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Evaluation of the Accelerator System String Test (ASST) Heat Leak Measurements and Their Uncertainties

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ABSTRACT

This note was prepared to review the status of heat leak calculations based on measurements from the accelerator systems string test (ASST) as they pertain to the estimation of the refrigerator loads on the cryogenics plants. The ASST dipole magnet heat leak data was re-evaluated to check its accuracy. The dipole heat leaks represent a large portion of the total refrigeration load. If the dipole heat leak can be determined with a high degree of accuracy, then the load on the cryogenic plants can be estimated with confidence.

PREVIOUS RESULTS

The dipole heat leak was determined by measuring the mass flow rate, the string test inlet pressure, and the inlet and outlet temperatures across a magnet. The heat leak is the mass flow times the enthalpy rise across the magnet;

$$Q = \dot{m}(h_{out} - h_{in}) \tag{1}$$

where

$$h = h(T, P) \tag{2}$$

Once the temperature and pressure are known, the enthalpy is determined using GASPAK[1] or HEPAK.[2]

The dipole heat leaks, based on ASST measurements, have been reported previously[3,4] and are listed in Table 1. The reader is referred to figure 1 from Weisend[3] for a schematic of the string test and the sensor placement. The average heat leaks were determined by taking the temperature difference across the three middle dipoles (dipoles 2, 3, and 4), calculating the total heat leak and dividing by three, i.e.;

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$$\underline{Q}_{ave} = \frac{\underline{Q}}{3} = \frac{\dot{m}[h(T_{5in}, P) - h(T_{2in}, P)]}{3} \tag{3}$$

The uncertainties given in Table 1 were calculated by comparing the temperature rise across the middle three dipoles with the absolute accuracy of the temperature sensors, i.e.;

$$\frac{\delta \underline{Q}}{\underline{Q}} = \frac{\varepsilon_T}{T_{5in} - T_{2in}} \tag{4}$$

Equation (4) assumes that the pressure and mass flow rate have little or no effect on the heat leak. It also assumes instantaneous temperature measurements because no standard deviation was included. No equations were given by Weisend[3] or Burgett,[4] so equation (4) is our interpretation of statements made in their respective papers.

To estimate the error in the pressure and flow measurements, a known amount of heat was input to the dipoles.[3,4] The total heat input to the dipoles with the heater and without the heater was compared to the additional heat input to the string, i.e.;

$$\varepsilon_{P,\dot{m}} \approx \frac{[(\dot{m}\Delta h)_w - (\dot{m}\Delta h)_{wo}] - \underline{Q}_h}{\underline{Q}_h} \tag{5}$$

From measurements and using equation (5), the flow and pressure errors were estimated to be less than 20% - 30%.[3,4] From Levin,[5] no parameter was held constant during the heater test. The temperature difference changed, the flow changed, and the pressure changed. How one distinguishes which error contributes more from these measurements is never explained by Weisend[3] or Burgett.[4]

The reported uncertainties do not represent the combined error in the measurements of flow, pressure, and temperature but represent a qualitative type of uncertainty. A more quantitative type of analysis follows.

UNCERTAINTY ANALYSIS

A proper uncertainty analysis should take into account the contribution of each component to the overall uncertainty.[6-8] Following the analysis given by ANSI/ASME,[6] the uncertainty of the calculated heat leak may be determined as;

$$\delta \underline{Q} = \sqrt{(\frac{\partial \underline{Q}}{\partial \dot{m}}\delta \dot{m})^2 + (\frac{\partial \underline{Q}}{\partial P_{in}}\delta P_{in})^2 + (\frac{\partial \underline{Q}}{\partial T_{in}}\delta T_{in})^2 + (\frac{\partial \underline{Q}}{\partial P_{out}}\delta P_{out})^2 + (\frac{\partial \underline{Q}}{\partial T_{out}}\delta T_{out})^2} \tag{6}$$

where

$$\frac{\partial \underline{Q}}{\partial \dot{m}} = h_{out} - h_{in} \tag{7}$$

$$\frac{\partial \underline{Q}}{\partial P_{in}} = -\dot{m}\frac{\partial h_{in}}{\partial P_{in}} \tag{8}$$

$$\frac{\partial \underline{Q}}{\partial T_{in}} = -\dot{m}\frac{\partial h_{in}}{\partial T_{in}} \tag{9}$$

$$\frac{\partial Q}{\partial P_{out}} = m\frac{\partial h_{out}}{\partial P_{out}} \tag{10}$$

$$\frac{\partial Q}{\partial T_{out}} = m\frac{\partial h_{out}}{\partial T_{out}} \tag{11}$$

The partial derivatives indicate the sensitivity of the overall uncertainty to the measured parameters.

To evaluate the total uncertainty of the heat leak, δQ, the uncertainty of the measured parameters, δT_{in}, δP_{in}, δT_{out}, δP_{out}, and δm must be determined from the accuracy of the instrumentation (ε) and the standard deviation (σ) of the measurements. These uncertainties are combined in a root sum squared fashion as shown in equation (12).

$$\delta T = \sqrt{\varepsilon_T^2 + (2\sigma_T)^2} \tag{12}$$

The use of two times the standard deviation (2σ) gives a confidence level of 95% in the measurements.

RESULTS

Using the above analysis, some of the ASST data was re-evaluated. The 4 K and 20 K data were taken on 12/10/92 from 0000 to 0230. The 80 K data were taken on 8/24/92. Listed in Table 2 are the measurement equipment and their inherent uncertainties. Shown in Tables 3, 4, and 5 are the ASST measurement data and their standard deviations. The uncertainties were combined using equation (12) and are also listed in the Tables.

The pressure used in the present calculations was the pressure measured at the feed can. The pressure drop for each line was estimated to be smaller than the accuracy of the pressure sensors and for most cases, it was. It would be impractical to measure a pressure drop using the present sensors. Therefore, the pressure was assumed to be constant at the feed can pressure.

Figures 1, 2, and 3 show the calculated heat leaks into each dipole and their calculated uncertainties. It is evident from Figure 1 that the measurement uncertainty is of the same order as the actual measurement for all dipoles except dipole 1. From Figures 2 and 3, it can be seen that the uncertainties in the 20 K and 80 K heat leaks are much smaller percentages of the average heat leak than the cold mass. However, the uncertainties are still significant.

Given in Table 6 are the average values across the three middle dipoles. When compared to Table 1, the average values are essentially the same. However, the uncertainties are much different. The 4 K and 20 K uncertainties are an order of magnitude greater than those in Table 1 and the 80 K uncertainty is about four times higher.

Also included is an analysis of the 4 K heat leak data supplied by Levin.[5] The data was taken as being the "true" values, i.e., no error was assumed in the temperature, pressure, and flow measurements. The data are shown in Table 7. The heat leak across dipoles 2, 3, and 4 were averaged and the standard deviation was calculated. The result is shown in Table 8. The average value was 1.36 watts with a standard deviation of 0.934 watts. This is for a 67% confidence level (1σ). For a 95% confidence level (2σ), the uncertainty would be 1.868 watts.

CONCLUSION

The dipole magnet heat leaks previously reported[3,4] are the only official estimates at this time. Based on standard uncertainty calculation methods, the uncertainties of the dipole heat leaks are much higher than previously reported. It is not correct to determine the heat leak uncertainty solely on

temperature considerations without proper combination of the other measured parameter uncertainties. The uncertainties reported in this paper are the minimum dipole heat leak uncertainties expected from the ASST measurements with the current instrumentation. Because of the large uncertainties in the heat leak values, no conclusion can be made regarding the load on the cryogenic plants at this time.

RECOMMENDATIONS

It is recommended for future testing that an error analysis, as specified by ANSI/ASME,[6] be performed prior to conducting the experiment and be used to direct the measurement techniques and data reduction. It is recommended that differential measurements of temperature and pressure be made as opposed to absolute measurements due to the small temperature and pressure differences involved.

NOMENCLATURE

h = enthalpy (J/g)
$\dot{m}$ = mass flow rate (g/s)
P = pressure (bar)
Q = heat leak (W)
T = temperature (K)
ε = absolute instrument uncertainty
σ = standard deviation of data
Δh = enthalpy difference (J/g)
δm = total measurement uncertainty for mass flow rate (g/s)
δP = total measurement uncertainty for pressure (bar)
δT = total measurement uncertainty for temperature (K)
δQ = total uncertainty in the calculated heat leak (W)

Subscripts

h = heater
in = inlet
out = outlet
T = temperature
w = with heater
wo = without heater
2 = dipole two
5 = dipole five

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2. CRYODATA, Inc., *HEPAK User's Guide*, version 2.2, Niwot, Colorado, (1990).

3. J. Weisend, et. al., "Heat Leak Performance of SSC Collider Dipole Magnets," SSCL-Preprint-508, September (1993).

4. W. Burgett, et. al., "Cryogenic Characteristics of the SSC Accelerator Systems String Test (ASST)", To be published in *Supercollider 5*, Plenum Press, New York, (1993).

5. M. Levin, Private Communication

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7. R. J. Moffat, "Describing the Uncertainties in Experimental Results", *Experimental Thermal and Fluid Science*, Elsevier Science Publishing Co., New York, pp. 3-17, (1988).

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Table 1: Previously Reported Dipole Magnet Cryostat Measured Heat Leaks from ASST and Uncertainties.[2,3]

	Run 1 (watts)	Run 2 (watts)	Uncertainty (watts)	Budget (watts)
Cold Mass	1.3	1.4	+/- 0.405	0.36
20 K Shield	N/A	5.59	+/- 0.112	5.06
80 K Shield	28.	24.5	+/- 3.94	37.

Table 2: Instrument Accuracy's.

	Temperature (K)[A]	Pressure (bar)[B]	Flow[C]
	Accuracy[D]	Accuracy	Accuracy[E]
4 K Cold Mass	0.0025	0.038	2%
20 K Tubes	0.0150	0.038	1%
80 K Tubes	0.5000	0.038	1%

A 4 K: Carbon-Glass Resistor
20 K: Germanium Resistor
80 K: Platinum Resistance Thermometer

B All are Setra Model 204E Pressure Transducers

C 4 K: Venturi
20 K: Diaphragm Meter
80 K: Diaphragm Meter

D Accuracy's given by Wiesand[3] and Burgett.[4]

E Percent of measured value.

Table 3: 4 K ASST Data and Uncertainties (12/10/92).

P (bar)	4.167	m (g/s)	51.19	
2*σ (bar)	0.008	2*σ (g/s)	2.28	
ε (bar)	0.038	ε (g/s)	1.02	
δP (bar)	0.039	δm (g/s)	2.50	
Sensor Location	Temperature (K)	2*σ (K)	ε (K)	δT (K)
Feed Can	4.6408	0.0035	0.0025	0.0043
Inlet Dipole 1	4.6935	0.0020	0.0025	0.0032
Inlet Dipole 2	4.7348	0.0019	0.0025	0.0031
Inlet Dipole 3	4.7427	0.0025	0.0025	0.0035
Inlet Dipole 4	4.7436	0.0016	0.0025	0.0029
Inlet Dipole 5	4.7498	0.0014	0.0025	0.0029
Spool	4.7601	0.0029	0.0025	0.0038

Table 4: 20 K ASST Data and Uncertainties (12/10/92).

P (bar)	1.124	m (g/s)	1.01
2*σ (bar)	0.001	2*σ (g/s)	0.15
ε (bar)	0.038	ε (g/s)	0.01
δP (bar)	0.038	δm (g/s)	0.15

Sensor Location	Temperature (K)	2*σ (K)	ε (K)	δT (K)
Feed Can	23.461	0.060	0.015	0.062
Inlet Dipole 1	20.341	0.050	0.015	0.052
Outlet Dipole 1	18.280	0.051	0.015	0.053
Outlet Dipole 2	17.333	0.049	0.015	0.051
Inlet Dipole 3	16.596	0.052	0.015	0.054
Outlet Dipole 3	16.333	0.053	0.015	0.055
Inlet Dipole 4	16.208	0.054	0.015	0.056
Outlet Dipole 4	15.206	0.060	0.015	0.062
Inlet Dipole 5	15.097	0.059	0.015	0.061
Outlet Dipole 5	14.356	0.063	0.015	0.065
End Can	9.467	0.066	0.015	0.068

Table 5: 80 K ASST Data and Uncertainties (8/24/92).

P (bar)	1.59	m (g/s)	15.13
2*σ (bar)	0.10	2*σ (g/s)	1.02
ε (bar)	0.04	ε (g/s)	0.15
δP (bar)	0.11	δm (g/s)	1.03

Sensor Location	Temp (K)	2*σ (K)	ε (K)	δT (K)
Feed Can	99.01	0.44	0.50	0.67
Inlet Dipole 1	99.30	0.38	0.50	0.63
Outlet Dipole 1	100.95	0.16	0.50	0.53
Inlet Dipole 2	101.06	0.16	0.50	0.52
Inlet Dipole 3	102.89	0.11	0.50	0.51
Outlet Dipole 3	104.58	0.07	0.50	0.50
Inlet Dipole 4	104.89	0.07	0.50	0.50
Outlet Dipole 4	105.78	0.13	0.50	0.52
Inlet Dipole 5	106.36	0.13	0.50	0.52
Outlet Dipole 5	107.60	0.30	0.50	0.58
Inlet Quad 1	109.91	0.37	0.50	0.62
Outlet Quad 1	110.70	0.41	0.50	0.65
End Can	112.92	0.50	0.50	0.71

Table 6: Dipole Magnet Cryostat Heat Leaks and Uncertainties.

	Heat Leak (watts)	Uncertainty (watts)
Cold Mass	1.3	+/- 1.4
20 K Shield	5.7	+/- 1.0
80 K Shield	29.6	+/- 12.6

Table 7: Data given by Levin.[5]

Date	Dipole 1	Dipole 2	Dipole 3	Dipole 4	Dipole 5
	(watts)	(watts)	(watts)	(watts)	(watts)
11/15/93	8.53	2.56	0.21	1.49	1.71
11/17/93	8.5	2.7	0.41	1.45	1.87
12/08/92	8.73	2.46	0.07	1.28	2.24
12/10/93	10.08	1.97	0.25	1.48	2.46
12/12/92	8.97	2.55	0.14	1.56	2.36
12/15/92	9.19	2.16	0.25	1.49	2.3

Table 8: Statistics for Dipoles 2, 3, and 4 using Data from Table 7.

Average Heat Leak (watts)	1.360
σ (watts)	0.934
$2*\sigma$ (watts)	1.867

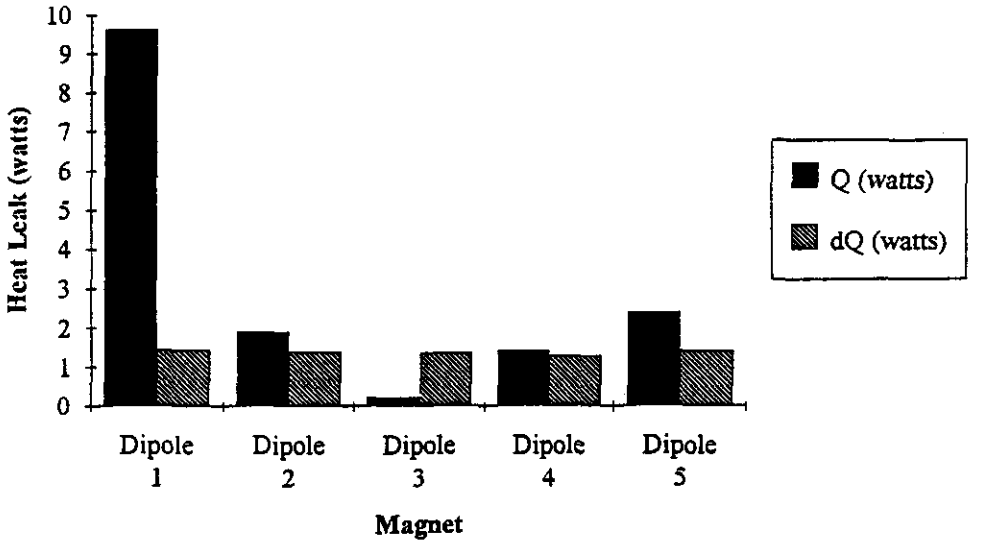

Figure 1: 4 K Dipole Heat Leaks

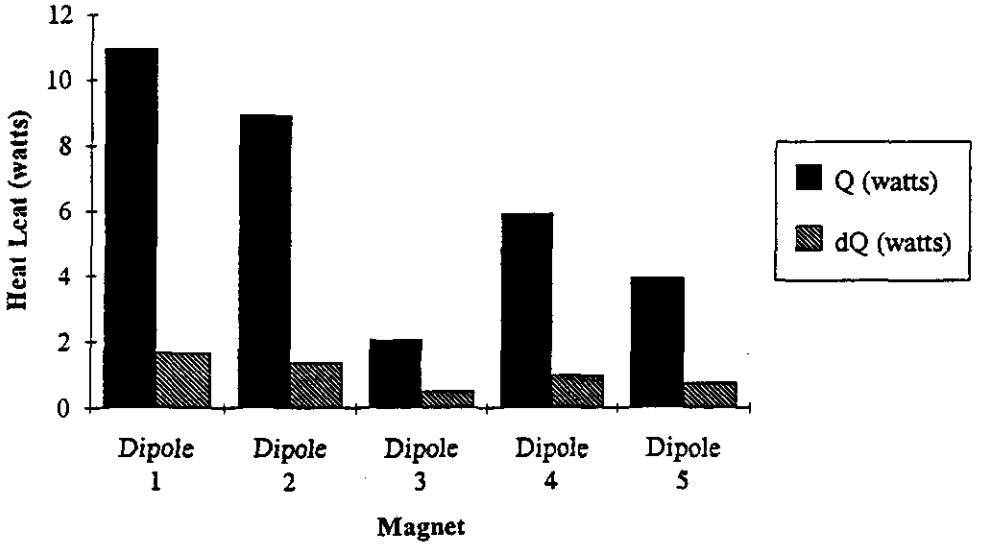

Figure 2: 20 K Dipole Heat Leaks

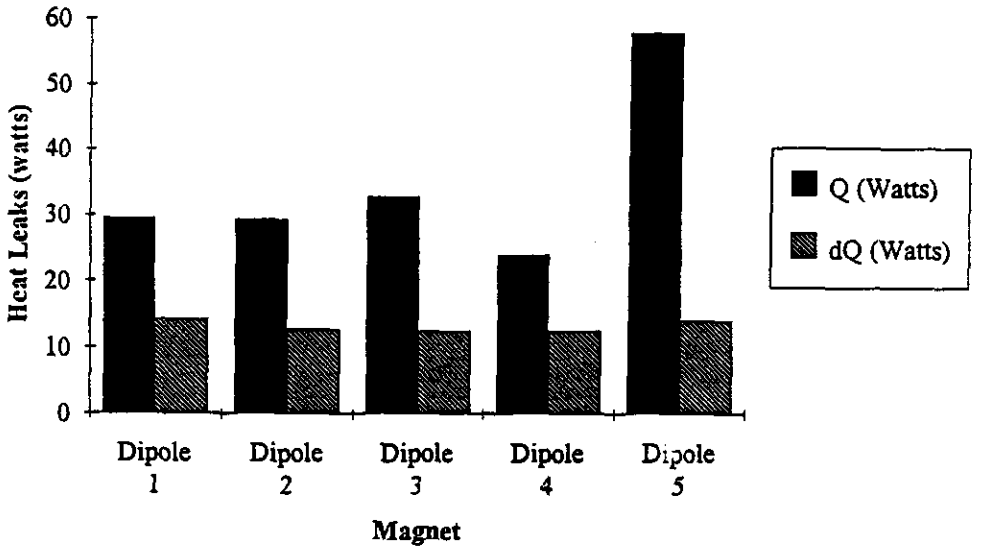

Figure 3: 80 K Dipole Heat Leaks