheel suspended in a pipe. This freely-suspended axial turbine, or rotor, is rotated by the flow of water through the flowmeter. The rotation speed of the turbine is proportional to the velocity of the water. Because the flow area of the meter is fixed, the turbine's rotation speed is also a true representation of the volumetric flowrate through the meter. That rate can be expressed in any desired engineering units, such as liters per minutes. Rotor rotation is usually sensed through the flowmeter body by an external electromagnetic or magnetic pickoff mounted on the surface directly above the flowmeter rotor. The rotation produces a train of electrical pulses in the pickoff, and the pulse frequency is directly proportional to the volumetric flow rate. Normal practice is to operate the transducer in a flow range where the number of pulses per volume unit of flow (the so-called K-factor) is nearly constant; departure of the actual K-factor curve from an ideal straight line is referred to as "non-linearity" and is expressed as a percent of flow rate. A radio frequency (rf) pickoff is necessary to obtain proper linearity in low flow ranges, such as those in portions of the SET tests. The pulses are transmitted to readout electronics, where they are amplified, counted, and sent to the data acquisition system.

Proper operation ("rule-of-thumb" developed from (experimental/theoretical considerations) of flow transducers requires that piping have a straight length equal to ten or more pipe diameters upstream from the flowmeter and five pipe diameters downstream, to produce fully developed flow in the region where the measurement is made. These conditions were met or exceeded in the tests; hence installation effects on the measurements are considered to be insignificant and they will be neglected.

2.2.2 Testing

The thermal mass flowmeters (Teledyne/Hastings-Raydist models HFM-200, HFM-201, and FST) are rated by the manufacturer to be accurate to $\pm 1\%$ of range, with an added uncertainty of nearly $\pm 1\%$ of range associated with the transducer's linearity (1%) and repeatability (.2%), and a temperature factor of $0.2\%/^{\circ}\text{C}$. Hastings FST is a fast responding transducer with a response 0 to 99% full scale of 2 seconds. The Manufacturers specifications are: accuracy $\pm 1\%$ of range; linearity 1%; repeatability 0.2%; and a temperature factor of $.1\%/^{\circ}\text{C}$.

Manufacturer's specifications for the turbine flowmeters (Flow Technology models FT-12C1, FT-16C1, FT-24C1, FT-24C1, FT-40C1, and FT-48C1 are $\pm 0.05\%$ of range for accuracy, $\pm 0.05\%$ of range for repeatability, and $\pm .5\%$ of range for linearity. All transducers were calibrated separately at the Standards and Calibration Laboratory at the INEL. The calibration references used are all traceable to National Institute of Standards and Technology (NIST) standards. All instruments calibrated at the Standards and Calibration Laboratory were found within the manufacturer's limits of accuracy.

2.2.3 Specific Uncertainties - Thermal Mass Flowmeters (Air)

2.2.3.1 Calibration

The Standards and Calibration Laboratory calibrated (with Nitrogen) the Thermal Mass Flowmeters at 70 °F. Several of the instruments were "Out-of-Tolerance". After Adjustment of the out-of-tolerance transducers, all of the instruments were within $\pm 1.2\%$ of Range. In addition, there are bias and random errors associated with the least squares fit to the calibration data. The bias error of +0.000006 SLPM is negligibly small, and will be ignored. The random error of ± 0.09 SLPM becomes ± 0.22 SLPM when the Student's t-distribution value of 2.571 is used to find the 95% confidence level for a system with five degrees of freedom.

The calibration data for another flow transducer (set for full-scale flow of about 57 SLPM) was found to fall within a 95% confidence interval of $\pm 1.50\%$ of reading. The bias error and random error found from the least squares fit to the calibration data are +0.003 SLPM and ± 0.14 SLPM, respectively. Again, the bias error is negligible, and the random error of the fit is ± 0.36 SLPM (5 degrees of freedom) at a confidence level of 95%.

2.2.3.2 Temperature/Pressure/Density

The heated-tube type of thermal mass flowmeter requires no corrections for temperature or pressure variations of 20% or less (the range for which the specific heat of most fluids is approximately constant). The manufacturer calibrates the transducer for flow at standard conditions ($T = 0^\circ\text{C} = 273\text{ K}$, $P = 760\text{ mm Hg}$) for any temperature and pressure within the design specifications of the transducer. The mass flow rate is found simply by using the density of air at standard conditions (0.001293 gm/ml). Therefore, no additional uncertainties are assigned for temperature, pressure, or density effects.

2.2.3.3 Transducer Electronics

As suggested by the manufacturer's specifications, an uncertainty of $\pm 1\%$ of range is assumed for the linearity and repeatability of the transducer's electronics.

2.2.3.4 Time Response

When the time response of a transducer is not small compared to the time variation of the measurand, a resultant time-lag (Phase Delay/Group Delay) uncertainty must be considered and estimated. The true mass flowmeter manufacturer reports that the transducer's time response (taken to be the "time constant"--the time required for the transducer output to reach 63.2% of a step-change input) is seven seconds (these specifications implicitly suggest that the flow time response can be characterized by a first order linear system). Air flow fluctuations in the SET tests were observed to occur with a period of about six to ten seconds, showing a need to consider phasing/group/amplitude errors that are generated because of the inability of the transducer to follow rapid changes in the flow rate. For a linear sensor, the mathematical technique for addressing the effect has been formulated.

Specifically if $X(t)$ is the input air flow fluctuations, and $h(t)$ (time constant) is the impulse response of the transducer then the output $Y(t)$ is given by $Y(t) = h(t) * X(t)$. Convolution is denoted by "*". Qualitatively, if the input excitation is sinusoidal, then the output signal is still sinusoidal with a reduced amplitude and a phase delay. For an input impulse $X(t)$ the output follows the time response of $h(t)$, reaching $1/e$ (e is Euler's number) of its maximum value in one time constant. A step response is just the integral of the impulse response and the output signal reaches $(1-1/e)$ of its final value in one time constant. Therefore, the relative uncertainty in the measurement depends on the AC amplitude, and its frequency content. For that reason, an estimated uncertainty of $\pm 1\%$ of reading because transducer response time is assigned to flow rates.

2.2.3.5 Specific Heat Variation

Inlet air to the SET test section had a low moisture content (estimated at 15% relative humidity), while the air outlet from the moderator tank under some test conditions had a relative humidity of about 60%. Consequently, the outlet air had a higher specific heat than did the inlet air. The manufacturer's calibration applies for standard air flow, and a correction factor must be applied when the meter is used to measure flow of nitrogen, carbon dioxide, or air with a high moisture content. For typical conditions for flow from the outlet of the moderator tank (RH = 60%, temperature = 300 K) the correction is about 4%, whereas for inlet flow the correction is about 1%.

2.2.3.6 Data System

The estimated precision and bias uncertainties contributed by the data system in this measurement are $\pm 0.11\%$ of range (random) and $\pm 0.0026\%$ of range (systematic).

2.2.3.7 Total Uncertainty

The total uncertainty, expressed at the 95% confidence level, for the mass flow measurements are summarized in Tables 3 and 4.

2.2.4 Air Mass Flow Uncertainty

The mass flow of air is found as the product of the air volumetric flow and the air density. Because the volumetric flow rate of a thermal mass flowmeter is valid for standard conditions, one need only multiply by the density at standard conditions to obtain the mass flow rate, without regard for adjustments in temperature (except for the indicated Relative Humidity correction). Air density in these calculations is thus a constant and it can be shown from an accepted method for analyzing propagation of errors³, that the uncertainty in the air mass flow rate is:

$$U_m = \pm \rho U_q,$$

where ρ = density of air at standard conditions
and U_q = the uncertainty in the volumetric flow rate of air.

2.2.4.1 Air Mass Flowmeter Ranges

A total of 15 Hastings flowmeters were used in the TMP-SET Tests. They include the following full scale instrument ranges:

0 - 30 Standard Liters per Minute (SLPM)
0 - 50 SLPM
0 - 100 SLPM
0 - 300 SLPM
0 - 500 SLPM
0 - 750 SLPM
0 - 1500 SLPM.

The two outlet flowmeters were ranged at 0 - 100 SLPM (low) and 0 - 1500 SLPM (high).

2.2.5 Specific Uncertainties - Turbine Flowmeters (Water)

2.2.5.1 Calibration

The 14 Flowtech turbine flowmeters, each with a different full-scale flow range, were assigned the following conversion equations based on the calibration results:

$$q(\text{l/min/volts}) = \frac{5.6 V + C_0}{5.7 V + C_0} \text{ sized at } 3/4"$$

$$q(\text{l/min/volts}) = \frac{22.8 V + C_0}{22.9 V + C_0} \text{ sized at } 1"$$
$$23.2 V + C_0$$
$$23.7 V + C_0$$

$$q(\text{l/min/volts}) = \frac{31.0 V + C_0}{38.8 V + C_0} \text{ sized at } 1 \frac{1}{2}"$$

$$q(\text{l/min/volts}) = \frac{73.5 V + C_0}{73.9 V + C_0} \text{ sized at } 2 \frac{1}{2}"$$

$$q(\text{l/min/volts}) = \frac{146.5 V + C_0}{148.4 V + C_0} \text{ sized at } 3"$$
$$192.3 V + C_0$$

$$q(\text{l/min/volts}) = 570.0 V + C_0 \text{ sized at } 4"$$

where V is the output voltage of the transducer and the offset constant C_0 is "zeroed-out" before the start of a test

Statistical analysis of the calibration data yielded different limits for each of the three transducers. The calibration data fell within 95% confidence limits of $\pm 0.31\%$ of reading. In addition, there are average bias and combined precision errors of $+0.138$ l/min and ± 0.204 l/min, respectively.

2.2.5.2 Transducer Linearity

The estimated uncertainty introduced by transducer non-linearity is $\pm 0.5\%$ of reading.

2.2.5.3 Temperature/Pressure/Viscosity

The SET tests were conducted in a non-pressurized test section, with maximum temperatures below 320 K. Based on this fact, on manufacturers' specifications, and on experience at the INEL with these transducers, the temperature/pressure/viscosity effects are negligible.

2.2.5.4 Response Time

The manufacturer specifies a five to six millisecond time constant. Because the test conditions changed slowly, relative to this time constant, the turbine response time is insignificant.

2.2.5.5 Signal Conditioning and Repeatability

Based on the manufacturer's specifications, an uncertainty of $\pm 0.2\%$ of reading is assumed for the transducer's electronic conversion circuit and signal conditioning, and $\pm 0.05\%$ of reading for the transducer's repeatability. This amounts to a maximum random error of ± 0.0039 l/s from this source for the types of transducers used.

2.2.5.6 Data System

The data acquisition system uncertainties must be included as a part of the overall flow transducer uncertainty. Those factors are tabulated in Section 2.1, and are included in the turbine flowmeter summary.

2.2.5.7 Total Uncertainty

The total uncertainty, expressed at the 95% confidence level, for the volumetric water flow measurements are summarized in Table 4.

2.2.6 Water Density Uncertainty

Mass flow for turbine transducers is computed as the product of the volumetric flow rate and the fluid density. The water density formula used in the SET tests is an equation of the following form:

$$q(T) = A + BT + CT^2$$

for a pressure of 1.224 standard atmospheres,

where q = water density in kg/m^3 ,

T = temperature in K,

$A = 760.48$,

$$B = 1.8370,$$

and

$$C = -0.0035030.$$

Statistical analysis showed this equation, based on the ASME steam tables, to have bias errors of +0.008% and +0.00015% of the density and precision errors (two sigma level) of $\pm 0.08\%$ and $\pm 0.08\%$ of the density for temperature and pressure variations, respectively.

Besides the statistical uncertainty in the fit of the above equation, the error in the measured temperatures used to calculate the water density must also be considered. It can be shown from the Taylor's series expansion of the variables the propagation of errors³ that the uncertainty in water density, for the equation used in the SET tests, is given by the following expression:

$$U_q(T) = \pm(B + 2CT)U_T$$

U_T is the uncertainty in the measured water temperature (see Table 7).

The total uncertainty for water density is summarized in Table 6.

2.2.7 Water Mass Flow Uncertainty

The estimated uncertainty in water mass flow can be found by using an expression derived from the Taylor's series expansion for a tractable approach to error propagation³.

With $m = q \cdot \rho$ = the mass flow rate of water,

where q = volumetric flow rate of water

and ρ = water density.

It can be shown that the uncertainty in the mass flow rate is

$$U_m = \pm[(q U_\rho)^2 + (\rho U_q)^2]^{1/2},$$

where U_ρ = the uncertainty in the water density

and U_q = the uncertainty in the volumetric flow rate.

TABLE 3. SUMMARY OF AIR MASS FLOWMETER UNCERTAINTIES

Parameter	Uncertainty	
	Precision	Bias
Calibration	±(0.36 SLPM + 1.50% q *)	
Transducer electronics	±0.1% of Range	
Zero adjustment	±0.3 SLPM	
Response time	±1% q	
Temperature	Not considered significant except for RH Correction	
Pressure	Not considered significant	
Fluid density	Not considered significant	
Change in specific heat (Inlet)		±1% q (Inlet Flow)
Change in specific heat (Outlet)		±4% q (Outlet Flow)
Data system	±0.11% of Range	
Installation effects	Not considered significant	
Time-averaged flow rates **		
RSS Totals (Inlet):	±0.47 SLPM ±1.8% q ±.15% of range	±1% q
RSS Totals (Outlet):	±0.47 SLPM ±1.8% q ±.15% of range	±4% q
Uncertainty _{95%} , U _{qave} :	[(0.47SLPM) ² +(.0015R) ² +(.021q) ²] ^{1/2} (Inlet)	
Uncertainty _{95%} , U _{qave} :	[(0.47SLPM) ² +(.0015R) ² +(.044q) ²] ^{1/2} (Outlet)	
* q = transducer reading (volumetric flow rate, SLPM) R = transducer range (volumetric flow rate, SLPM)		

TABLE 4. SUMMARY OF TURBINE FLOWMETER UNCERTAINTIES

Parameter	Uncertainty	
	Precision	Bias
Calibration	$\pm(0.2 \text{ l/min} + 0.31\% q \text{ *})$	+0.14 l/min
Linearity	$\pm 0.5\% q \text{ *}$	
Repeatability	$\pm 0.05\% q \text{ *}$	
Temperature effects	Not considered significant	
Pressure effects	Not considered significant	
Viscosity effects	Not considered significant	
Response time	Not considered significant	
Transducer electronics	$\pm 0.20\% q \text{ *}$	
Data system	$\pm 0.0011 \text{ Range}$	$\pm 0.000026 q$
Installation	Not considered significant	
RSS Totals:	$\pm 0.2 \text{ l/min} \quad \pm 0.62\% q \quad \pm 0.11\% R^*$	$\pm 0.14 \text{ l/min}$
Uncertainty _{95%} , U _q :	$\pm [(0.24 \text{ l/min})^2 + (0.62\% q)^2 + (.11\% R)^2]^{1/2}$	
q = volumetric flow rate, l/min		
R = Instrument Range		

TABLE 5. SUMMARY OF WATER DENSITY UNCERTAINTIES *

Parameter	Uncertainty	
	Precision	Bias
<u>Polynomial approximation</u>		
Temperature	$\pm 0.08\% \rho$	$\pm 0.008\% \rho$
Pressure	$\pm 0.08\% \rho$	$\pm 0.00015\% \rho$
Measured temperature	$\pm (B + 2CT)U_T$ **	
RSS Total:	$\pm 0.113\% \rho \pm (B + 2CT)U_T$ ** $\pm 0.008\% \rho$	
Uncertainty _{95%} , U_ρ :	$\pm \{(0.113\% \rho)^2 + [(B + 2CT)U_T]^2\}^{1/2}$ **	

* The water mass flow uncertainty is found from the uncertainties for the volumetric flow rate and the water density according to the following expression:

$$U_m = \pm [(q U_q)^2 + (\rho U_\rho)^2]^{1/2}$$

** The water density is approximated by an expression of the following form (see Section 2.2.6):

$$q = A + BT + CT^2.$$

2.3 Liquid Inventory

2.3.1 Measurement Description

2.3.1.1 Moderator Tank Liquid Inventory

Three Sensotec Model 41 load cells, mounted on the bottom, at the apex, and at the two corners of the pie section of the moderator tank, measured the liquid inventory. The Sensotec load cells uses bonded strain gages. The strain gages are bonded to a strain post(s) (support column(s)), so that elastic deformation of the support causes a change in the cross sectional area of the strain gage, which in turn changes the electrical resistance of the wire. The strain gages are configured in a resistive Wheatstone Bridge along with additional internal temperature compensation, and balancing resistors. The load cell are designed to prevent slight off-center forces from introducing bending or torsional moments in the support column of the instrument, through two stabilizing diaphragms. However severe off-center loading can cause significant errors in the system. Care was taken during installation to eliminate this potential error.

Figure 5. Load Cell (Strain Gage) channel block diagram.

2.3.1.2 Specific Uncertainties

The uncertainties estimates were derived from, the INEL calibration, Manufacturer's specification, the signal conditioning/DAS uncertainty estimates, and gross analytical estimates.

2.3.1.3 Vendor Specification

The Vendor specifies the load cell uncertainties for Tension/Compression (0 - 1000 lbs) as:

Non-linearity: 0 to 1000 lbs = $\pm 0.1\%FS$, ± 4.45 N (± 1 lbs)

Hysteresis: 0 to 1000 lbs = $\pm 0.08\%$, ± 3.56 N ($\pm .8$ lbs)

Non-Repeatability: 0 to 1000 lbs $\pm 0.03\%$, ± 1.34 N ($\pm .3$ lbs)

Temperature coeff:

Zero Offset 0 to 1000 = $\pm 0.002\%FS/^{\circ}F$ (± 1.78 N
[$\pm 0.002 \cdot 1000 \text{ lbs} \cdot 20^{\circ}F$])
Span (Max) 0 to 1000 = $\pm 0.002\%FS/^{\circ}F$ (± 1.78 N
[$\pm 0.002 \cdot 1000 \text{ lbs} \cdot 20^{\circ}F$])

2.3.1.4 Calibration

The Load cells were calibrated at the Standards and Calibration Lab. The results of this calibration were:

Reference load = ± 13.35 N (± 3 lbs) (bias error)

Range $\pm 0.4\%$ full scale (precision error)

2.3.1.5 Vibration/Shock

In view of the benign SET-TMP test conditions, the uncertainty for vibration and shock is considered negligible.

2.3.1.6 Transducer Zeroing

At the start of each test all signal conditioning cards of the transducers are balanced with a Dial-a-Source. The accuracy of the Dial-A-Source is $\pm 0.005\%$ of full scale.

2.3.1.7 Data System.

The uncertainty analysis of the data system is included in Section 2.1 of this uncertainty report.

2.3.2 Total Uncertainty

The combined uncertainties for the load cells measurements at the 95% confidence level, calculated by the root-sum-square method, are summarized in Table 6.

TABLE 6. SUMMARY OF LOAD CELL UNCERTAINTIES

Parameter	Uncertainty	
	Precision	Bias
Calibration	$\pm 0.4\%$ of R_g ± 1.78 N (± 4 lbf)	± 17.8 N (± 4 lbf)
Linearity		± 4.45 N (1.0 lbf)
Repeatability	± 3.56 N (± 0.8 lbf)	
Temperature Effects (Zero Offset and Span)		± 2.54 N (± 0.57 lbf)
Excitation Voltage		± 0.45 N (± 0.1 lbf)
Data System	± 2.45 N (± 0.55 lbf)	± 0.13 N (± 0.03 lbf)

Installation Effects Not estimated

RSS Totals: $\pm 18.2 \text{ N } (\pm 4.1 \text{ lbf})$ $\pm 18.5 \text{ N } (\pm 4.16 \text{ lbf})$

Uncertainty_{95%}, $U_f = \pm 26.2 \text{ N } (\pm 5.9 \text{ lbf})$

2.3.3 Liquid Level

2.3.3.1 Measurement Description

Liquid Level was measured at 7 locations in the moderator tank (1 ea for flow Zones 1 thru 4 and 3 each for flow zone 5 for the simulated core loading with Lundahl Model DCU-7 (6 ea.) and DCR-1/DST-C (in Zone 2). The transducer is an ultrasonic device, which uses an acoustic waveguide (hollow tube), and an Electrostatic sound generator/sensor. It measures the time interval between the generated pulse, and the reflected pulse. The generated pulse travels down the waveguide, and is reflected back to sensor by the liquid/gas interface. The sensor emits a tone burst at a repetition rate of 8 Hz and at a frequency of 50 kHz. An internal electronic clock measures the interval between the transmitted and reflected pulse. Because the sonic velocity is a function of the temperature of the gas acoustic coupling (The sound velocity is proportional to the square root of the gas temperature), an external temperature sensor must be used to compensate for the temperature sensitivity of the transducer. In addition the technique is also slightly sensitive to the atmospheric pressure, because of deviations of the real gas from the ideal gas law.

2.3.3.2 Specific Uncertainties

The Vendor quotes an accuracy with no temperature gradient of $\pm 0.25\%$ of range $\pm 7.6 \text{ cm } (\pm 3 \text{ in})$.

The pressure sensitivity was estimated using the 2nd virial coefficient (deviations from the ideal gas law) for air and was about $\pm 0.008 \text{ cm } (\pm 0.003 \text{ in})$.

2.3.3.3 Installation Uncertainties

Installation effects may dominate the measurement uncertainties. This technique measures the liquid level within the hollow tube. However the physical quantity of interest is the liquid level of the Moderator Tank. Water in the moderator tank drains into or out-of the gage through the bottom end fitting (about 60% of the tube flow area). Because of the large radial velocities near the bottom of the tank, there are large local dynamic pressure changes which affect the level in the measurement tubes (biasing the data high or low). As a result, at certain locations, the liquid level inside the tube is not equal to the liquid level of the moderator tank. These level variations are a function of the liquid flowrate through the tank. Further analysis may allow removal of this measurement bias. However this data correction has not been applied to the data.

TABLE 7. SUMMARY OF LIQUID LEVEL UNCERTAINTIES

Parameter	Uncertainty	
	Precision	Bias
Calibration (In place Calibration)	±0.1 cm	
Linearity	Not Applicable	
Repeatability		±.76 cm
Pressure Effects		±.00076 cm
Installation Effects*		
Data Systems	±0.025 cm	±.00025 cm
RSS Totals:	±0.1 cm	±.76 cm.
Uncertainty _{95%} , $U_{LL} = \pm[(0.1)^2 + (0.76)^2]^{1/2}$ cm		

* The uncertainty estimate does not include the dominate contribution from the flow hydraulics on the moderator tank. This component of the uncertainty may be greater than ±6.0 in.₁₅.

2.4 Relative Humidity

2.4.1 Measurement Description

External building atmospheric relative humidity (RH) along with the temperature, and the Moderator Tank-Air Vent-Atm side of flowmeter were measured with a Solomat 900 V/358T Sensor.

The humidity segment of the gage uses a polymer capacitive element. The polymer membrane adsorbs water from the air, which changes the effective dielectric constant. The change in dielectric constant alters the effective capacitance of the transducer. The relative humidity is converted to an AC voltage change. After signal conditioning and demodulation, the AC voltage can be converted into either a 4 to 20 ma current loop, or 0 to 5 V range for 0 to 100% Relative Humidity (RH). The transducer's transmitter houses voltage excitation source and the signal conditioning .

2.4.2 Calibration/Testing

The standards and calibration laboratory calibrated the two Solomet relative humidity gages used in the SET/TMP test series to ensure that the transducers met the manufacturer's specification. The calibration results were:

- Gage [S/N 1495] (20 - 70% RH), deviation of +0.2 Rdg from manufacture, calibration, and
- Gage [S/N 7187] (20 - 90 % RH), deviation of +.08 of Rdg from the Vendor's calibration.

In addition, the calibration was in-situ verified by using the Vendor supplied portable calibration kit.

2.4.3 Specific Uncertainties

The units were calibrated by the vendor at four points; 0%, 11%, 54%, and 75% RH.

The accuracy quoted by the Vendor is $\pm 3\%$ for RH of 0 to 100%, and $\pm 2\%$ for RH between 5-75%.

The Vendor also lists the Electronics and Sensor Temperature Coefficient as $.033\%/^{\circ}\text{F}$.

The estimated in-situ verification is 5% RH.

TABLE 8. SUMMARY OF RELATIVE HUMIDITY UNCERTAINTIES

Parameter	Uncertainty	
	Random	Bias
Calibration Lab		+0.2 Rdg RH
Verification (In-Situ)		$\pm .05$ Rdg RH *
Temperature	± 0.0033 of range RH	
Vendor Calibration		$\pm .03$ Rdg RH
Excitation voltage	Negligible	Negligible
Data System	± 0.0006 of range RH	Negligible
RSS Totals:	± 0.0034 of range RH	$0.20 \cdot \text{Rdg RH}$
Uncertainty _{95%} , U_{RH} :	$= [B^2 + (2 \cdot \sigma)^2]^{1/2} = [(.20 \cdot \text{RH})^2 + (.68\%)^2]^{1/2}$	

* Not included in the RSS

2.4.4 RTD Temperature Measurement

The temperature measuring component of the gauge is discussed in the temperature section of the uncertainty report.

2.5 Temperature

2.5.1 Measurement Description

All temperature measurements (with the exception of the integral RTD in the Relative Humidity sensor probe) in the SET tests were made with MgO insulated, 304 stainless steel-sheathed, Type-K thermocouple having insulated grounded measuring junctions. They measured fluid temperatures at the following positions:

- Moderator tank-muff Outlet
- In the piping at the Moderator Tank outlet (A fluid temperature measurement used for Densitometer Calibration)
- In the piping- vertical Pump Suction Segment (2 thermocouples)
- In the storage tank, and in the storage tank cooling coil Inlet and Outlet, and
- The supply dump Discharge.

A thermocouple consists of two dissimilar metals, usually in the form of wires, joined at one end to form the "measuring junction". When a net temperature gradient exists along the length of the thermocouple, a voltage is produced by the so-called Seebeck effect. The magnitude of that voltage depends primarily on the magnitude of the temperature gradient and the nature of the two metals (the proportionality is defined by the "Seebeck coefficient"). Common thermocouple combinations produce output voltages that are relatively linear over a wide temperature range and with Seebeck coefficients of the order of 10-75 $\mu\text{V/K}$. For type K thermocouples the Seebeck thermopower is about 40 $\mu\text{V/K}$.

It is clear that a thermocouple is a differential device, and the temperature must be accurately known at one end (the reference junction) to accurately determine the temperature at the other end (the measuring junction). In addition the thermocouple output can be sensitive to the uniformity of the two wires (chemical composition, physical and metallurgical condition) and to the position of any such inhomogeneities with respect to the temperature gradient existing for a particular measurement. The ability of an insulating material to electrically isolate the two wires from each other, the ability of a sheath to protect the wires from degrading environmental conditions, and the extent to which a thermocouple disturbs the temperature field in which it is located also play a part in the ability of a thermocouple to make accurate measurements. All these factors, and others that generally produce smaller effects on the accuracy of thermocouple measurements are discussed in the following sections.

2.5.2 Testing

All of the thermocouple used in the SET test section were checked at 300 K and for conformance to the precision Type-K calibration. All these instruments met the precision-grade error limits of ± 1.1 K at this temperature. No additional calibration was performed on these instruments.

2.5.3 Specific Uncertainties

2.5.3.1 Thermocouple Wire Uncertainty. Thermocouple wires and finished thermocouple assemblies may have nonuniformities in chemical composition or physical/metallurgical properties that limit the repeatability of the thermoelectric output at different locations along the length of the thermocouple. Each lot of wire is checked by the manufacturer to find out the uncertainty band met by that lot; this figure is called the "manufacturers' tolerance". An error band of ± 1.1 °C or $\pm 0.375\%$ of the Celsius reading, whichever is greater, is the accepted tolerance for "precision grade" wire as used in the SET tests. In SI units this translates to ± 1.1 K for temperatures up to 566 K.

2.5.3.2 Thermocouple Manufacture and Cold Working. The thermocouple used throughout the tests have stainless steel sheaths, magnesium oxide insulation, and insulated measuring junctions. Cold working, which results from bending, drawing, or swaging during the manufacturing process, alters the thermoelectric properties of the wires; however, that effect can be removed almost entirely by proper annealing of metal-sheathed thermocouple during and after manufacturing. Thus, no additional uncertainty is assigned for the instrument fabrication process.

Cold working can also result from severe handling and manipulation during installation of thermocouple in a test assembly. Such cold-worked areas on thermocouple, however, must be located in a temperature gradient of significant magnitude for errors in the thermoelectric signal. In the SET installation, cold worked sections were not in any temperature gradient.

2.5.3.3 Short-Range Ordering. The Chromel thermoelement used in most Type-K thermocouple is subject to a phenomenon known as short-range ordering. In Short range ordering the crystal lattice tends to take on an ordered arrangement as a function of the time-temperature history of the material, rather than retaining the disordered arrangement typical of binary alloys. This takes place between about 470 K and 870 K, and thermoelectrically the result is a slight change in the Seebeck coefficient of the thermocouple. Studies have shown that the effect may introduce errors as large as $\pm 1.3\%$. However the SET-TMP temperatures were always below 470 K, and this effect will be ignored in this document.

2.5.3.4 Aging and Drift. In addition to the short-range ordering effect noted above, other slow, long-term changes can take place in the composition and metallurgical state of a Type-K thermocouple as a function of time and temperature. These effects also depend on the type and purity of insulating and sheath materials in the thermocouple and on the chemistry and

temperature of the thermocouple's environment. Because none of the SET-TMP thermocouples are above 400 K during the course of the tests, these effects are assumed to be negligible small.⁸⁻¹⁰

The decalibration noted in studies by Anderson et al.¹⁰ due to diffusion of small quantities of sheath and insulation components into the thermocouple wires at temperatures above about 1270 K is considered to be a negligible effect in the instruments of interest here because of the much lower temperature range at which they operated.

2.5.3.5 Shunting Effects. The electrical resistivity of the ceramic insulating materials used in thermocouple inevitably decreases with temperature. If that decrease is sufficiently large, the insulation resistance will be low enough to allow electrical shunting of the thermoelectric signal between the two thermoelements, so that a part of the thermocouple signal will be lost and the temperature indication will be in error. Such effects are usually limited to operation at temperatures above about 1200 K, and thus can be considered not relevant to the SET thermocouple.

2.5.3.6 Magnetic Field Effects. Kollie et al.¹² have reported on the effect of the interaction of magnetic fields with Chromel-Alumel thermocouple. The Ettingshausen-Nernst (EN) effect quantifies the relationship among the magnetic field, the temperature gradient, and the length of a ferromagnetic thermocouple or thermoelement (such as Alumel). The size of the "parasitic" voltage produced by the EN effect in such a thermocouple is proportional to the scalar product of the vector thermocouple length with the vector product of the magnetic field vector and the temperature gradient vector:

$$e = (Q \nabla T \times B) \cdot l_0$$

where

e = the parasitic EN emf,

Q = the EN coefficient for an individual thermoelement,

∇T = the temperature gradient,

B = the magnetic induction produced in the thermoelement by the magnetic field,

l_0 = the length of thermoelement situated in the magnetic field.

As a non-magnetic material, the Chromel thermoelement contributes insignificantly to magnetic field errors. Alumel, however, is magnetic and experiences EN effect-induced errors. The effect is maximum when the three vectors are mutually perpendicular and minimum (i.e., zero) when any two of them are parallel (as for the fluid thermocouple in the coolant channels). The temperature gradient across a typical thermocouple is estimated to be no more than five kelvin. Therefore the resultant error for the longest thermocouple is no greater than 2 K. The relative orientation of a

thermocouple with respect to the magnetic field determines the polarity of the induced EN voltage in that instrument. Above the Curie temperature of the Al₂O₃ thermoelement (about 420 K) the EN effect is greatly reduced.

2.5.3.7 Polynomial Approximation

A third-order polynomial, which approximates the standard Type-K thermocouple calibration over the temperature range of interest, is used to convert the thermoelectric voltage signal to temperature values. That expression is as follows:

$$T(V) = 338.72 + 24.4671 V + 0.02536817 V^2 - 0.00223218 V^3$$

where T = temperature in kelvin

and V = thermocouple output signal in millivolts.

The resultant error in computing the temperature from this polynomial is found by plotting the difference between the standard and calculated temperatures as a function of the standard Type-K calibration temperature. The mean error for this operation is -0.115 K, with a standard deviation of ± 0.517 K. These figures are treated as bias and precision errors, respectively, and the standard deviation must be multiplied by a Student's t-distribution value of two to obtain the 95% statistical confidence level used throughout this report.

2.5.3.8 Reference Temperature

A Validyne Engineering Corp. model TR41 temperature reference junction, which maintains a reference temperature of 338.72 K (150 °F), is a part of each thermocouple measurement channel. This apparatus maintains a constant reference temperature to within ± 0.2 K, which is considered a bias error because of its systematic nature.

2.5.3.9 Data System

The uncertainty contributed by the data system has been discussed in Section 2.1. The thermocouple's channel of the data system have a precision error (95% confidence level) of $\pm 0.11\%$ of range and bias errors of 0.0026% of range. For a full-scale signal range of 8 volts, these values are ± 0.53 K and ± 0.013 K, respectively, where a gain of 400 and an average Seebeck coefficient of 41.4 $\mu\text{V/K}$ were used to make the conversion.

2.5.3.10 Installation Effects

Errors resulting from improper thermocouple choice or installation are assumed to have been corrected during system check-out or initial operation and thus are not discussed in this report.

Perturbations produced on test components by the presence of measurement devices can also be significant if proper installation methods are not used to minimize such effects. The errors resulting from installation generally fall

into the categories of conduction, radiation, velocity, and dynamic errors. The temperature range of the SET tests is low enough to preclude the possibility of radiation errors. All thermocouple installations followed the rule-of-thumb in which the portion of the thermocouple leading in to the measurement location has a length-to-diameter ratio of at least ten; under these conditions, any conduction errors should be negligibly small. Any velocity errors for fluid thermocouple extending into flow regions are similarly negligibly small by virtue of the fact that flow rates were low and fluid temperature slewing rates were also low. Dynamic errors also are judged to be negligible, because the rate of temperature change is extremely slow in comparison to the response times of the thermocouple (less than 200 milliseconds for all thermocouple types in the assembly). That condition allows the actual temperature of the instruments to keep up with the temperature of the region or test component where each instrument is installed, without concern for time lag. No additional uncertainties are assigned to the thermocouple for these types of installation effects.

2.5.4 Total Thermocouple Uncertainty

The total uncertainties for the fluid thermocouple, determined to 95% confidence limits, are summarized in Tables 9.

TABLE 9. SUMMARY OF THERMOCOUPLE UNCERTAINTIES

Parameter	Uncertainty	
	Precision	Bias
Thermocouple wire		
$T \leq 560$ K	± 1.1 K	
Manufacture and cold working		Not considered significant
Short-range ordering		Not considered significant
Shunting effects		Not considered significant
Magnetic field effects		Not considered significant
Polynomial approximation	± 1.034 K	-0.115 K
Reference temperature	± 0.2 K	
Data system	± 0.53 K	$+0.013$ K
Installation effects		Not considered significant
RSS Totals		

$T \leq 560 \text{ K}$:

$\pm 1.61 \text{ K}$

$0.116 \text{ K} \pm 0.1\% (T - 273 \text{ K})$

Uncertainty, 95% , U_T

$T \leq 560 \text{ K}$:

$\pm [(1.61 \text{ K})^2 + [0.1\% (T - 273 \text{ K})]^2]^{1/2}$

2.5.5 Measurement Description RTD

The temperature measuring section of the Solomat RH probe has a Pt100 Resistive Temperature Device (RTD) mounted in bifilar mechanical configuration (which minimizes mounting strains). Four lead-wires are used: two to supply an excitation voltage; and two to measure the voltage generated by the resistance change in the Platinum. The four-wire configuration nearly eliminates the effects of lead wire resistance.

The Vendor uses the notation Pt 100 Grade 1 (alpha = .00385) 4 wire configuration. The 100 notation indicates that the resistance of the element is 100 ohms at 0 °C. An alpha of .00385 means that the resistance of the RTD is 138.5 ohm at 100. The RTD is calibrated using the standardized three constant Callendar equation.

2.5.5.1 Signal Conditioning

The electronic's in the Vendor transmitter supplies the signal conditioning.

2.5.5.2 Excitation Voltage

An excitation voltage is required, because the RTD is a passive device. The excitation is supplied by the sensor transmitter. The accuracy of the excitation voltage is $\pm 0.01\%$ of range.

2.5.6 Specific Uncertainties

2.5.6.1 Vendor Uncertainties

The Vendor quotes an uncertainty $\pm 0.2\%$ for the electronics and sensor and , $\pm 0.01\%$ for excitation voltage accuracy and $\pm 0.011\%$ per °F for the electronic temperature coefficient.

2.5.6.2 Calibration

The Standards and Calibration Lab calibrated the RTDs. Both RTDs were within $\pm 0.3 \text{ }^\circ\text{C}$.

2.5.6.3 Installation effects

Installation effects are considered negligible.

TABLE 10. SUMMARY OF RTD UNCERTAINTIES

Parameter	Uncertainty	
	Precision	Bias
Electronics and Sensor	$\pm 0.2\%$	
Calibration		$\pm 0.3 \text{ K}$
Deviation from Callendar's Eqn		$\pm 0.2\%$ of R_d
Electronic Temp Coeff	$\pm 0.11\%$	
Data system	$\pm 0.055\%$	$\pm 0.0026\%$
Installation effects	Not considered significant	
RSS Totals	$\pm 0.23\% R_g$	$\pm (0.2\% \text{ of } R_g + 0.3 \text{ K})$
Uncertainty _{95%} , U_{RTD}	$\pm 0.38 \text{ K}$	

2.6 Pump Power

2.6.1 Description

A Himmelstein (Model MCRT 9-02T) combination torquemeter/shaft speed meter measured the mechanical power supplied to the pump from the motor. The torque (shaft angular velocity) was rated at 0.2-226 Newton-Meters (0-7200 RPM).

The mechanical power delivered from the driver (pump motor) to the load (pump) is the product of the torque and RPM. The torquemeter portion of the assembly consists of a stainless steel shaft, which is mechanically coupled to the pump shaft/motor shaft. The torque can be measured by detecting the angular strain on the stainless steel shaft through bonded foil strain gauges. The strain gauges are configured into a wheatstone bridge array with AC excitation (3 kHz). The wheatstone bridge is mechanically attached to the rotating shaft. Rotary transformers couple the signal/excitation from the moving bridge to the stationary signal conditioning/readout by means of a stationary transformer. The difference in the AC signal after removing a phase shift is proportional to the rotation strain of the calibrated shaft.

Proper mechanical installation is vital to realizing the quoted accuracy of the transducer. Proper Bridge "Set-Up" (Zero, Phase, Internal Calibration, and external Cable Capacitance) is also essential to the correct operation of the instrument.

A stationary proximity sensor detects the movement of a toothed cylinder attached to the rotating shaft of the pump. Each positive pulse registered by this sensor is directly proportional to a fractional angular displacement of the shaft.

2.6.2 Specific Uncertainties

2.6.2.1 Vendor General Specifications

The Vendor rates the torquemeter (not the speed indicator) under dynamic conditions as:

Nonlinearity ($\pm 0.1\%FS$) = ($\pm .25$ N-m)
Hysteresis ($\pm 0.1\%FS$) = ($\pm .25$ N-m)
NonRepeatability ($\pm 0.05\%FS$) = ($\pm .125$ N-m)
Zero Balance (predominately phase effects) ($\pm 1.0\% FS$) (± 2.5 N-m)

Temperature Effects

Zero Balance ($\%FS/^{\circ}F = \pm .002$) = ($\pm .09$ N-m Rg)
Span ($\%Rdg/^{\circ}F = \pm .002$) = ($\pm .0004 * Rdg$)

2.6.2.2 Calibration

The EG&G Standards Lab calibrated both the torquemeter and rotational speed indicator. The laboratory only calibrated the torquemeter statically (not under dynamic conditions), but it did calibrate the speed indicator dynamically.

Total Reported basic accuracy of the torquemeter was $\pm 0.15\% F.S.--$ ($\pm .33$ N-m)

Total Accuracy of the Torquemeter system including the display unit is ($\pm 0.5\%F.S.--$) (± 1.2 N-m)

Total Rotation Speed accuracy ($\pm 1\%$ of Rdg) = ($.01 * RPM$)

2.6.3 Installation Uncertainties

Any bending moment (other than the axial twisting moment) can bias the data. Off-center installation can compromise the measured torque data. Improper installation has a negligible effect on the speed indicator.

TABLE 11. TORQUEMETER/SPEED INDICATOR UNCERTAINTIES

Torquemeter		Uncertainty	
Parameter	Precision	Bias	
Nonlinearity		±0.25 N-m	
Hysteresis		±0.25 N-m	
Non-Repeatability	±0.125 N-m		
Zero Balancing (Phase Adjustment)		±2.5 N-m	
Temperature Sensitivity	±0.127 N-m		
Data system	±0.123 N-m	±.006N-m	
Calibration		±0.338 N-m	
Installation effects	Not estimated		
<hr/>			
RSS Totals	±(0.217 N-m + .0004 Rdg)	±2.54 N-m	
Uncertainty _{95%} , U _{TM}	±[(2.54) ² + (.434) ² + (.0008 * Rdg) ²] ^{1/2} N-m		
<hr/>			
Speed Indicator			
<hr/>			
Calibration	±.01 * Rdg		
<hr/>			
RSS Totals	±.01 * Rdg		
<hr/>			
Uncertainty _{95%} , U _{RPM} = ±0.01 Rdg (rpm)			

2.7 Absolute Pressure

2.7.1 Measurement Description

Absolute and Barometric pressure transducers, with their accompanying excitation voltage and signal conditioning circuits, measured the required pressures in the SET-TMP test series. The pressure measurements monitored test conditions throughout the system.

2.7.1.1 Transducer

Sensotec, models TJE (absolute) and EB (barometric), bonded-foil strain gage transducers were used for the SET-TMP test pressure measurements. These transducers use a diaphragm with strain gages attached to convert the diaphragm deflections into electrical signals. The electrical signals are conditioned, amplified, sampled, recorded, and then converted into pressure readouts.

The strain gages are attached to a pressure-sensitive element (diaphragm) that deforms elastically when pressure is applied. The resistance of the conductor of the strain gage depends upon its geometry (length and cross-sectional area) and resistivity. Small changes in the strain gage geometry produce resistance changes. The deformation of the pressure-sensing element produces elongation (shortening) of the strain gage and produces an increase (decrease) in the strain gage resistance. The strain gage elements are electrically configured in a wheatstone bridge circuit. In addition the circuit contains a temperature compensating and balancing resistors. The strain gage resistance, which is proportional to the pressure applied to the transducer, is determined by measuring the voltage produced by an unbalanced wheatstone bridge.

Absolute pressures were measured by transducers with the following ranges:

- seven gages with a range of 0-172 kPa (0-25 psia)
- one gage with a range of 0-512 kPa (0-75 psia)
- five gages with range of 0-690 kPa (0-100 psia)

A Sensotec model EB electronic barometer measured the barometric pressure. This measurement was used to monitor atmospheric conditions [range: 54-108 kPa (7.9-15.7 psia)] throughout the test.

2.7.1.2 Excitation Voltage

A constant external voltage supply (excitation is ± 15 V) powers the strain gages.

2.7.1.3 Signal Conditioning

The pressure signal is amplified by either an amplifier or an "in-line" amplifier. Both types condition and amplify the millivolt strain gage output to the standard output range of 0-5 VDC.

2.7.2 Calibration

The transducers used in the pressure measurements were tested by the manufacturer before shipment and then calibrated at the INEL Standards and Calibration Laboratory for the SET-TAP test series. The calibration data determined the calibration coefficients and ensured that the transducers met the manufacturer's specifications.

Prior to shipment to the INEL, the vendor checked the PSD at five points. This check consisted of a step change from zero to 100% capacity and back to zero in 50% steps. The INEL calibration consisted of one cycle from zero to full scale and back to zero in 10% steps. A curve fit equation was determined from these points and used as a part of the engineering unit conversion process.

Each pressure transducer has a unique engineering unit conversion equation based on the calibration data. The equation takes the form of:

$$P = a_0 + a_1V + a_2V^2 + a_3V^3 + a_4V^4$$

where P = the indicated pressure,

a = the calibration coefficients,

V = the voltage output of the measurement channel.

The coefficients a_2 through a_4 are normally zero, depending on the order of the curve fit chosen. The order of the curve fit is based on the calibration data.

2.7.3 Specific Uncertainties

Testing activities, along with manufacturers' specifications, current literature, and engineering judgment, were used to estimate the uncertainty bands for specific features of the pressure measurement channels. Uncertainties for specific measurement channel components are quantified in this section. The RSS summation of the cumulative uncertainties for each type of transducer and its associated measurement equipment is tabulated in Table 12.

2.7.3.1 Calibration Coefficients

Uncertainty factors associated with the calibration are considered as part of the total uncertainty. These factors include linearity, repeatability, and hysteresis. The uncertainty for these factors was decided from the laboratory calibration and manufacture's specification. The following are the results of the calibration:

Repeatability:	$\pm 0.14\%$ of range
Linearity:	$\pm 0.1\%$ of range
Hysteresis:	$\pm 0.1\%$ of range.

The estimated uncertainty for the bonded-foil strain-gage transducers, after the random errors were multiplied by the appropriate two-tailed Student's *t* value of two and the RSS of the values were performed, is approximately $\pm 0.2\%$ of range.

In finding the uncertainty of a calibration, it is necessary to include the uncertainties accumulated on up the hierarchy to the National Institute of Standards and Technology (NIST). Values given for the calibration facilities at the INEL for pressure are a bias uncertainty of $\pm 0.015\%$ of reading (assumed to be a 95% confidence level) and for the random component, a two-sigma uncertainty of $\pm 0.02\%$ of reading.

2.7.3.2 Thermal Sensitivity

The thermal sensitivity for the pressure transducers was obtained from the manufacturer's specifications. These uncertainties are as follows:

Thermal zero shift:	$\pm 0.0025\%$ of range/ $^{\circ}\text{F}$,
Thermal sensitivity shift:	$\pm 0.0025\%$ of range/ $^{\circ}\text{F}$.

The change in temperature throughout the test is estimated to be 5.6 K (10°F), and the corresponding uncertainty for thermal sensitivity is estimated at $\pm 0.035\%$ of range.

2.7.3.3 Vibration/Shock/Reference Pressure

In view of the benign SET-TMP test conditions, the uncertainty in the pressure measurements resulting from vibration and shock is considered to be negligible. The pressure measurements were made with absolute pressure transducers. No reference or atmospheric pressure measurements were used for corrections.

2.7.3.4 Transducer Zeroing

At the start of each test all pressure transducers were zeroed to a common known value based on the system conditions at that time.

2.7.3.5 Excitation Voltage

The excitation voltage accuracy, as specified by the manufacturer, is $\pm 0.01\%$ of range.

2.7.4 Total Uncertainty

The total uncertainties for absolute pressure measurements in three separate pressure ranges, expressed to a 95% confidence level, are summarized in Table 12.

TABLE 12. SUMMARY OF ABSOLUTE PRESSURE UNCERTAINTIES

Parameter	Pressure Transducer Range					
	0-172 kPa		0-512 kPa		0-690 kPa	
	Random	Bias	Random	Bias	Random	Bias
Calibration *	±0.344		±1.03		±1.38	
Traceability *	±0.034	0.026	±1.103	0.078	±0.136	0.104
Temperature *		0.060		0.18		0.24
Zero offset *		0.009		0.027		0.036
Excitation voltage *		Negligible		0.035		0.070
Data system *	±0.19	0.005	±0.57	0.01	±0.76	0.01
RSS Totals *: ± 0.394		0.066	±1.18	0.199	±1.58	0.271
Uncertainty _{95%} , U _p :	±0.40 kPa		±1.20 kPa		±1.60 kPa	

Parameter	Pressure Transducer Range	
	54-108kPa**	
	Random	Bias
Calibration	±0.11	
Traceability	±0.011	0.008
Temperature		0.015
Zero offset		0.003
Excitation Voltage		0.005
Data System	±0.059	0.002

RSS Totals:	± 0.125	0.018
Uncertainty _{95%}	± 0.126 kPa	

* All values are expressed in kilopascals (kPa).

** This is the pressure range covered by the electronic barometer in monitoring atmospheric pressure.

2.8 Differential Pressure

2.8.1 Measurement Description

Differential pressure measurements are defined as the actual pressure of the fluid whether at rest or in motion as sensed by a single transducer. Pressure is transmitted from each measurement location to a port of the differential pressure transducer through water-filled impulse lines. Each transducer utilizes a diaphragm with strain gages bonded to opposite sides. The two strain gages comprise two of the four arms of a wheatstone bridge. The strain gages convert the diaphragm deflections into an unbalanced bridge condition that generates a differential voltage. The voltage is conditioned, amplified, sampled and then recorded (digitally) and finally converted by computer into a differential pressure readout.

Small changes in strain gage geometry produce resistance changes in the wires of the gage. The strain gages are attached to a pressure-sensing element (diaphragm). The sensing element is deformed elastically when increased fluid pressure is applied to either side of the element. The total deformation is the difference in the pressure on the two ports. This deformation of the pressure-sensing element produces elongation (shortening) of the strain gage and causes an increase (decrease) in the strain gage resistance. Strain gage resistance, which is proportional to the differential pressure applied to the transducer, is determined by measuring the voltage drop in the circuit containing the strain gage (through a wheatstone bridge). Another component of the wheatstone bridge is temperature compensating resistor.

2.8.1.1 Transducer

Two different models of differential pressure transducers manufactured by two companies were used for the SET-TMP tests. They include the following:

- Six Sensotec Model Z, range 0-6.9 kPa (0-1 Psid)
- Three Sensotec Model Z, range 0-13.8 kPa (0-2 Psid)
- One Sensotec Model Z, range 0-517 kPa (0-75 Psid)
- Two BLH Range 0-20 in.: 0-4.97 kPa (0-.7213 Psid)
- Four BLH, Range 0-50 in.: 0-12.43 kPa (0-1.803 Psid)

- Two BLH, Range 0-100 in.: 0-.24.9 kPa (0-3.607 Psi)
- Two BLH, Range 0-300 in.: 0-74.6 kPa (0-10.82 Psi)
- One BLH, Range 0-690 kPa (0-100 Psid)

2.8.1.2 Excitation Voltage

The Sensotec differential pressure transducers are internally amplified and powered by a separate ± 15 V power supply. The BLH transducers are powered by a constant voltage (excitation), which is supplied by a control module (SCV-484) within the Megadac 5033A.

2.8.1.3 Signal Conditioning

Signal conditioning is provided by the 885D input module of the Megadac 5033A. The input module takes the signal from the differential pressure transducer and amplifies the millivolt signal to a standard range of 0 to 10 VDC. The amplified analog signal is then converted to a 16 bit digital word through the Megadac's Analog to Digital (A/D) converter.

2.8.2 Calibration

The transducers used in the differential pressure measurements were tested by the vendor before shipment to the INEL. This testing was to find out calibration coefficients and to ensure that the transducers met the manufacturer's specifications. The specific uncertainties reported in this document were determined from (1), historical data obtained during the Semiscale test series (performed from 1975 - 1984)¹⁴, from (2), calibration performed at the INEL Standards and Calibration Laboratory, and from (3), manufacturer's specifications supplied in the Design and Specifications Document.

Each transducer is calibrated in a laboratory environment by performing one cycle from zero to full scale and back to zero in 10% steps for each side of the pressure cell. A curve fit is then obtained from these points and used in the engineering unit conversion. Each differential pressure transducer has a unique engineering unit conversion equation based on calibration data. The following equation represents the engineering unit conversion:

$$dP = a_0 + a_1V + a_2V^2 + a_3V^3 + a_4V^4$$

where dP = the indicated differential pressure,

a = the calibration coefficients,

and V = the voltage output of the measurement channel.

The coefficients a_2 to a_4 normally are zero, depending on the order of the curve fit chosen, and the statistical significance of including higher order terms in the fitting equation. The order of the curve fit is based on the calibration data, and statistical "goodness of fit tests".

2.8.3 Specific Uncertainties

Testing activities performed during the Semiscale experiments, the calibration data, and engineering judgement were used to estimate the uncertainty bands of the differential pressure measurements. The RSS summation of the cumulative uncertainties are tabulated in Tables 13 & 14. The number of degrees of freedom for each of the specific random uncertainties is taken to be greater than 30, giving a Student's t-distribution value very close to 2 unless otherwise specified.

2.8.3.1 Calibration Coefficients

Uncertainty factors associated with the calibration include repeatability, linearity and hysteresis. Linearity and hysteresis were determined from the calibration data. The following are the results of the calibration coefficient uncertainties:

	<u>BLH Transducers</u>	<u>Sensotec</u>
Repeatability:	±0.5% of range	±0.05% of range
Linearity:	±0.5% of range	±0.15% of range
Hysteresis:	±0.25% of range	±0.10% of range

The estimated uncertainty, taken from the calibration results and after the random errors were multiplied by the appropriate two-tailed student's t value (2) is ±0.75% (±.19%) of range for the BLH (Sensotec) transducers.

2.8.3.2 Calibration Traceability

The uncertainties associated with the laboratory calibration accumulated to NIST are a bias uncertainty of +0.015 % of reading and ±0.01% of reading for the random component. These are assumed to be 95% confidence levels.

2.8.3.3 Thermal Sensitivity

Testing performed in the Semiscale program on several differential pressure transducers including the BLH (not the Sensotec) type showed temperature related uncertainties of up to ±0.05% of range per K. The change in temperature during testing is estimated to be 5.6 K (10 °F). This temperature variation propagates into an estimated uncertainty of ±0.275% of range for the BLH type of Pressure transducer.

Manufacturer's specification for the Sensotec Model Z reported and environmental temperature sensitivity for the "0" of the sensor as .005% /°F of range, and .005% / °F of Reading. This temperature sensitivity propagates into an uncertainty of .072% (1 sigma) of range.

Because testing is performed at near-atmospheric conditions, the high-pressure line effect is considered negligible for the SET-TMP type of

tests. The effect of the length of the hydraulic lines does not seriously degrade the time response of the differential pressure transducer.

2.8.3.5 Transducer Zeroing

At the start of each test all pressure transducers are zeroed by isolating the cell from its sense lines and balancing the bridge.

2.8.3.6 Data System

The uncertainty analysis of the data system is included in Section 2.1 of this uncertainty report.

2.8.4 Total Uncertainty

The combined uncertainties for the differential pressure measurements at the 95% confidence level, calculated by the root-sum-square method, are summarized in Tables 13 and 14.

Table 13. SUMMARY OF BLH DIFFERENTIAL PRESSURE TRANSDUCER UNCERTAINTIES

	Uncertainty	
Parameter	Precision	Bias
Calibration coefficient	±0.75% of range	
Laboratory calibration traceability	±0.01% of range	±0.015% of range
Thermal sensitivity		±0.28% of range
Line pressure		
Negligible		
Signal conditioning		±0.01% of range
Data system	±0.11% of range	±0.0026% of range
RSS Total:	±0.758% of range	±(0.281% of range)
Uncertainty _{95%} , U _{dp} :	±(0.808% of range)	
•	BLH Range 0-20 in.: 0-4.97 kPa (0-0.7213 Psi/) 2 sigma = ±0.04 kPa (±.16 in/±.006 Psi/)	
•	BLH, Range 0-50 in: 0-12.43 kPa (0-1.803 Psi) 2 sigma = ±0.1kPa (±0.41 in/±.015 Psi)	
•	BLH, Range 0-100 in: 0-24.8 kPa (0-3.607 Psi) 2 sigma = ±.207 kPa (±.81 in/.03 Psi)	
•	BLH, Range 0-300 in: 0-74.6 kPa (0-10.82 Psi) 2 sigma = ±.607 kPa (±2.4 in/±.088 Psi)	
•	BLH, Range 0-690 kPa (0-100 Psid) 2 sigma = ±5.58 kPa (±.81 Psid)	

TABLE 14. SUMMARY OF SENSOTEC DIFFERENTIAL PRESSURE TRANSDUCER UNCERTAINTIES

Parameter	Uncertainty	
	Precision	Bias
Calibration coefficient	±0.19% of range	
Thermal sensitivity		±0.14% of range
Line pressure Negligible		
Signal conditioning		±0.01% of range
Transducer zeroing		±0.005% of range
Data system	±0.11% of range	±0.0026% of range
RSS Total:	±0.22% of range	±(0.14% of range)
Uncertainty _{95%} , U _{dp} :	±(0.26% of range)	
<ul style="list-style-type: none"> • Sensotec Model Z, range 0-6.90 kPa (0-1 Psid) 2 sigma = ±0.018 kPa (±0.0026 Psid) • Sensotec Model Z, range 0-13.79 kPa (0-2 Psid) 2 sigma = ±0.036 kPa (±0.005 Psid) • Sensotec Model Z, range 0-517 kPa (0-75 Psid) 2 sigma = ±1.34 kPa (±0.19 Psid) 		

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