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**SAVANNAH RIVER SITE ECS-2 TESTS
UNCERTAINTY REPORT**

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ABSTRACT

This document presents a measurement uncertainty analysis for the instruments used in the ECS-2 test series conducted for the Savannah River Site at the Idaho National Engineering Laboratory. The tests are a series of downflow dryout heat transfer experiments designed to support computer code development and verification in setting limits for the Savannah River Production reactors. The measurements include input current, voltage, and power; air and water flows, fluid and metal temperatures, and absolute and differential pressures. An analysis of the data acquisition system as it relates to these measurements is also included.

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SUMMARY

This document describes the potential error sources and the quantitative contribution of each to the overall uncertainty in various key measurements made during the Savannah River Laboratory dryout heat transfer tests designated as the ECS-2 test series, conducted at the Idaho National Engineering Laboratory. Those measurements include voltage and current to the test section (used to determine the input power to the test), the air and water mass flows, fluid and metal temperatures within the test section, the mass-energy balance, and absolute and differential pressures at selected points in the test section, as well as the contribution of the data acquisition system to each of those measurements.

The possible error sources for these measurements were combined by the root-sum-square (RSS) method of summing bias and precision errors, and are given at the 95% (2σ) confidence level. The single exception to this is the metal thermocouple uncertainties, where bias errors were summed algebraically in order to preserve the sign of the dominant bias term. A summary of the specific measurement uncertainties (U) is outlined below.

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

Power: $U_{POW} = \pm [(I U_E)^2 + (E U_I)^2]^{1/2}$

where $U_E = \pm [(0.11 \text{ volt})^2 + (0.2\% E)^2]^{1/2}$

and $U_I = \pm [(5.16 \text{ amps})^2 + (1.02\% I)^2]^{1/2}$

Flow:

Inlet air: $U_q = \pm [(0.586 \text{ SLPM})^2 + (0.95\% q)^2]^{1/2}$

Outlet air: $U_q = \pm [(0.677 \text{ SLPM})^2 + (1.50\% q)^2]^{1/2}$

Water: $U_q = \pm [(0.0045 \text{ l/s})^2 + (0.37\% q)^2]^{1/2}$

where $q = \text{volumetric flow reading (SLPM for air, l/s for water)}$

Temperature:

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

Metal:

Upper TCs $U_T = \pm \{(3.33 \text{ K})^2 + [6\% (T-273) \text{ K}]^2\}^{1/2}$
 $- [2.102 \text{ K} + 10.1\% (T-273 \text{ K})]$

Lower TCs $U_T = \pm \{(3.33 \text{ K})^2 + [6\% (T-273 \text{ K})]^2\}^{1/2}$
 $- [-1.898 \text{ K} + 10.1\% (T-273 \text{ K})]$

SUMMARY (cont.)

Mass-energy balance:

$$U_Q = \pm[(c_p \Delta T U_{\dot{m}})^2 + (\dot{m} c_p U_{\Delta T})^2]^{1/2}$$

where

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

and

$$U_{\Delta T} = \pm[(U_{T_{in}})^2 + (U_{T_{out}})^2]^{1/2}$$

Absolute Pressure:

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

$$(0-345 \text{ kPa}): U_p = \pm 0.80 \text{ kPa}$$

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

Differential Pressure:

$$(\text{BLH}): U_{dp} = \pm[(0.808\% \text{ RG})^2 + (0.28 \text{ kPa})^2]^{1/2}$$

$$(\text{CEC/Genisco}): U_{dp} = \pm[(0.917\% \text{ RG})^2 + (0.28 \text{ kPa})^2]^{1/2}$$

where

RG = differential pressure reading

SUMMARY (cont.)

The low- to high-range uncertainties for the measured parameters can be summarized as follows:

Parameter	Low Range	High Range
Power	± 0.15 kW	± 1.7 kW
Instantaneous inlet air flow	± 1.05 SLPM	± 2.32 SLPM
Average inlet air flow	± 0.71 gm/min)	± 0.99 gm/min)
Instantaneous outlet air flow	± 1.38 SLPM	± 3.42 SLPM
Average outlet air flow	± 1.15 SLPM	± 2.61 SLPM
Water flow	± 0.0045 l/s	± 0.011 l/s
Fluid temperature	± 3.37 K	± 4.85 K
Metal temperature	± 3.33 K	-12/-43 K
Mass-energy balance	± 8.18 kW ($\pm 10.2\%$)	± 23.6 kW ($\pm 30.3\%$)
Absolute pressure		
0 - 172 kPa range		Uniformly ± 0.40 kPa
0 - 345 kPa range		Uniformly ± 0.80 kPa
54 - 108 kPa range		Uniformly ± 0.126 kPa
Differential pressure		
BLH transducers	± 0.28 kPa	± 0.345 kPa
CEC transducers	± 0.28 kPa	± 0.447 kPa

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SAVANNAH RIVER SITE ECS-2 TEST SERIES UNCERTAINTY REPORT

1. INTRODUCTION

A series of downflow dryout heat transfer experiments called the ECS-2 Experiments, conducted by EG&G Idaho, Inc., at the Idaho National Engineering Laboratory (INEL), supports computer code development and verification for criteria used to set limits for the Savannah River Laboratory (SRL) production reactors. The objectives of these tests include obtaining thermal excursion data over a broad range of operating conditions that are comparable to those likely to occur during a postulated loss-of-coolant-accident in the SRL reactor. Conditions that must be comparable for such studies include inlet water flow rate and temperature, entrained air flow rate, system back pressure, surface heat flux profile, and axial and azimuthal heat flux profile. Visual measurement and recording of phenomena related to the above conditions and correlation with transducer measurements will assist in defining the phenomena that control the onset of temperature excursions for various operating conditions. Figure 1 shows a diagram of the ECS-2 test system.

The tests were conducted in the Semiscale Test Facility at the INEL. This facility constituted part of the overall Nuclear Regulatory Commission (NRC) water reactor research program to investigate the response of a pressurized water reactor system to hypothetical loss-of-coolant accidents. The electrically-heated, scaled-down "core" and auxiliary systems helped to quantify the physical processes that control system behavior during operational reactor transients, and as such the facility was ideal for smaller tests of a similar nature, such as the ECS-2 test series for the Savannah River Laboratory.

This document details the estimated uncertainties for the measurements made in the ECS-2 test series. Those measurements include current and voltage in the heater section (for total power determination), mass flow, fluid and metal temperatures, and absolute and differential pressures at various positions in the test. An estimate of the uncertainty contributed by the data acquisition system (DAS) is also included, and the mass energy balance uncertainty is estimated from the transducer uncertainties. The estimated confidence level is 95%, using the root-sum-square (RSS) method of combining bias (systematic) and precision (random) errors.¹

2. DETAILED UNCERTAINTY ANALYSIS

2.1 Data Acquisition System²

A Megadac 2200C interfaced to an IBM System/2 PC made up the data acquisition system (DAS) used for the ECS-2 tests (see Figure 2). The Megadac 2200C is a high-speed data acquisition, signal conditioning, and data recording system capable of a continuous sampling rate of up to 20,000 samples per second. Expandable modules allow the Megadac to provide amplification, multiplexing, and analog-to-digital conversion for up to 128 channels of differential input. Figure 3 represents the Megadac 2200C options and accessories for the ECS-2 tests. The IBM PC is used to perform engineering unit conversion and obtain calculated parameters from various measurements.

Figure 1. ECS-2 test system diagram.

2.1.1 Measurement Description

2.1.1.1 Amplifiers. Two different types of amplifier modules are used to support the 128 input channels of the DAS. Six Megadac model AD1614D modules with 16 channels each allow up to ± 10 volts input with a selectable gains of 1:1, 2:1, 5:1, 10:1, 20:1, and 50:1. These modules provide input for channel numbers 0 to 95 which support the thermocouple, flow, voltage, and current measurements. The other type of module consists of four model 885D modules with eight input channels each. Each 885D module has a common mode of ± 10 volts and allows a selectable gain of up to 500:1. The 885D modules support the pressure and differential pressure (DP) measurements connected to channels 96 through 127.

2.1.1.2 Multiplexer. The Megadac has two possible options for the multiplexer. The AD1614D module serves as both an amplifier and multiplexer combined. The measurement signal is sent to the AD1614D module, then amplified and multiplexed for input into the A/D converter. The other option takes the signal from the 885D module and the ADC2016 module performs the multiplexing and the A/D conversion. The uncertainty of the multiplexer is accounted for in the specifications for each type of control module.

Figure 2. Megadac 2000C data system configuration.

Figure 3. Megadac 2000C data system options and accessories.

2.1.1.3 Analog-to-Digital Converter. An analog-to-digital converter module (ADC2016) 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 (calibrated to $\pm 32,000$ counts) with a full-scale voltage range of ± 10 volts. The digital reading is transferred by an IEEE 488 interface to an IBM System/2 PC for engineering unit conversion and primary storage by a Bernoulli disk system and backed up on a 60 megabyte tape cartridge in the Megadac.

2.1.1.4 Excitation Voltage. Excitation voltage for the absolute pressure and differential pressure measurements is provided by a power supply within the Megadac 2200C. 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 lead, a return, and two sense leads.

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 transform equation is applied to each type of measurement to convert counts into engineering units.

2.1.1.6 Filtering. Data were recorded at a rate of two sample sets per second. Low-pass filters in the system were set at 2 Hz for the thermocouples and at 5 Hz for other instruments, the lowest attainable under the individual circumstances. Although this is less than ideal, the effects of frequency folding are believed to be negligible, because the steady-state components of primary interest are dominant.

2.1.2 Calibration

A checkout on each of the input modules and the A/D converter was performed by the vendor prior to shipment. Each channel underwent a two-point calibration check before the ECS-2 tests were conducted. A reference voltage of zero and a full-scale voltage for the transducer were applied to each channel, with the Megadac software automatically making a scale adjustment for offset. The uncertainty in this process is some 25 parts in 32,000, and is included in the overall 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 converter. Excitation voltage and engineering unit conversion uncertainties are reported with the overall transducer uncertainties; see the specific section for each instrument type.

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 microvolts rms
Temperature coefficient	$+0.25$ microvolts per $^{\circ}\text{C}$ $= 0.25$ microvolts per K

The published manufacturer's specifications for the 1614D differential input module include:

Accuracy	$\pm 0.05\%$ of full scale
Linearity	$\pm 0.02\%$ of full scale
Noise	± 7 microvolts rms
Temperature coefficient	$+0.005\%$ per $^{\circ}\text{F}$ $= 0.0028\%$ 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. Table 1 summarizes the various DAS uncertainties.

TABLE 1. SUMMARY OF DATA ACQUISITION SYSTEM UNCERTAINTIES *

Parameter	Uncertainty *	
	Precision, S	Bias, B
Input Modules		
885D	$\pm 0.054\%$ of range	± 0.55 ppm
AD1614D	$\pm 0.054\%$ of range	± 250 ppm
Analog-to-digital converter		
ADC 2016 module	$\pm 0.01\%$ of range	± 255 ppm
RSS Totals:	$\pm 0.055\%$ of range	$\pm 0.0026\%$ 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 Voltage/Current/Power

2.2.1 Measurement Description

Power was supplied to the ECS-2 test section from the low power bus of the Transrex power supply used with the Semiscale Test Facility at the INEL. Test power is determined from the product of the voltage and the current applied to the Inconel heater of the test section. The applied voltage was visually monitored in the control room with a digital multimeter, the data acquisition system simultaneously recording a parallel signal. The current was determined from the voltage drop across a calibrated shunt in the circuit with the power supply and the test section. That signal also was monitored in the control room and recorded in parallel by the data acquisition system.

2.2.2 Calibration

Calibration of the General Electric 10,000 amp shunt used to determine the current in the test section heater dates from 1982. The time delay (six months) required for a new calibration, plus the difficulty in removing and reinstalling the shunt, was deemed to be unacceptable. The amplifier interface control and signal conditioning circuits used for the voltages across both the power supply and the shunt were calibrated and thus assumed to be within manufacturer's tolerance.

2.2.3 Specific Uncertainties

2.2.3.1 Signal Conditioning. Based on published manufacturer's specifications, the signal conditioning and amplifier circuit used with both the voltage and current measurements is estimated to contribute an uncertainty of $\pm 0.2\%$ of reading to the system.

2.2.3.2 Data Acquisition System. The data acquisition system, as discussed in Section 2.1, contributes precision and bias errors of $\pm 0.11\%$ of range and $\pm 0.0026\%$ of range, respectively.

2.2.3.3 Shunt Resistor Calibration. The most recent shunt calibration has a bias uncertainty of ± 0.02 amperes and a standard deviation (at the two sigma level) of ± 1.35 amperes. Because the calibration had not been repeated in several years, those uncertainties have been doubled as a precaution to account for possible calibration drift during the intervening period. Repeatability of the calibration was within $\pm 1\%$ of reading.

2.2.4 Total Uncertainty

Table 2 summarizes the combined uncertainties for the voltage and current measurements at the 95% confidence level, calculated by the root-sum-square method. The power uncertainty follows as the combined voltage and current uncertainties for a given set of readings, according to the "law of propagation of errors" as derived from the Taylor's series expansion method for functions calculated from measured parameters:³

$$U_{\text{POW}} = \pm [(E U_I)^2 + (I U_E)^2]^{1/2}.$$

TABLE 2. SUMMARY OF VOLTAGE, CURRENT, AND POWER UNCERTAINTIES

Parameter	Uncertainty	
	Precision	Bias
Voltage E		
Signal conditioning	±0.2% of E	
Data system	±0.11 volt	+0.0026 volt
RSS Totals:	±0.2% E ±0.11 volt	±0.0026 volt
Uncertainty _{95%} , U _E :	±[(0.11 volt) ² + (0.2% E) ²] ^{1/2}	
Current I		
Calibration	±2.70 amps	+0.04 amp
Repeatability	±1.0% of I	
Signal conditioning	±0.2% of I	
Data system	±4.40 amps	+0.104 amp
RSS Total:	±5.16 amps ±1.02% I	±0.111 amp
Uncertainty _{95%} , U _I :	±[(5.16 amps) ² + (1.02% I) ²] ^{1/2}	
Power		
Uncertainty _{95%} , U _{POW} :	±[(I U _E) ² + (E U _I) ²] ^{1/2}	

2.3 Flow

2.3.1 Measurement Description

2.3.1.1 Air Flow. Air flow at the test section inlet and outlet was measured with mass flowmeters of the heated-tube style.⁴ The so-called linear, or true, mass flowmeter uses a capillary tube heated uniformly by a transformer. At zero flow the temperature distribution is symmetrical about the mid-point of the tube, and two external thermocouples located at symmetrical positions develop equal but opposite outputs. 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, the differential thermocouple output is a function of 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 units. (It is traditional, however, to use a volumetric flow display/output with these transducers.) 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 wide variety of gases. High flow rates can be measured with such meters by dividing the flow with a fixed ratio shunting arrangement. Only a small portion of the total gas then needs to be heated, resulting in low power requirements while retaining the meter's mass-measuring characteristics.

2.3.1.2 Water Flow.⁵ Water flow at the test section inlets (two ranges) and at the lower plenum cooling coil was 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 rotational speed of the turbine is proportional to the velocity of the water. Because the flow area of the meter is fixed, the turbine's rotational 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 second. Rotor rotation is usually sensed through the flowmeter body by an external 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 "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 ECS-2 tests. The pulses are transmitted to read-out electronics, where they are amplified, counted, and sent on to the data acquisition system.

Proper operation 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 ECS-2 tests, allowing installation effects on the measurements to be neglected.

2.3.2 Testing

The two mass flowmeters (Teledyne/Hastings model LU-3M) are rated by the manufacturer to be accurate to $\pm 2\%$ of range, with an added uncertainty of $\pm 1\%$ of range associated with the transducer's linearity and repeatability. Manufacturer's specifications for the three turbine flowmeters (Flowtech models FT-12M and FT-8M) are $\pm 0.05\%$ of range for accuracy, $\pm 0.05\%$ of range for repeatability, and $\pm 0.5\%$ 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 were found to be within the manufacturer's limits of accuracy.

2.3.3 Specific Uncertainties - Mass Flowmeters (Air)

2.3.3.1 Calibration. Calibration data for the air inlet mass flow transducer (set for full-scale flow of about 54 SLPM) was found to fall within a 95% confidence interval of $\pm 0.95\%$ of reading. 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. 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 of five degrees of freedom.

The calibration data for the air outlet mass 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 becomes ± 0.36 SLPM for a confidence level of 95%.

The two transducers thus have calibration equations as follows:

$$q_{\text{AIR IN}} \text{ (SLPM)} = 10.76689 V + C_1$$

$$q_{\text{AIR OUT}} \text{ (SLPM)} = 11.33494 V + C_2$$

where V is the output voltage of the transducer and the offset constants C_1 and C_2 are to be zeroed out before the start of a test.

2.3.3.2 Temperature/Pressure/Density. The heated-tube type of 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.

2.3.3.3 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. In addition, empirical checks showed that the zero adjustment stability of the transducers is approximately ± 0.3 SLPM.

2.3.3.4 Time Response. When the time response of a transducer is not small compared to the time variation of the measurand, a resultant time-lag error must be considered. The true mass flowmeter manufacturer gives the transducer time response (taken to be the "time constant"--the time required for the transducer output to reach 63.2% of a step-change input) as seven seconds. Air flow fluctuations in the ECS-2 tests were observed to occur with a period of six to ten seconds, indicating a need to consider errors due to the inability of the transducer to follow rapid changes in the flow rate. If a sinusoidal curve of varying amplitude is used to approximate the flow rate as a function of time, the transducer can follow time variations more closely than would be the case for step changes in flow rate. Under these conditions, the transducer can reach about 96% of measurand fluctuation peaks.⁶ An estimated uncertainty of $\pm 4\%$ is therefore attached to the instantaneous flow rates. Note also that the time-averaged flow rate is affected less by slow transducer response when periodic fluctuations occur about a relatively constant mean. For that reason, an uncertainty of $\pm 1\%$ arising from the true mass flowmeter response time is assigned to average flow rates.

2.3.3.5 Specific Heat Variation. Inlet air to the ECS-2 test section had a low moisture content (as low as 15% relative humidity), while the outlet air was moisture-saturated after separation from the water at the outlet plenum. 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 any gas having a specific heat different from that of air. A simple partial pressure approach, using dry air and water vapor, was used to estimate the specific heat of moisture-saturated air. A specific heat of 1170 joules/kg-K was found by this method, which indicates that a correction factor of 0.86 should be applied to air outlet flow values. Using individual partial pressure contributions covering a 30% range of variation, an estimated uncertainty of $\pm 4\%$ was established for the contribution of the change in the specific heat to the outlet air flow rate.

2.3.3.6 Data System. The data acquisition system contributed an estimated precision error of $\pm 0.11\%$ of range and a bias error of $\pm 0.0026\%$ of range, as discussed in Section 2.1, to the total uncertainty of the air flow measurements.

2.3.3.7 Total Uncertainty. The total uncertainty, expressed at the 95% confidence level, for the air inlet and air outlet mass flow measurements are summarized in Tables 3 and 4.

2.3.4 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 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 and pressure. Air density in these calculations is thus a constant and it can be shown from the "law of propagation of errors", using the Taylor's series expansion method³, that the uncertainty in the air mass flow rate is

$$U_{\dot{m}} = \pm \rho U_q,$$

where ρ = density of air at standard conditions

and U_q = the uncertainty in the volumetric flow rate of air.

2.3.5 Specific Uncertainties - Turbine Flowmeters (Water)

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

$$q_{\text{WATER IN}} \text{ (l/s)} = 0.155 V + C_3$$

$$q'_{\text{WATER IN}} \text{ (l/s)} = 0.032 V + C_4$$

$$q_{\text{WATER COIL}} \text{ (l/s)} = 0.050 V + C_5$$

where V is the output voltage of the transducer and the offset constants C_3 , C_4 , and C_5 again are zeroed out before the start of a test.

Statistical analysis of the calibration data yielded slightly 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 $+0.0023$ l/s and ± 0.0034 l/s, respectively.

2.3.5.2 Transducer Linearity. An uncertainty of $\pm 0.5\%$ of reading is assumed for the transducer linearity, based on the manufacturer's specifications.

2.3.5.3 Temperature/Pressure/Viscosity. The ECS-2 tests were conducted in a non-pressurized test section, with maximum temperatures generally below 320 K in the inlet and outlet areas. Based on these facts, on manufacturer's specifications, and on past experience at the INEL with these and similar transducers, pressure and temperature effects on the transducers themselves are assumed to be negligible. Viscosity effects in air under these conditions are likewise considered negligible.

2.3.5.4 Response Time. The response time of the turbine flowmeters is quoted by the manufacturer to be five to six milliseconds. Because the test conditions changed slowly, it is assumed that the response time of the turbine, in terms of both the electronics and the mechanical inertia of the rotor, contributes nothing significant to the uncertainty of the flow measurement.

2.3.5.5 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.

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

2.3.5.7 Total Uncertainty. The total uncertainty, expressed at the 95% confidence level, for the volumetric water flow measurements are summarized in Table 5.

2.3.6 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 ECS-2 tests is an equation of the following form:

$$\rho(T) = A + BT + CT^2$$

for a pressure of 1.224 standard atmospheres,

where ρ = water density in kg/m^3 ,

T = kelvin temperature,

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.

In addition to 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 taken into account. It is easily shown from the Taylor's series expansion method for the "law of propagation of errors"³ that the uncertainty in water density, for the equation used in the ECS-2 tests, is given by the following expression:

$$U_{\rho}(T) = \pm(B + 2CT)U_T$$

where B, C, and T are as given above, and U_T is the uncertainty in the measured water temperature (see Table 7).

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

2.3.7 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 the "law of propagation of errors"³.

With $\dot{m} = q \rho$ = 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

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

where U_{ρ} = the uncertainty in the water density

and U_q = the uncertainty in the volumetric flow rate.

TABLE 3. SUMMARY OF AIR INLET MASS FLOWMETER UNCERTAINTIES

Parameter	Uncertainty	
	Precision	Bias
Calibration	$\pm(0.22 \text{ SLPM} + 0.95\% q \text{ *})$	
Transducer electronics	$\pm 0.54 \text{ SLPM}$	
Zero adjustment	$\pm 0.3 \text{ SLPM}$	
Time response	$\pm 4\% q \text{ / } \pm 1\% q \text{ **}$	
Temperature	Not considered significant	
Pressure	Not considered significant	
Fluid density	Not considered significant	
Data system	$\pm 0.059 \text{ SLPM}$	$\pm 0.001 \text{ SLPM}$
Installation effects	Not considered significant	
Instantaneous flow rates **		
RSS Totals:	$\pm 0.658 \text{ SLPM} \pm 4.11\% q \text{ *}$	$\pm 0.001 \text{ SLPM}$
Uncertainty _{95%} , U_q :	$\pm [(0.658 \text{ SLPM})^2 + (4.11\% q \text{ *})^2]^{1/2}$	
Time-averaged flow rates **		
RSS Totals:	$\pm 0.0658 \text{ SLPM} \pm 1.38\% q \text{ *}$	$\pm 0.001 \text{ SLPM}$
Uncertainty _{95%} , $U_{q_{ave}}$	$\pm [(0.658 \text{ SLPM})^2 + (1.38\% q \text{ *})^2]^{1/2}$	

* q = transducer reading (volumetric flow rate, SLPM). The manufacturer calibrates the transducer in volumetric flow rate, rather than mass flow rate, units.

Accordingly, the air mass flow rate uncertainty is

$$U_m = \pm \rho U_q$$

** The time response uncertainties apply to instantaneous flow rates ($\pm 4\% q$) and to time-averaged flow rates ($\pm 1\% q$), respectively.

TABLE 4. SUMMARY OF AIR OUTLET MASS FLOWMETER UNCERTAINTIES

Parameter	Uncertainty	
	Precision	Bias
Calibration	$\pm(0.36 \text{ SLPM} + 1.50\% q \text{ *})$	
Transducer electronics	$\pm 0.57 \text{ SLPM}$	
Zero adjustment	$\pm 0.3 \text{ SLPM}$	
Response time	$\pm 4\% q / \pm 1\% q \text{ **}$	
Temperature	Not considered significant	
Pressure	Not considered significant	
Fluid density	Not considered significant	
Change in specific heat		$\pm 4\% q \text{ *}$
Data system	$\pm 0.063 \text{ SLPM}$	$\pm 0.001 \text{ SLPM}$
Installation effects	Not considered significant	
Instantaneous flow rates **		
RSS Totals:	$\pm 0.741 \text{ SLPM} \pm 4.27\% q \text{ *}$	$\pm 0.001 \text{ SLPM} \pm 4\% q \text{ *}$
Uncertainty _{95%} , U_q :	$\pm [(0.741 \text{ SLPM})^2 + (5.85\% q \text{ *})^2]^{1/2}$	
Time-averaged flow rates **		
RSS Totals:	$\pm 0.741 \text{ SLPM} \pm 1.80\% q \text{ *}$	$\pm 0.001 \text{ SLPM} \pm 4\% q \text{ *}$
Uncertainty _{95%} , $U_{q_{ave}}$:	$\pm [(0.741 \text{ SLPM})^2 + (4.39\% q \text{ *})^2]^{1/2}$	

* q = transducer reading (volumetric flow rate, SLPM). The manufacturer calibrates the transducer in volumetric flow rate, rather than mass flow rate, units.

Accordingly, the air mass flow rate uncertainty is

$$U_{\dot{m}} = \pm \rho U_q$$

** The time response uncertainties apply to instantaneous flow rates ($\pm 4\% q$) and to time-averaged flow rates ($\pm 1\% q$), respectively.

TABLE 5. SUMMARY OF TURBINE FLOWMETER UNCERTAINTIES

Parameter	Uncertainty	
	Precision	Bias
Calibration	$\pm(0.0034 \text{ l/s} + 0.31\% q^*)$	$+0.0023 \text{ l/s}$
Linearity	$\pm 0.5\% q^*$	
Repeatability	$\pm 0.05\% q^*$	
Temperature effects	Not considered significant	
Pressure effects	Not considered significant	
Viscosity effects	Not considered significant	
Response time	Not considered significant	
Transducer electronics	$\pm 0.20\% q^*$	
Data system	$\pm 0.0017 \text{ l/s}$	$\pm 0.00004 \text{ l/s}$
Installation	Not considered significant	
RSS Totals:	$\pm 0.0039 \text{ l/s} \pm 0.62\% q^*$	$\pm 0.0023 \text{ l/s}$
Uncertainty _{95%} , U_q :	$\pm [(0.0045 \text{ l/s})^2 + (0.62\% q^*)^2]^{1/2}$	

* q = volumetric flow rate, l/s

TABLE 6. SUMMARY OF WATER DENSITY UNCERTAINTIES *

Parameter	Uncertainty	
	Precision	Bias
Polynomial approximation		
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:

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

** The water density is approximated by an expression of the following form (see Section 2.3.6):

$$\rho = A + BT + CT^2.$$

2.4 Temperature

2.4.1 Measurement Description

All temperature measurements in the ECS-2 tests were made with MgO-insulated, 304 stainless steel-sheathed, Type-K thermocouples having insulated measuring junctions. These thermocouples were of two different diameters: (1) 1.59 mm (0.0625 in.) for thermocouples measuring fluid temperatures, located in the air and water inlets and outlets to the test section, in the inlet and outlet plena, in the coolant channels inside the flow shroud, at the plenum cooling coil inlet and outlet, and at the heat exchanger outlet; and (2) 0.80 mm (0.032 in.) for thermocouples embedded in grooves in the inside surface of the aluminum inner shroud (see Figure 4).

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 $\mu\text{V/K}$.

Figure 4. Cross section of ECS-2 test section, showing thermocouples embedded in the aluminum inner shroud, viewed from the bottom of the assembly.

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 such inhomogeneities with respect to the temperature gradient present for a given 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. These factors, plus others that generally produce smaller effects on the accuracy of thermocouple measurements are discussed in the following sections.

2.4.2 Testing

All of the thermocouples used in the ECS-2 test section were checked at 300 K and 600 K for conformance to the standard Type-K calibration. All of these instruments met the standard-grade error limits of ± 2.2 K at the above two temperatures. No additional calibration was performed on these instruments.

Each thermocouple was checked at various stages during the assembly of the instrumented test section to ensure that loop and insulation resistances were unchanged as a result of the splicing and installation operations. These checks assure that the thermocouples were not damaged or degraded during such operations.

An isothermal check was made on the thermocouples in the test section before and after each test of the ECS-2 series. All of the fluid thermocouples indicated temperatures that were within the expected limits; three of the metal thermocouples, installed in the aluminum inner flow shroud, were outside the accepted limits. Data from those three instruments (TI-C-0-6, TI-D-U-6, and TI-D-S-7) were flagged for scrutiny in analysis of the test data. Evidence suggests that the measuring junctions of those thermocouples became dislodged from proper contact with the grooves in the inner shroud in which they were installed, resulting in faulty measurements from those instruments.

2.4.3 Specific Uncertainties

2.4.3.1 Thermocouple Wire Uncertainty. Thermocouple wires and finished thermocouple assemblies may have nonuniformities in chemical composition or physical and metallurgical properties at locations along the length of the thermocouple that limit the repeatability of the thermoelectric output. Each lot of wire is checked by the manufacturer to determine the uncertainty band met by that lot; this figure is referred to as the "manufacturer's tolerance". An error band of $\pm 2.2^\circ\text{C}$ or $\pm 0.75\%$ of the Celsius reading, whichever is greater, is the accepted tolerance for "standard grade" wire as used in the ECS-2 tests. In SI units this translates to $\pm 2.2\text{K}$ for temperatures up to 566 K, or $\pm 0.75\%(T-273\text{ K})$ above 566 K (where T is the kelvin temperature).

2.4.3.2 Thermocouple Manufacture and Cold Working. The thermocouples used throughout the tests have stainless steel sheaths, magnesium oxide insulation, and isolated measuring junctions. Those used for fluid temperature measurements are 1.59 mm in diameter, and those used for metal temperatures are 0.80 mm in diameter. Cold working that results from bending, drawing, or swaging during the manufacturing process alters the thermoelectric properties of the wires slightly; however, that effect can be removed almost entirely by proper annealing of metal-sheathed thermocouples 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 thermocouples in a test assembly. Such cold-worked areas on thermocouples, however, must be located in a temperature gradient of significant magnitude if errors in the thermoelectric signal are to result. Neither fluid nor metal thermocouples in the ECS-2 tests were installed with a cold-worked section of the instruments in the temperature gradient; therefore, no contribution to the uncertainty is assigned for the installation process.

2.4.3.3 Short-Range Ordering. The Chromel thermoelement used in most Type-K thermocouples is subject to a phenomenon known as short-range ordering in which 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. Studies⁷ have shown that the effect can produce errors as large as +1.3%.

The fluid thermocouples of the ECS-2 tests experience little time in the temperature range above 470 K where short-range ordering effects occur, so no additional error is assigned for those instruments due to this effect. The metal thermocouples experience somewhat longer times in that temperature range; consequently, a short-range order error of +0.25 K is estimated for those instruments, based on data given in Reference 7.

2.4.3.4 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 ECS-2 thermocouples is above 400 K for more than a few hours total during the course of the tests, these effects are assumed to be small, and an estimated uncertainty of 0.1% of reading is assigned, based on the available literature.⁸⁻¹⁰

Studies by Anderson et al.¹⁰ noted decalibration in Type-K thermocouples due to diffusion of small quantities of sheath and insulation components into the thermoelements at temperatures above about 1270 K. Such effects are considered to be negligible in the instruments of interest in the ECS-2 tests because of the much lower operating temperatures.

2.4.3.5 Shunting Effects. The electrical resistivity of the ceramic insulating materials used in thermocouples inevitably decreases with temperature. If that decrease is sufficiently large, the insulation resistance will be low enough to permit electrical shunting of the thermoelectric signal between the two thermoelements, with the result that a part of the thermocouple signal will be lost and the temperature indication will be in error. Fortunately, such effects are usually limited to operation at temperatures above about 1200 K, and thus can be considered not relevant to the ECS-2 thermocouples. This assumption is confirmed by the results of the two-point "calibration" performed on those instruments at the end of the fabrication process, and no uncertainty is assigned for electrical shunting effects.

2.4.3.6 Magnetic Field Effects. Kollie et al.¹² have reported on the effect of the interaction of magnetic fields with Chromel-Alumel thermocouples. 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 magnitude 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:

$$\epsilon = (Q \vec{\nabla} T \times \vec{B}) \cdot \vec{l}_0$$

where

ϵ = the parasitic EN emf,

Q = the EN coefficient for an individual thermoelement,

$\vec{\nabla} T$ = the temperature gradient,

$\vec{B}$ = the magnetic induction produced in the thermoelement by the magnetic field,

$\vec{l}_0$ = 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 (this is the case for the metal thermocouples of the ECS-2 tests) and minimum (i.e., zero) when any two of them are parallel (as for the fluid thermocouples in the coolant channels). The temperature gradient across the metal thermocouples is estimated to be no more than five kelvin because they are installed in an aluminum component, and the resultant error for the longest thermocouples then 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. For those thermocouples entering the test section from the top this is a negative bias error, and for those entering from the bottom it is a positive bias error. Above the Curie temperature of the Alumel thermoelement (about 420 K) the EN effect is greatly reduced and no additional uncertainty is assigned for the metal thermocouples in that temperature range.

2.4.3.7 Polynomial Approximation. A third-order polynomial, which approximates the standard Type-K thermocouple calibration over the temperature range of interest, was 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.

Plotting the temperature difference between the standard Type-K calibration and the polynomial, as a function of temperature, gives the resultant uncertainty in computing the temperature from this expression. 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.

2.4.3.8 Extension Wires. Extension wires are spliced to each of the fluid and metal thermocouples where the metal-sheathed portions extend outside the high-temperature or severe-environment regions of the test assembly. These extension wires have the same error limits as standard-grade Type-K thermocouple wires; the temperature rating is limited by the type of insulation covering the wires (usually PVC or braided fiber-glass). Thus, the potential uncertainty contributed by the extension wires is ± 2.2 K, and this figure is included as a part of the overall thermocouple uncertainty.

2.4.3.9 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 to be a bias error because of its systematic nature.

2.4.3.10 Data System. A discussion of the uncertainty contributed by the data system appears in Section 2.1. The thermocouples use channels 0 through 79 in the data system, and have precision errors (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 the conversion was made using a gain of 400 and an average Seebeck coefficient of $41.4 \mu\text{V/K}$.

2.4.3.11 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 ECS-2 tests is

low enough to preclude the possibility of radiation errors. All thermocouple installations followed the rule-of-thumb wherein 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 thermocouples extending into flow regions are likewise negligibly small by virtue of the fact that flow rates were low and the flow regimes uniform and well-dispersed. 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 thermocouples (less than 200 milliseconds for all thermocouple types in the assembly). That condition allows the actual temperature of the instruments to follow 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 thermocouples for these types of installation effects.

Another source of installation effect uncertainty must be considered for the metal thermocouples. These stainless steel-sheathed instruments were fixed in grooves machined on the inside surface of the aluminum shroud section (see Figure 4). Installation was accomplished by peening the thermocouples into the grooves, inevitably resulting in a certain variability from one thermocouple to another in the thermal contact between instrument and shroud. The rectangular cross section of the grooves on the ECS-2a assembly compounds the problem of attaining uniform and efficient heat transfer. (Grooves of semicircular cross section were used in the ECS-2b assembly.) Intrinsically lower thermal conductivity in the thermocouple and poor thermal contact (which implies smaller heat transfer coefficients in those regions) lead to temperature indications lower than the actual bulk aluminum temperature. Resultant errors can be expected to be roughly proportional to the size of the gap or total void area between the thermocouple junction and the underlying substrate. Precise determination of such errors requires empirical studies or exact modelling of the particular geometry involved. Alternatively, estimates of the error can be made based on published studies of similar geometries and materials.

Core heater rods used in the Semiscale program at the INEL had internal axial thermocouples that were used for rod cladding temperature measurements during blowdown tests. The thermocouples were located between the two layers of a composite stainless steel sheath. The inner sheath was creased along its total length at four equally-spaced azimuthal positions to accept four 0.625-mm diameter sheathed thermocouples. With the thermocouples in position, the outer sheath was positioned over the inner sheath and the composite assembly redrawn to fix the thermocouples in place. Metallographic sectioning of finished heater rods showed that a large variation existed from one instrument to another in the void space surrounding the thermocouples, leading to the probability of sizable errors in measuring actual rod cladding temperatures. Study of blowdown test data in Reference 13 showed temperature differences as large as 15% in a given test for thermocouples with measuring junctions at the same elevation on adjacent heater rods. Part of that difference is no doubt attributable to varying fluid conditions around the individual heater rods, but even under steady-state conditions there was some five percent variation among thermocouples measuring nominally the same temperature. A broad sampling of such variations yielded an average difference of 9.8%,

due predominantly to variable thermal contact between sheath and thermocouple in our judgment. Comparison of test data with predicted temperatures from refined code calculations as reported in the same reference tend to support that conclusion.

Other studies^{14,15,16}, describing thermocouples installed in grooves or surface mounted by a variety of brazing, spot welding, and strapping techniques, report errors in the range of minus seven to ten percent for the temperatures of interest in the ECS-2 tests. Although the installation geometries of these studies bear only a general similarity to that of the ECS-2 tests, the important point is that a distinct pattern emerges regarding the order of magnitude of errors ascribed to thermocouples installed by such methods.

Lacking empirical data for installation errors specific to the ECS-2 metal thermocouples, it is impossible to assign a 95% uncertainty limit to those errors with a high degree of confidence. Based on the corroborative evidence reported in the references noted above, however, a bias error of -10% and a precision error of $\pm 6\%$ is assigned to those instruments for installation effects.

2.4.4 Total Uncertainty

The total uncertainties for the fluid and metal thermocouples, determined to 95% confidence limits, are summarized in Tables 7 and 8, respectively.

TABLE 7. SUMMARY OF FLUID THERMOCOUPLE UNCERTAINTIES

Parameter	Uncertainty	
	Precision	Bias
Thermocouple wire	± 2.2 K	
Manufacture and cold working	Not considered significant	
Short-range ordering	Not considered significant	
Aging and drift		-0.1% (T-273 K)
Shunting effects	Not considered significant	
Magnetic field effects	Not considered significant	
Polynomial approximation	± 1.034 K	-0.115 K
Extension wires	± 2.2 K	
Reference temperature	± 0.2 K	
Data system	± 0.53 K	+0.013 K
Installation effects	Not considered significant	
RSS Totals:	± 3.33 K	± 0.116 K $\pm 0.1\%$ (T-273 K)
Uncertainty _{95%} , U_T	$\pm \{(3.33 \text{ K})^2 + [0.1\% (T-273 \text{ K})]^2\}^{1/2}$	

TABLE 8. SUMMARY OF METAL THERMOCOUPLE UNCERTAINTIES

Parameter	Uncertainty	
	Precision	Bias
Thermocouple wire	± 2.2 K	
Manufacture and cold working	Not considered significant	
Short-range ordering	Not considered significant	
Aging and drift		-0.1% (T-273 K)
Shunting effects	Not considered significant	
Magnetic field effects (<420 K)		
Upper TCs *		-2 K
Lower TCs *		+2 K
Polynomial approximation	± 1.034 K	-0.115 K
Extension wires	± 2.2 K	
Reference temperature	± 0.2 K	
Data system	± 0.53 K	+0.013 K
Installation effects	$\pm 6\%$ (T-273 K)	-10% (T-273 K)
RSS Totals:		
Upper TCs	± 3.33 K $\pm 6\%$ (T-273 K)	-2.102 K -10.1% (T-273 K) **
Lower TCs	± 3.33 K $\pm 6\%$ (T-273 K)	+1.898 K -10.1% (T-273 K) **

(cont.)

TABLE 8. (CONT.) SUMMARY OF METAL THERMOCOUPLE UNCERTAINTIES

Uncertainty_{95%}, U_T :

Upper TCs	$\pm \{ (3.33 \text{ K})^2 + [6\% (T-273 \text{ K})]^2 \}^{1/2}$ $- [2.102 \text{ K} + 10.1\% (T-273 \text{ K})]**$
Lower TCs	$\pm \{ (3.33 \text{ K})^2 + [6\% (T-273 \text{ K})]^2 \}^{1/2}$ $- [-1.898 \text{ K} + 10.1\% (T-273 \text{ K})]**$

* "Upper TCs" refer to those thermocouples entering the test section from the top, and "lower TCs" to those entering from the bottom.

** Precision uncertainties have been combined by the root-sum-square method, but bias uncertainties have been summed algebraically in order to preserve the sign of the dominant bias term.

2.5 MASS-ENERGY BALANCE

2.5.1 Measurement Description

The uncertainty in the thermal energy of the ECS-2 tests is of interest in comparing the thermal energy to the electrical energy input of the test and in calculating heat losses. It is straightforward to show that the fraction of the thermal energy carried by air in these tests is a very small part of the total--0.01% or less--and can be neglected as a part of the global calculations. Therefore, we need consider only the thermal energy carried by the water, which can be expressed as

$$\dot{Q} = \dot{m} c_p \Delta T$$

where

$\dot{m} = \rho q$ = the mass flow rate of water,

q = the volumetric flow rate of water,

ρ = the water density,

c_p = the specific heat of water,

and

$\Delta T = T_{out} - T_{in}$ = the water temperature change.

2.5.2 Specific Uncertainties

In the above expression, the volumetric flow rate and the inlet and outlet temperatures are measured parameters for which uncertainties have been estimated elsewhere in this report. The water density ρ is determined from a second-order polynomial in the temperature T , and consequently has uncertainties associated with it; those uncertainties are estimated in Section 2.3.6. The specific heat c_p is a constant for a given value of temperature, and the temperature uncertainty is sufficiently small that the uncertainty in c_p can be neglected.

The water mass flow rate uncertainty is estimated from (Sec. 2.3.7)

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

The uncertainty in ΔT is likewise readily shown to be

$$U_{\Delta T} = \pm [(U_{T_{in}})^2 + (U_{T_{out}})^2]^{1/2},$$

where the uncertainties in the inlet and outlet temperatures are as outlined in Table 7.

2.5.3 Total Uncertainty

The total uncertainty in the thermal energy can also be shown by the Taylor's series expansion method to be

$$U_{\dot{Q}} = \pm [(c_p \Delta T U_{\dot{m}})^2 + (\dot{m} c_p U_{\Delta T})^2]^{1/2}$$

where

$U_{\dot{m}}$ = the water mass flow rate uncertainty, as given above,

and

$U_{\Delta T}$ = the uncertainty in the temperature difference.

TABLE 9. SUMMARY OF MASS-ENERGY BALANCE UNCERTAINTIES

Parameter	Uncertainty
Mass flow rate, $\dot{m}$	$U_{\dot{m}} = \pm[(q U_{\rho})^2 + (\rho U_q)^2]^{1/2} *$
Specific heat, c_p	Negligible
Temperature change, ΔT	$U_{\Delta T} = \pm[(U_{T_{in}})^2 + (U_{T_{out}})^2]^{1/2} **$
Total Uncertainty 95% $U_{\dot{Q}}$:	$\pm[(c_p \Delta T U_{\dot{m}})^2 + (\dot{m} c_p U_{\Delta T})^2]^{1/2}$

* U_{ρ} = uncertainty in water density (see Section 2.3.6)

U_q = uncertainty in volumetric flow rate of water (see Table 5)

** $U_{T_{in}}$ = uncertainty in inlet water temperature (see Table 7)

$U_{T_{out}}$ = uncertainty in outlet water temperature (see Table 7)

2.7 Absolute Pressure⁻¹⁷

2.6.1 Measurement Description

Six absolute and one barometric pressure transducer, with their accompanying excitation voltage and signal conditioning circuits, made the required pressure measurements in the ECS-2 test series. A block diagram of a pressure transducer measurement channel is shown in Figure 5 below. The pressure measurements are used to monitor test conditions throughout the system and to control backpressure in the standpipe.

2.6.1.1 Transducer. Sensotec model TJE bonded-foil strain gage transducers were used for the ECS-2 test pressure measurements. These transducers utilize a diaphragm with strain gages attached to convert the diaphragm deflections into electrical signals. The electrical signals are conditioned, amplified, recorded, and then converted into pressure readouts.

The strain gages are attached to a pressure-sensitive element that deforms elastically when pressure is applied. The deformation of the pressure-sensing element produces elongation or shortening of the strain gage and causes an increase or decrease in the strain gage resistance. The resistance of the conductor depends upon its geometry (length and cross-sectional area) and resistivity. Small changes in the strain gage geometry produce resistance changes. The strain gage resistance, which is proportional to the pressure applied to the transducer, is determined by measuring the voltage drop in the circuit containing the strain gage.

The barometric pressure is measured by a Sensotec model EB electronic barometer. This measurement is used to monitor atmospheric conditions (range: 54-108 kPa) throughout the test.

Figure 5. Strain-gage type pressure transducer measurement channel block diagram.

2.6.1.2 Excitation Voltage. A constant power voltage (excitation) is supplied to the strain gage by one of two methods. One method uses an in-line amplifier connected to the pressure transducer to provide a power voltage of 10 volts dc for excitation. The other method uses a control module (SCV-484) within the Megadac 2200C to provide a precision voltage of 10 volts dc for bridge excitation.

2.6.1.3 Signal Conditioning. Signal conditioning is provided by either an in-line amplifier or a control module within the Megadac 2200C. The in-line amplifier provides an electronic conditioning of the transducer signal and amplifies the strain gage millivolt signal to a standard output range of 0-5 volts dc. The differential input modules of the Megadac also provide some of the pressure transducers with signal conditioning and amplification of the strain gage signal. The Megadac input modules provided excitation voltage and signal conditioning for the atmospheric pressure and the inlet and outlet pressure measurements.

2.6.2 Calibration

The transducers used in the pressure measurements were tested by the manufacturer prior to shipment and then calibrated at the INEL Standards and Calibration Laboratory prior to the ECS-2 test series. The calibration data was used to determine the calibration coefficients and to ensure that the transducers meet the manufacturer's specifications.

A five-point check was performed by the vendor prior to shipment to the INEL. 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.

2.6.3 Specific Uncertainties

Testing activities, along with manufacturer's specifications, current literature, and engineering judgment, were used to evolve 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 9.

2.6.3.1 Calibration Coefficients. Uncertainty factors associated with the calibration are considered as part of the overall uncertainty. These factors include linearity, repeatability, and hysteresis. The uncertainty for these factors was determined from the laboratory calibration. 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 determining 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.

2.6.3.2 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.

2.6.3.3 Vibration/Shock/Reference Pressure. In view of the benign ECS-2 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.

2.6.3.4 Transducer Zeroing. At the start of each test all pressure transducers were zeroed by connecting them to a Dial-a-Source and adjusting the input module of the Megadac. A zero-level and full-scale reference voltage is applied and the software within the Megadac automatically zeroes the channel. The zeroing accuracy within the Megadac is included in the $\pm 0.11\%$ of range derived for the DAS in Section 2.1; the accuracy of the Dial-a-Source is $\pm 0.005\%$ of range.

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

2.6.4 Total Uncertainty

The total uncertainties for absolute pressure measurements in three separate pressure ranges, expressed to a 95% confidence level, are summarized in Table 10.

TABLE 10. SUMMARY OF ABSOLUTE PRESSURE UNCERTAINTIES

Parameter	Pressure Transducer Range					
	0-172 kPa		0-345 kPa		54-108 kPa**	
	Random	Bias	Random	Bias	Random	Bias
Calibration *	± 0.344		± 0.69		± 0.11	
Traceability *	± 0.034	0.026	± 0.069	0.052	± 0.011	0.008
Temperature *		0.060		0.121		0.015
Zero offset *		0.009		0.017		0.003
Excitation voltage *		None		0.035		0.005
Data system *	± 0.19	0.005	± 0.38	0.01	± 0.059	0.002
RSS Totals *:	± 0.395	0.066	± 0.791	0.138	± 0.125	0.018
Uncertainty _{95%} , U_p :	± 0.40 kPa		± 0.80 kPa		± 0.126 kPa	

* All values are expressed in kilopascals (kPa).

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

2.7 Differential Pressure⁻¹⁸

2.7.1 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 by water-filled impulse lines. Each transducer utilizes a diaphragm with strain gages attached. The strain gages convert the diaphragm deflections into electrical signals. These voltages are conditioned, amplified, recorded and finally converted by computer into pressure readouts.

Small changes in strain gage geometry produce resistance changes. The strain gages are attached to a pressure-sensing element. The sensing element is deformed elastically when 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 or shortening of the strain gage and causes an increase or 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.

2.7.1.1 Transducer. Five different models of differential pressure transducers manufactured by three companies were used for the ECS-2 tests. These include: three 0-5 kPa, five 0-13 kPa, and seven 0-25 kPa cells made by BLH Electronics; five 0-37 kPa cells from CEC; and one 0-40 kPa cell from Genisco.

2.7.1.2 Excitation Voltage. A constant power voltage (excitation) is supplied by a control module (SCV-484) within the Megadac 2200C that provides a precision voltage of 10 volts dc for bridge excitation (see Figure 6).

2.7.1.3 Signal Conditioning. Signal conditioning is provided by the 885D input module of the Megadac 2200C. The input module takes the signal from the differential pressure transducer and amplifies the millivolt signal to a standard range of 0 to 10 volts dc (see Figure 6).

Figure 6. Differential pressure measurement channel block diagram.

2.7.2 Calibration

The transducers used in the differential pressure measurements were tested by the vendor prior to shipment to the INEL. This testing was to determine calibration coefficients and to ensure that the transducers met the manufacturer's specifications. Since these transducers were manufactured several years ago the manufacturer's specifications were not used to determine the uncertainties. The specific uncertainties were determined from results obtained during the Semiscale test series and from calibration performed at the INEL Standards and Calibration Laboratory prior to the ECS-2 tests.

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. The order of the curve fit is based on the calibration data.

2.7.3 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 Table 11. 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.

2.7.3.1 Calibration Coefficients. Uncertainty factors associated with the calibration include repeatability, linearity and hysteresis. Linearity and hysteresis were determined from the calibration data. Since only a one step calibration was performed the repeatability was determined from previous testing performed during the Semiscale program. The following are the results of the calibration coefficient uncertainties:

	<u>BLH Transducers</u>	<u>CEC & Genisco Transducers</u>
Repeatability:	$\pm 0.5\%$ of range	$\pm 0.5\%$ of range
Linearity:	$\pm 0.5\%$ of range	$\pm 0.5\%$ of range
Hysteresis:	$\pm 0.25\%$ of range	$\pm 0.5\%$ 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 $\pm 0.75\%$ of range for the BLH transducers and $\pm 0.866\%$ range for the CEC and Genisco transducers.

2.7.3.2 Calibration Traceability. The uncertainties associated with the laboratory calibration accumulated to NIST are a bias uncertainty of $\pm 0.015\%$ of reading and $\pm 0.01\%$ of reading for the random component. These are assumed to be 95% confidence levels.

2.7.3.3 Thermal Sensitivity. Testing performed in the Semiscale program on several differential pressure transducers showed temperature related uncertainties of up to $\pm 0.05\%$ of range per K. The change in temperature during testing is estimated to be 5.6 K (10°F). This is an estimated uncertainty of $\pm 0.275\%$ of range.

2.7.3.4 Vibration/Shock/Line Pressure. In view of the benign ECS-2 test conditions, the uncertainty for vibration and shock is considered negligible. Because testing is performed at near-atmospheric conditions, the high-pressure line effect is considered negligible for the ECS-2 type of tests.

2.7.3.5 Transducer Zeroing. At the start of each test all pressure transducers are zeroed by connecting a Dial-a-source and adjusting the input module of the Megadac. A zero and full scale reference voltage is applied and the Megadac software automatically zeroes the channel; the uncertainty associated with the Megadac process is included in that of the data system, noted in the following paragraph. The accuracy of the Dial-A-Source is $\pm 0.005\%$ of full scale.

Each morning during testing the lines to all differential pressure transducers were completely filled. All transducers were then opened to atmosphere with the three-way valve in each installation and zeroed by means of software in the data acquisition system. Finally, the transducers were valved back to the lines and their readings compared with those expected based on the known water head difference in the lines. Each line's length was measured to within one-fourth of an inch, and given the possibility of water loss in the lines by evaporation and aspiration during the course of a day, the uncertainty in the water head difference may be as great as one-half inch. Thus, for a 95% confidence interval, an uncertainty of approximately ± 1 inch of water ($1/2$ inch times a Student's t value of two), or ± 0.25 kPa, is assumed for differential pressure transducer zeroing.

2.7.3.6 Data System. An uncertainty of $\pm 0.11\%$ of range for the data system is derived in Section 2.1 of this report.

2.7.4 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 11 and 12.

Table 11. SUMMARY OF BLH DIFFERENTIAL PRESSURE TRANSDUCER UNCERTAINTIES

Parameter	Uncertainty	
	Precision	Bias
Calibration coefficient	$\pm 0.75\%$ of range	
Laboratory calibration traceability	$\pm 0.01\%$ of range	$\pm 0.015\%$ of range
Elevation difference		± 0.125 kPa
Thermal sensitivity		$\pm 0.28\%$ of range
Line pressure	± 0.25 kPa	
Signal conditioning		$\pm 0.01\%$ of range
Transducer zeroing		$\pm 0.005\%$ of range
Data system	$\pm 0.11\%$ of range	$\pm 0.0026\%$ of range
RSS Total:	$\pm(0.758\% \text{ of range} + 0.25 \text{ kPa})$	$\pm(0.281\% \text{ of range} + 0.125 \text{ kPa})$
Uncertainty _{95%} , U_{dp} :	$\pm[(0.808\% \text{ of range})^2 + (0.28 \text{ kPa})^2]^{1/2}$	

TABLE 12. SUMMARY OF CEC & GENISCO DIFFERENTIAL PRESSURE TRANSDUCER UNCERTAINTIES

Parameter	Uncertainty	
	Precision	Bias
Calibration coefficient	$\pm 0.866\%$ of range	
Laboratory calibration traceability	$\pm 0.01\%$ of range	$\pm 0.015\%$ of range
Elevation difference		± 0.125 kPa
Thermal sensitivity		$\pm 0.28\%$ of range
Line pressure	± 0.25 kPa	
Signal conditioning		$\pm 0.01\%$ of range
Transducer zeroing		$\pm 0.005\%$ of range
Data system	$\pm 0.11\%$ of range	$\pm 0.0026\%$ of range
RSS Total:	$(\pm 0.873\% \text{ of range} + 0.25 \text{ kPa})$	$\pm (0.281\% \text{ of range} + 0.125 \text{ kPa})$
Uncertainty _{95%} , U_{dp} :	$\pm [(0.917\% \text{ of range})^2 + (0.28 \text{ kPa})^2]^{1/2}$	

3. CONCLUSIONS

A summary of the uncertainty ranges for the various parameters measured or determined from those measurements in the ECS-2 tests follows.

Based on a sampling of current and voltage measurements, the estimated uncertainty in the electrical power input to the ECS-2 test section ranges from about ± 0.15 kW at low power (10 kW) to about ± 1.7 kW at relatively high test power (160 kW).

Instantaneous air inlet flow rates had estimated uncertainties that ranged from ± 1.05 SLPM at low flow to ± 2.32 SLPM at full-scale flow. The corresponding mass flow uncertainties are ± 1.36 gm/min (± 0.082 kg/hr) and ± 3.00 gm/min (± 0.180 kg/hr). Estimated uncertainties in the instantaneous air outlet flow rates varied from ± 1.38 SLPM at low flow to ± 3.42 SLPM at full-scale flow. The corresponding mass flow uncertainties are ± 1.79 gm/min (± 0.107 kg/hr) and ± 4.42 gm/min (± 0.265 kg/hr).

Time-averaged air flow rate uncertainties were smaller than those for instantaneous flow rates by virtue of the smaller error contributed by time response considerations. Estimated uncertainties for average air inlet flow rates ranged from ± 0.71 SLPM at low flow to ± 0.99 SLPM at full-scale flow. The corresponding mass flow uncertainties are ± 0.923 gm/min (± 0.055 kg/hr) and ± 1.29 gm/min (± 0.077 kg/hr). For average air outlet flow rates, the uncertainties varied from ± 1.15 SLPM at low flow to ± 2.61 SLPM at full-scale flow. The corresponding mass flow uncertainties are ± 1.49 gm/min (± 0.089 kg/hr) and ± 3.37 gm/min (± 0.202 kg/hr).

Water flow rate uncertainties ranged from ± 0.0045 l/s at low flow to ± 0.0073 l/s at full-scale flow. The estimated uncertainty in water density, as a function of temperature, ranged from $\pm 0.22\%$ to $\pm 0.42\%$.

Estimated fluid temperature uncertainties varied from ± 3.33 K to ± 4.85 K over the range from 270-525 K. The predominant uncertainty source is the manufacturer's calibration tolerance, a factor that could be reduced by half with the use of special, rather than standard, grade thermocouple wire.

Uncertainty in metal temperatures varied from ± 3.3 K at cold conditions to a range from -12 K to -43 K at the trip set-point temperature of 525 K. Installation effects, largely the result of highly variable thermal contact between the thermocouple and the aluminum substrate, account for the bulk of the uncertainty in these measurements.

Estimated uncertainties in the water mass-energy balance, calculated from sample data sets collected during actual testing, range from ± 8.18 kW at 80.1 kW thermal power ($\pm 10.2\%$) to ± 23.6 kW at 77.9 kW thermal power ($\pm 30.3\%$). The calculations are dominated by the uncertainty in the inlet/outlet water temperature difference, compounded by the fact that ΔT is determined from the difference of two separate thermocouple measurements, rather than from a single differential instrument.

The estimated uncertainties in the absolute pressure measurements vary with the pressure range for which each transducer was selected. Those ranges and the corresponding uncertainties are as follows:

0 - 172 kPa:	± 0.40 kPa
0 - 345 kPa:	± 0.80 kPa
54 - 108 kPa:	± 0.126 kPa (atmospheric pressure)

Differential pressure measurements were made with transducers from two different manufacturers, with several ranges covered by the various instruments. The estimated uncertainties for the BLH transducers varied from ± 0.28 kPa to ± 0.345 kPa, depending on the transducer range. The estimated uncertainties for the CEC transducers varied from ± 0.28 kPa to ± 0.447 kPa.

It is apparent that estimated uncertainties in the input power, water flow rate, fluid temperature, and absolute and differential pressure measurements, including the contribution to each from the data acquisition system, in the ECS-2 tests fall within generally accepted limits. It is also evident in other cases that narrower uncertainty limits might have been attained with other instrumentation, had certain problems been anticipated beforehand. Large uncertainties associated with the slow time response of true mass flowmeters and with the change in specific heat of the outlet air would be difficult to foresee without a previous sampling of test data. Installation effects account for the predominant uncertainty in metal temperature measurements; significant improvement may have resulted in that area by brazing or welding the thermocouples in place rather than relying on simple mechanical installation. The mass-energy uncertainty is dominated by the uncertainty in water inlet/outlet temperature difference, which could have been reduced by the use of a differential instrument for that specific measurement.

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