BNL-101885-2014-TECH

AD/RHIC/RD/102;BNL-101885-2013-IR

Performance of RHIC Refrigerator IV: Heat Exchangers

K. C. Wu

May 1996

Collider Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

DISCLAIMER

AD/RHIC/RD-102

RHIC PROJECT

Brookhaven National Laboratory

Performance of RHIC Refrigerator IV: Heat Exchangers

K. C. Wu

May 1996

PERFORMANCE OF RHIC REFRIGERATOR IV: HEAT EXCHANGERS

K. C. WU

ABSTRACT

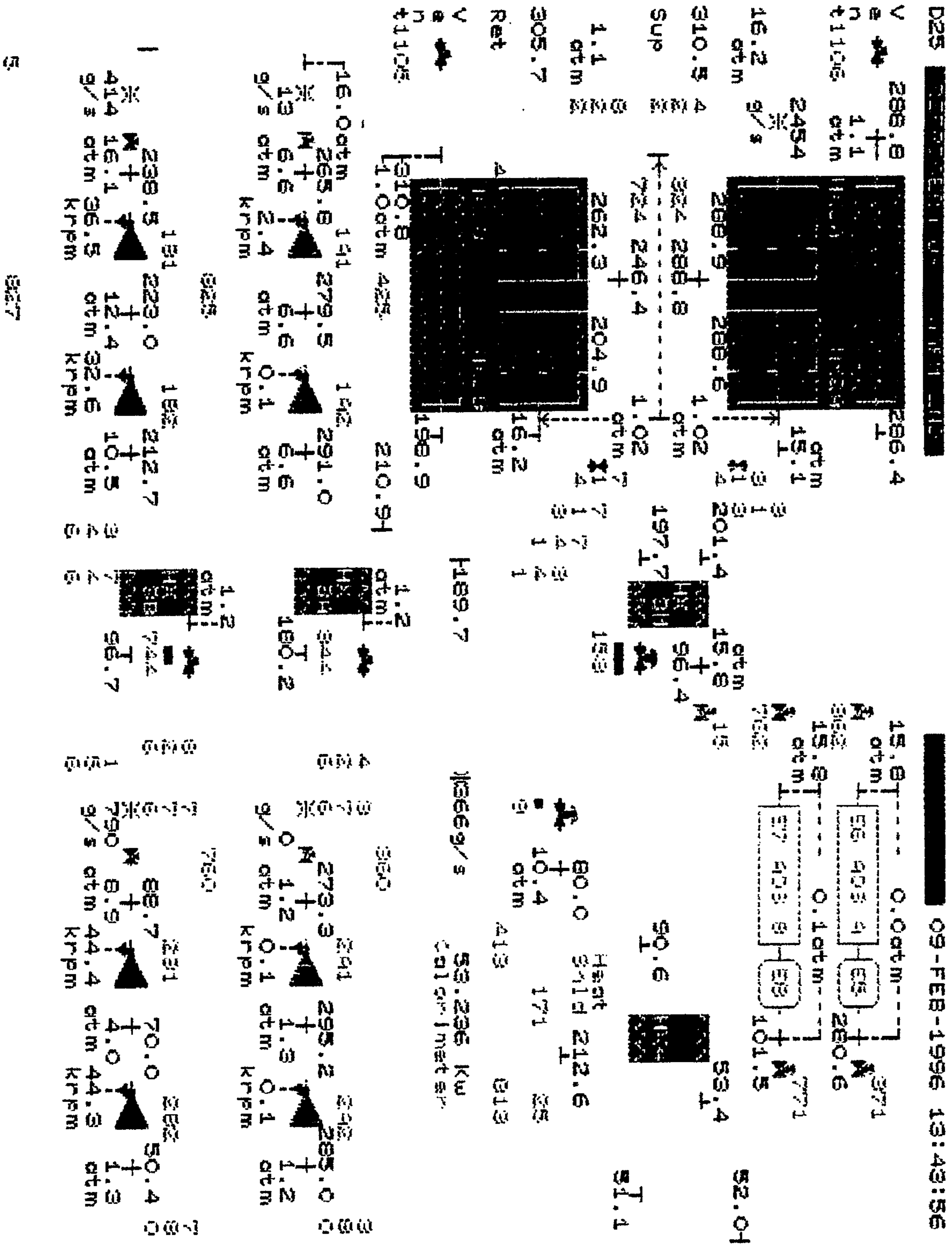
In February 1996, the RHIC Refrigerator was successfully cooled to liquid helium temperature with 10 kilowatts of heat input at 4.5 K, 53 kilowatts of heat input at 60 K and 44 grams per second of liquid extraction. A comprehensive analysis was performed to evaluate the performance of the refrigerator including the turbines, the cold vacuum compressor and the heat exchangers. Because of the amount of data and the number of charts involved, the report is divided into five technical notes on, respectively: 1). Flowmeters, 2). Turbines, 3). Cold Vacuum Compressor, 4). Heat Exchangers and 5). Refrigerator Overall Performance. This technical note presents the performance of the Heat Exchangers.

I. INTRODUCTION

Heat exchangers and the turbines are two major components in a helium refrigerator. The turbines are used to generate cooling and the heat exchangers are used for cooling recovery. The performance of both the turbines and the heat exchangers is important to the helium refrigerator. Deterioration in the performance of the heat exchangers from flow maldistribution or contamination could significantly reduce the capacity of the refrigerator. The heat exchangers were previously found to perform satisfactorily during the 1984 refrigerator acceptance tests for the proposed ISABELLE machine. For RHIC, the helium flow through these heat exchangers is smaller. The main purposes of the present study are: 1) to demonstrate that heat exchangers which were originally sized for the ISABELLE machine are suitable for RHIC and 2) to present quantitative results for these heat exchangers that were not documented after the 1984 refrigerator run.

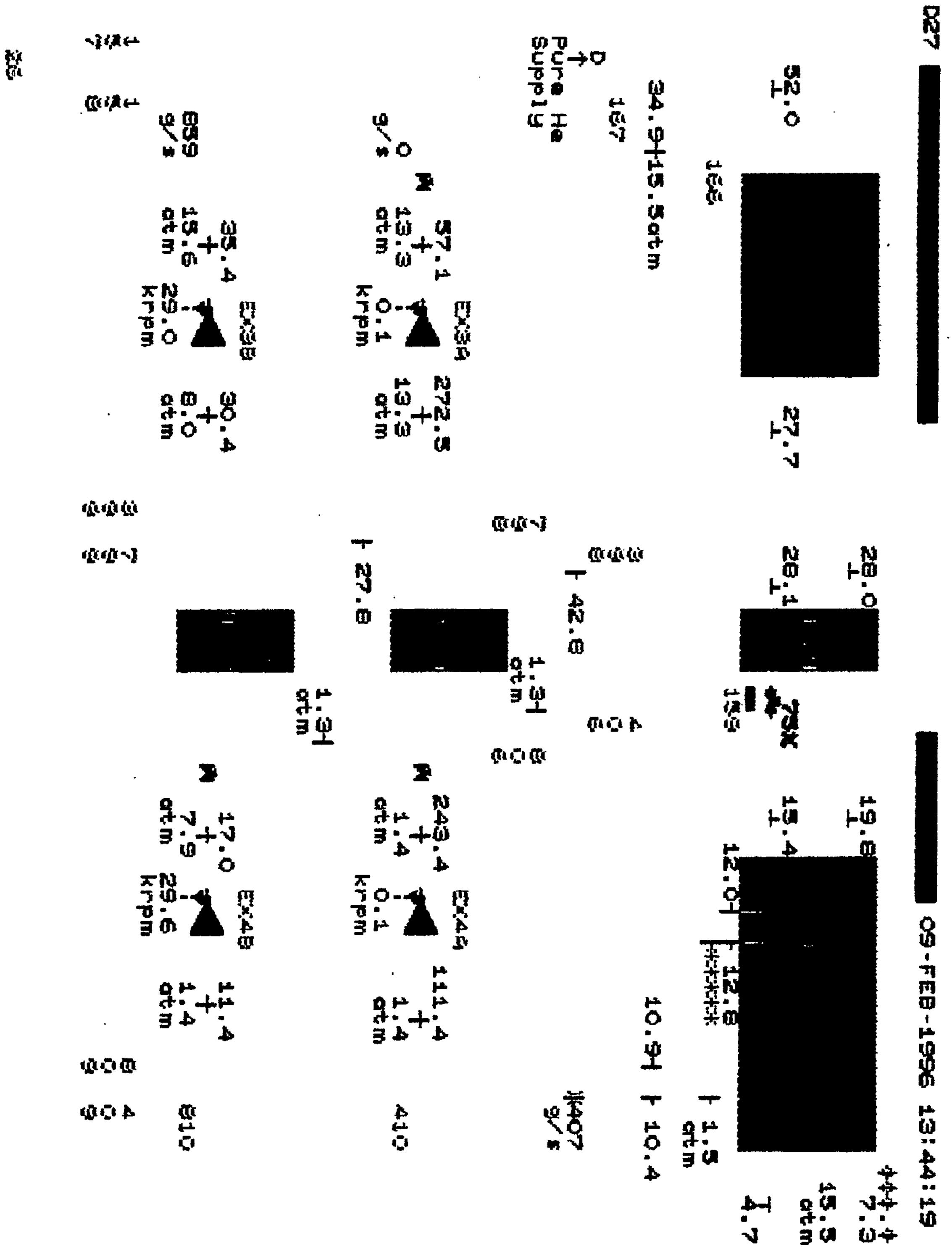
II. OVERVIEW

As shown in Figures 1 and 2, counter flow heat exchangers HX 1 to HX 9 are used to cool the high pressure helium utilizing the low pressure cold return helium. Figure 1 and 2 are identified, respectively, as the warm section and the middle section of the RHIC refrigerator. The cold end of the RHIC refrigerator is shown in Figure 3.



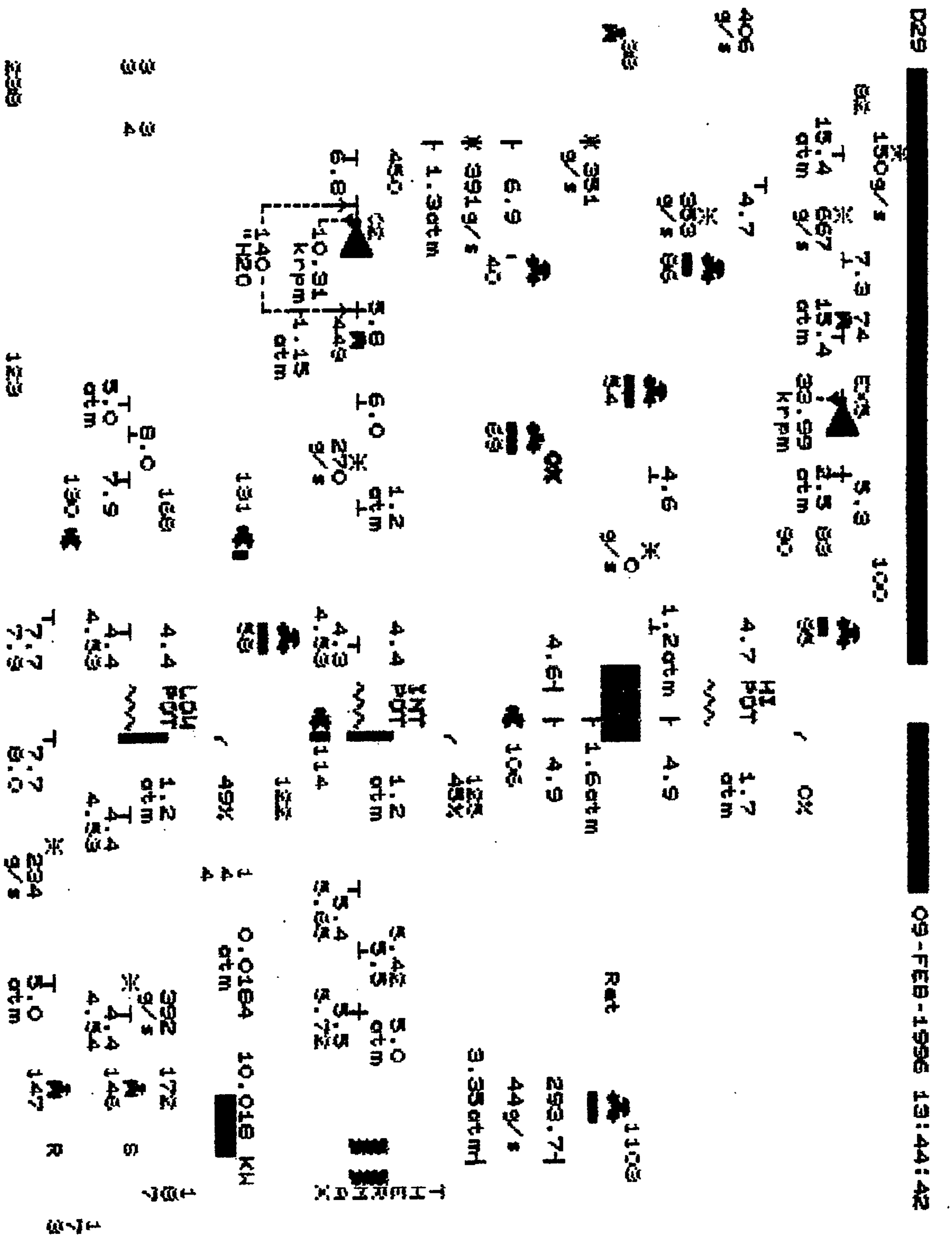
Screen 25, from CRT1, 09-FEB-96 14:02:45 Refrigerator - Warm End

FIGURE 1. WARM END OF RHIC REFRIGERATOR



Screen 27, from CRT1, 09-FEB-96 14:03:08 Refrigerator - Middle

FIGURE 2. MIDDLE SECTION OF RHIC REFRIGERATOR



Screen 29, from CRT1, 09-FEB-96 14:03:32 Refrigerator - Cold End

FIGURE 3. COLD END OF RHIC REFRIGERATOR

Normally both the heat transfer rate and pressure drop must be evaluated simultaneously to determine the performance of a heat exchanger. Since the pressure drops are small, only the heat transfer rates are analyzed. Three parameters, the Effectiveness, AU and NTU, as defined in the following paragraphs, are considered.

The Heat Exchanger Effectiveness is defined as the ratio of the actual heat transfer rate from one stream to the other stream in a given heat exchanger to a thermodynamically limited maximum possible heat transfer rate. It is equivalent to the efficiency of the heat exchanger in an operating condition.

AU is the product of the heat transfer area and the overall heat transfer conductance. AU depends on both the flow rates and the operating conditions. AU can be calculated from the ratio of the heat transfer rate and the log mean temperature difference. A heat exchanger is often rated by AU.

NTU, number of transfer unit, is defined as the ratio of AU to the minimum product of the specific heat and flow. NTU designates the dimensionless "heat transfer size" of the exchanger. For evaluating the performance of a heat exchanger with a large variation of operating flows, NTU is a more suitable parameter to be examined than AU.

The Effectiveness, AU and NTU are commonly related to the Heat Capacity Rate Ratio, C_{min} / C_{max}, which is the ratio of the smaller to the larger heat capacity rate for the two flows in the heat exchanger. The calculations for the above mentioned quantities are straight forward provided the flow rates and the terminal temperatures are known. Unfortunately in the refrigerator, flowmeters are mainly installed in lines connected to the turbines and not directly to the heat exchangers. The flows through the heat exchangers must be obtained by adding or subtracting flows from other parts of the refrigerator. Liquefaction of helium, flow leakage and the long time constant to reach quasi-steady operation all contribute some uncertainties to the flow calculation.

In addition, while the temperature sensors installed in the refrigerator are adequate for the operation of the refrigerator, they are not accurate enough for determining the small temperature differences required for precise analysis. Occasionally inaccuracies in temperature measurements lead to a violation of 2nd Law of Thermodynamics.

For this reason, calculated temperatures are used as described in Section III for the temperatures between HX 6, HX 7M and HX 8 for the heat exchanger evaluations. The flow calculation is given in Section IV. The performance of the heat exchangers and a brief description of the calculating procedure are given in Sections V to VIII. Large uncertainties associated with the results are expected.

III. TEMPERATURE READINGS ASSOCIATED WITH HX 6, HX 7 AND HX 8

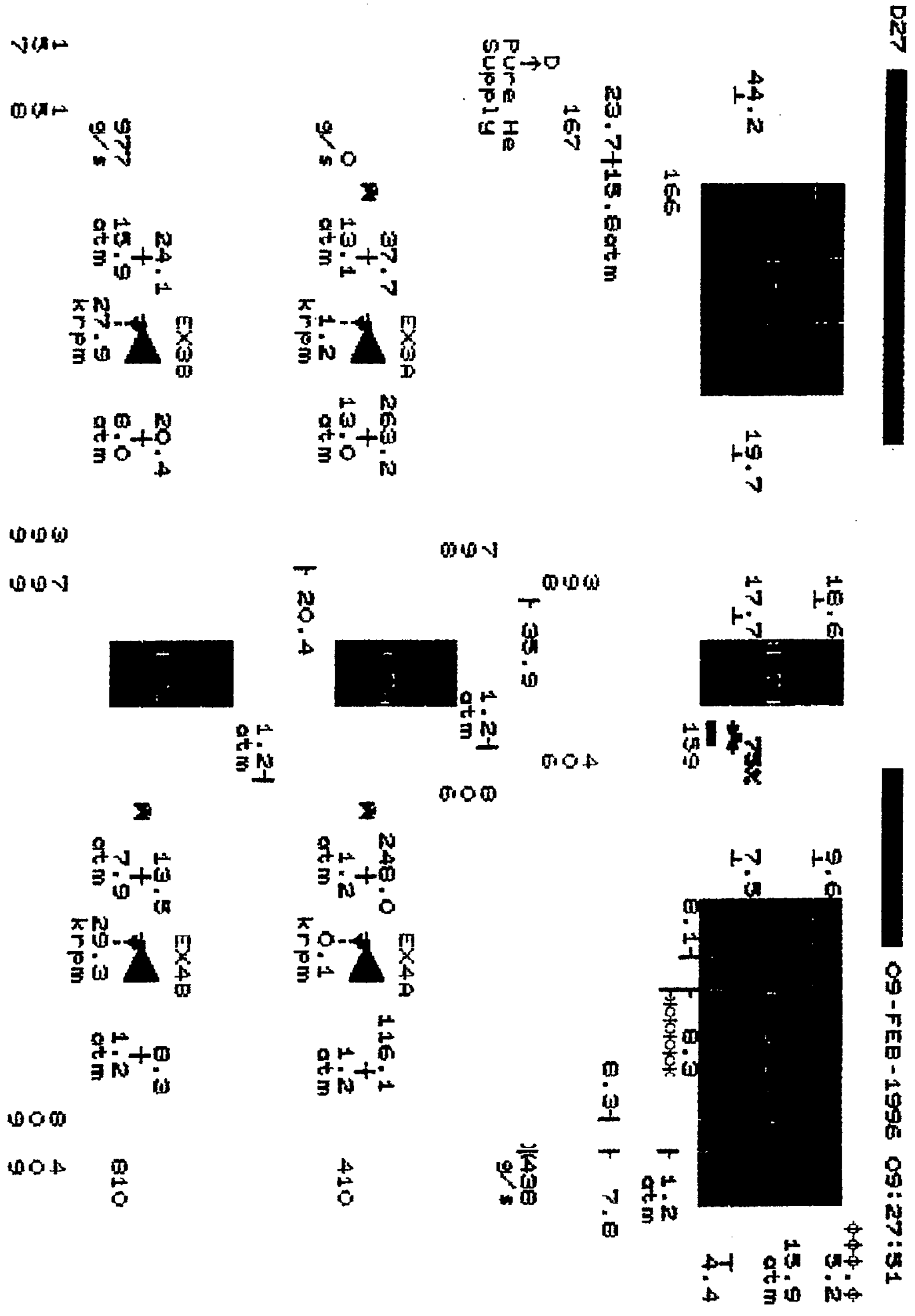
As an example to illustrate the inadequate temperature measurements, the process conditions in the middle section of the refrigerator at time 9:27, February 9, are given in Figures 4. As can be seen, the temperature at the high pressure exit from HX 6 is 18.6 K. The temperature at the low pressure inlet side of HX 6 is 19.7 K. Since the high pressure exit temperature must be greater than the low pressure inlet temperature in the heat exchanger, either one temperature sensor is not accurate or both temperature sensors have large errors. In this report, temperature readings are assumed accurate and used "as is" with the following two exceptions.

The temperature reading at the high pressure side between HX 6 and HX 7M is discarded and is replaced by a calculated value from the energy balance of HX 7M, HX 7B and HX 8/18/9.

The temperature sensor installed at the low pressure side between HX 7M and HX 8 reads low as compared to the temperature reading between HX 8 and HX 18 as shown in Figure 4. This temperature reading is replaced by a calculated value from the energy balance of HX 7M and HX 7B.

IV. FLOW CALCULATIONS

The flow calculations start from the cold end and progress toward the warm end of the refrigerator. By adding or subtracting flow through the turbines and return lines, the flow through the heat exchangers is obtained. The flow splits associated with HX 7M and HX 7B, and HX 3M and HX 3B are calculated from the energy balance. Leakage and liquefaction of helium are ignored. Detailed descriptions are given in each of the following sections.



Screen 27, from CRT1, 09-FEB-96 09:46:41 Refrigerator - Middle

FIGURE 4. EXAMPLE OF INADEQUATE TEMPERATURE MEASUREMENTS IN HX6, HX7 AND HX8

V. HEAT EXCHANGER HX 8, HX 18 AND HX 9

Heat exchangers 8, 18 and 9 are packaged in one core as shown in Figure 2. There is a temperature sensor installed in each line connected externally to the heat exchangers. There are no temperature sensors installed at the high pressure side between HX 8 and HX 18 and between HX 18 and HX 9. These two temperatures are calculated from the energy balances of HX 9 and HX 18 respectively.

The flow through the high pressure side of these heat exchangers is obtained from flow through Turbine 5 (EX 5) and make up flow in the cold end of the refrigerator as shown in Figure 3. The flow through the low pressure side of these heat exchangers is obtained from the cold end of the refrigerator and flow through Turbine 4B (EX 4B) as shown in Figure 2.

The Effectivenesses, AUs, NTUs and C_{min} / C_{max}s for HX 8, HX 18 and HX 9 are given in Table 1. The AU and NTU for process calculations for the RHIC refrigerator given in RHIC Design MANUAL, for a heat load of 11500 watts at 4.5 K, and for the original values specified for ISABELLE are also shown for reference.

As shown from Table 1, there is a large variation in the requirement for AU and NTU among the two calculated RHIC cases and the ISABELLE case.

As shown in Table 1, the Effectivenesses for all three heat exchangers in most cases are greater than 0.8 and exceed 0.9 in many cases. The NTU values are also close to the projected RHIC requirements. The AUs for HX 8 and HX 9 but not for HX 18 exceed the required value for RHIC at 11500 watts heat load. The total AUs of the HX 8, HX 18 and HX 9 are fairly close to the total required AUs. Considering the uncertainties associated with the low temperature measurements and the numerical sensitivity of the calculation to the temperature differences, these results are reasonable. In Table 1, some data were discarded because they led to a violation of the 2nd Law of Thermodynamics.

It should be noted that it is not necessary to have the AU of every heat exchanger exceed its design value. The lack of AU in a heat exchanger is often compensated for by a neighboring heat exchanger in a refrigerator.

Table 1. Performance of Heat Exchangers 8, 18 and 9

HX8				HX18				HX9			
AU kW/K	Ntu	Effectiveness	C_{min} / C_{max}	AU kW/K	Ntu	Effectiveness	C_{min} / C_{max}	AU kW/K	Ntu	Effectiveness	C_{min} / C_{max}
ISABELLE Design spec.				**ISABELLE Design spec.**				**ISABELLE Design spec.**			
22.7	**2.3**			**45.4**	**5.1**			**8.2**	**3.10**		
RHIC Design Manual				**RHIC Design Manual**				**RHIC Design Manual**			
13.9	**3.1**			**14.0**	**4.7**			**3.1**	**1.69**		
RHIC at 11500 W				**RHIC at 11500 W**				**RHIC at 11500 W**			
4.1	**0.48**			**64.4**	**7.9**			**13.8**	**3.88**		
Present Test				**Present Test**				**Present Test**			
16.1	2.37	0.782	0.709	2.7	0.37	0.269	0.994	10.8	3.07	0.862	0.582
22.8	3.54	0.874	0.692	26.0	3.57	0.811	0.902	20.4	4.52	0.907	0.696
14.5	2.22	0.769	0.686	22.1	3.05	0.794	0.851	18.9	3.73	0.851	0.787
21.1	3.42	0.874	0.684	35.1	5.03	0.868	0.899	18.8	4.36	0.896	0.716
16.3	2.76	0.819	0.664	30.9	4.68	0.874	0.842	17.4	3.99	0.874	0.744
16.5	3.27	0.868	0.625	63.7	11.24	0.974	0.814	17.6	5.37	0.919	0.748
14.1	2.91	0.840	0.611	N.A.	N.A.	N.A.	N.A.	17.1	5.70	0.923	0.764
9.3	1.80	0.709	0.578	11.3	2.26	0.780	0.631	13.9	4.56	0.871	0.839
N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	15.8	10.16	0.951	0.885
11.4	3.78	0.909	0.306	N.A.	N.A.	N.A.	N.A.	11.7	5.42	0.860	0.954
N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
27.7	3.22	0.844	0.731	53.4	5.63	0.868	0.945	23.7	3.72	0.876	0.685
27.0	3.12	0.848	0.752	31.9	3.95	0.848	0.836	20.6	5.23	0.963	0.495

VI. HEAT EXCHANGERS HX 7M AND HX 7B

The temperature correction at the high pressure side between HX 6 and HX 7M has been described in Section III. The high pressure flow through HX 7B equals the flow through Turbine 3B. The flow through the low pressure side of HX 7B is calculated from the energy balance of HX 7B. The flow through the low pressure side of HX 7M equals that through HX 8 minus that through HX 7B. The flow through the high pressure side of HX 7M equals that through HX 8.

The Effectivenesses, AUs, NTUs and C_{min} / C_{max}s for HX 7M and HX 7B are given in Table 2. The AU and NTU for process calculations for the RHIC refrigerator given in RHIC Design MANUAL, for a heat load of 11500 watts at 4.5 K, and for the original values specified for ISABELLE are also shown for reference.

As shown from Table 2, there is a large variation in the requirement of AU and NTU among the two calculated RHIC cases and the ISABELLE case. Generally speaking the ISABELLE case requires a larger AU because of a larger flow rate.

For heat exchanger HX 7B, the AUs are lower than the ISABELLE design specified primarily due to a lower flow. The AUs exceed the process calculation for RHIC. The NTUs exceed the projected RHIC values in most cases and are slightly lower than the original ISABELLE design specification. The Effectivenesses are all in the range between 0.9 and 0.99.

For heat exchanger HX 7M, the AUs, NTUs and Effectivenesses are all low due primarily to an over correction on the high pressure inlet temperature. Using the direct temperature reading and ignoring process data that violate the 2nd Law of Thermodynamics, the AUs , NTUs and Effectivenesses are all much greater and would then exceed the projected RHIC requirement as shown in the far right in Table 2. The actual AU, NTU and Effectiveness for HX 7M are probably between the values calculated with and without temperature corrections.

In Table 2, some data are discarded because they violate the 2nd Law of Thermodynamics. The overall performance of HX 7M and HX 7B is quite good.

Table 2. Performance of Heat Exchangers 7M and 7B

Temperature modified HX7M				HX7B				No modification on Temperature HX7M		
AU kW/K	Ntu	Effectiveness	C_{min} / C_{max}	AU kW/K	Ntu	Effectiveness	C_{min} / C_{max}	AU kW/K	Ntu	Effectiveness
ISABELLE Design spec.				**ISABELLE Design spec.**				**ISABELLE Design spec.**		
103	**13.8**			**110**	**13.7**			**103.0**	**13.80**	
RHIC Design Manual				**RHIC Design Manual**				**RHIC Design Manual**		
26.6	**7.96**			**31.0**	**7.95**			**26.6**	**7.96**	
RHIC at 11500 W				**RHIC at 11500 W**				**RHIC at 11500 W**		
43.4	**6.78**			**35.9**	**6.75**			**43.4**	**6.78**	
Present Test				**Present Test**				**Present Test**		
28.4	5.89	0.914	0.814	46.1	10.60	0.921	0.982	59.9	12.55	0.992
23.8	4.81	0.877	0.845	36.7	8.75	0.898	0.999	53.1	10.83	0.990
22.8	4.63	0.879	0.818	37.9	8.76	0.906	0.979	N.A.	N.A.	N.A.
32.1	7.38	0.951	0.771	42.8	10.19	0.936	0.933	N.A.	N.A.	N.A.
26.8	6.04	0.918	0.813	41.8	9.81	0.913	0.986	N.A.	N.A.	N.A.
33.3	8.42	0.937	0.875	47.0	11.96	0.955	0.912	N.A.	N.A.	N.A.
32.1	8.03	0.916	0.928	43.4	11.51	0.969	0.847	N.A.	N.A.	N.A.
29.0	6.78	0.910	0.889	38.5	10.08	0.985	0.697	N.A.	N.A.	N.A.
18.7	6.45	0.965	0.621	30.7	8.51	0.991	0.542	N.A.	N.A.	N.A.
20.9	7.13	0.977	0.595	30.2	8.19	0.990	0.524	N.A.	N.A.	N.A.
19.8	6.97	0.975	0.593	29.5	8.23	0.990	0.525	N.A.	N.A.	N.A.
20.0	6.92	0.973	0.607	31.2	8.40	0.990	0.539	N.A.	N.A.	N.A.
24.6	6.75	0.964	0.654	29.9	8.14	0.990	0.519	N.A.	N.A.	N.A.
21.3	7.05	0.954	0.734	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
23.8	7.60	0.956	0.760	33.7	9.93	0.992	0.614	N.A.	N.A.	N.A.
23.4	7.38	0.950	0.776	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
50.6	8.59	0.970	0.741	54.5	11.48	0.972	0.835	50.6	8.82	0.964
58.6	10.20	0.980	0.746	51.9	10.84	0.958	0.877	70.7	12.42	0.982

VII. HEAT EXCHANGERS HX 5 AND HX 6

Heat exchangers HX 5 and HX 6 are packaged in one core as shown in Figure 2. There are temperature sensors installed in the lines connected to this heat exchanger assembly. There are no temperature sensors at the low pressure side between HX 5 and HX 6. This temperature is calculated from the energy balance of HX 6 in the following analysis.

The flow through the high pressure side of HX 6 equals that through HX 8. The flow through HX 5 equals the sum of those through HX 6 and Turbine 3B shown as EX 3B in Figure 2. The flow through the low pressure side of these heat exchangers equals that through HX 8.

The Effectivenesses, AUs, NTUs and C_{min} / C_{max}s for HX 5 and HX 6 are given in Table 3. The AU and NTU for process calculations of the RHIC refrigerator given in RHIC Design MANUAL, for a heat load of 11500 watts at 4.5 K, and for the original values specified for ISABELLE are also shown for reference.

As shown from Table 3, there is a large variation in the requirement of AU and NTU among the two calculated RHIC cases and the ISABELLE case. Generally speaking the ISABELLE case requires a larger AU because of a larger flow rate.

For heat exchanger HX 5, the AUs are slightly less than the projected requirement for RHIC and are lower than the ISABELLE design value primarily due to a lower flow. The NTUs are close to both RHIC and ISABELLE values and the Effectivenesses all exceed 0.93.

For heat exchanger HX 6, the AUs, NTUs and Effectivenesses are all low due primarily to the over correction of the high pressure exit temperature. Using the direct temperature reading and ignoring process data which violate the 2nd Law of Thermodynamics, the AUs, NTUs and Effectivenesses are all greater than the specification as shown to the far right in Table 3. The real AUs, NTUs and Effectivenesses for HX 6 are probably between the values calculated with and without temperature corrections.

In Table 3, some data are discarded because they violate the 2nd Law of Thermodynamics. The performance of HX 5 and HX 6 is good.

Table 3. Performance of Heat Exchangers 5 and 6

HX5				Temperature modified HX6				No modification on Temperature HX6		
AU kW/K	Ntu	Effectiveness	C_{min} / C_{max}	AU kW/K	Ntu	Effectiveness	C_{min} / C_{max}	AU kW/K	Ntu	Effectiveness
ISABELLE Design spec.				**ISABELLE Design spec.**				**ISABELLE Design spec.**		
159	**10.5**			**45.1**	**5.5**			**45.1**	**5.50**	
RHIC Design Manual				**RHIC Design Manual**				**RHIC Design Manual**		
94.9	**13.4**			**12.7**	**3.38**			**12.7**	**3.38**	
RHIC at 11500 W				**RHIC at 11500 W**				**RHIC at 11500 W**		
103	**8.97**			**17.5**	**2.54**			**17.5**	**2.54**	
Present Test				**Present Test**				**Present Test**		
64.5	7.05	0.934	0.950	11.5	2.05	0.759	0.611	39.8	7.08	0.964
62.5	6.89	0.940	0.947	9.3	1.66	0.699	0.616	40.3	7.17	0.964
69.8	7.55	0.940	0.943	10.3	1.79	0.720	0.621	51.9	8.98	0.983
75.2	8.58	0.943	0.940	17.0	3.15	0.860	0.613	49.5	9.17	0.982
66.2	7.63	0.931	0.941	12.4	2.38	0.799	0.599	46.1	8.81	0.981
61.0	7.83	0.935	0.936	8.7	2.04	0.771	0.547	N.A.	N.A.	N.A.
59.8	7.78	0.935	0.932	5.9	1.46	0.678	0.526	N.A.	N.A.	N.A.
64.4	7.58	0.947	0.934	2.1	0.54	0.383	0.464	N.A.	N.A.	N.A.
68.4	8.49	0.952	0.922	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
83.7	10.05	0.956	0.925	0.3	0.09	0.089	0.320	N.A.	N.A.	N.A.
78.4	9.63	0.953	0.926	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
81.3	9.90	0.955	0.925	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
89.3	9.97	0.951	0.926	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
75.3	10.20	0.953	0.926	0.2	0.06	0.054	0.377	N.A.	N.A.	N.A.
73.5	9.98	0.955	0.927	0.7	0.23	0.198	0.385	N.A.	N.A.	N.A.
66.9	9.15	0.946	0.929	0.3	0.09	0.088	0.397	N.A.	N.A.	N.A.
114.9	10.03	0.934	0.953	53.0	6.95	0.965	0.663	53.6	7.03	0.958
111.2	10.08	0.931	0.953	48.7	6.71	0.963	0.655	57.6	7.93	0.969

VIII. HEAT EXCHANGERS HX 3M, HX 3B AND HX 4

Heat exchangers 3M, 3B and 4 are shown in Figure 1. The terminal temperatures of these heat exchangers are available and appear to be reasonable. There is some uncertainty in the temperature at the high pressure inlet of HX 4 as some flow from HX 3M passes through the Adsorber Bed.

The flow through the high pressure side of HX 3M and HX 4 equals that through HX 5 plus flow through the Shield Calorimeter. The flow through the high pressure side of HX 3B equals that through Turbine 1B2 (1B2) as shown in Figure 1. The flow through the low pressure side of HX 4 equals that through HX 5 plus flow through Turbine 2B2 (2B2). The flow through the low pressure side of HX 3B is calculated from the energy balance of HX 3B. The flow through the low pressure side of HX 3M equals that through HX 4 minus the flow through HX 3B.

The Effectiveness Ratios, AUs, NTUs and C_{min} / C_{max}s for HX 3M, HX 3B and HX 4 are given in Table 4. The AU and NTU for process calculations of the RHIC refrigerator given in RHIC Design MANUAL, for a heat load of 11500 watts at 4.5 K, and for the original values specified for ISABELLE are also shown for reference.

As shown from Table 4, there is a large variation in the requirement of AU among the two calculated RHIC cases and the ISABELLE case. Generally speaking the ISABELLE case requires a larger AU because of a larger flow rate.

For heat exchanger HX 3B, the AUs are lower than the ISABELLE design specified primarily due to a lower flow. The AUs are close to or exceed the projected process requirement for RHIC. The NTUs exceed both the projected RHIC value and the original ISABELLE design specification. The Effectivenesses exceed 0.98.

For heat exchanger HX 4, the AUs are lower than the ISABELLE design specified primarily due to a lower flow. The AUs are close to the projected process requirement for RHIC. The NTUs are very close to both the projected RHIC value and the original ISABELLE design specification. The Effectivenesses exceed 0.95.

For heat exchanger HX 3M, the AUs, NTUs and Effectivenesses are all low due to a larger than expected temperature difference. The NTUs are close to the original ISABELLE design specification.

Generally speaking, the performance of HX 3B, HX 4 and HX 3M is acceptable. The lack of AU in HX 3M maybe a result of a flow split between HX 3M and HX 3B. It is possible to enhance the performance of HX 3M by directing more flow through it and less flow through HX 3B.

Table 4. Performance of Heat Exchangers 3M, 3B and 4

HX3M				HX3B				HX4			
AU kW/K	Ntu	Effectiveness	C_{min} / C_{max}	AU kW/K	Ntu	Effectiveness	C_{min} / C_{max}	AU kW/K	Ntu	Effectiveness	C_{min} / C_{max}
ISABELLE Design spec.				**ISABELLE Design spec.**				**ISABELLE Design spec.**			
478	**28.2**			**91.6**	**27.9**			**225**	**12.7**		
RHIC Design Manual				**RHIC Design Manual**				**RHIC Design Manual**			
241	**26.0**			**81.3**	**25.7**			**114**	**11.6**		
RHIC at 11500 W				**RHIC at 11500 W**				**RHIC at 11500 W**			
458	**33.6**			**72.9**	**33.0**			**150**	**10.6**		
Present Test				**Present Test**				**Present Test**			
273	26.2	0.978	0.971	75.5	39.8	0.984	0.831	125	11.9	0.957	0.834
284	27.4	0.979	0.972	75.0	40.8	0.986	0.813	128	12.2	0.957	0.838
273	25.8	0.978	0.970	85.3	46.9	0.986	0.794	128	11.9	0.957	0.840
264	26.1	0.978	0.970	84.2	43.8	0.991	0.799	128	12.5	0.961	0.828
271	27.1	0.980	0.972	80.3	45.2	0.990	0.795	122	12.0	0.959	0.838
256	27.9	0.982	0.974	83.9	45.2	0.992	0.818	108	11.7	0.958	0.823
261	28.8	0.982	0.975	88.8	46.4	0.992	0.823	110	12.0	0.960	0.819
269	27.3	0.980	0.973	73.7	40.6	0.986	0.802	114	11.4	0.954	0.835
258	26.9	0.981	0.973	81.3	41.4	0.988	0.823	116	12.0	0.957	0.821
270	28.0	0.978	0.970	75.1	45.0	0.987	0.784	126	12.9	0.959	0.840
257	26.8	0.978	0.971	73.3	46.4	0.990	0.773	122	12.6	0.960	0.845
264	27.1	0.979	0.972	89.9	47.2	0.993	0.808	124	12.6	0.962	0.825
280	26.8	0.979	0.972	82.8	44.3	0.990	0.795	129	12.2	0.960	0.837
249	27.6	0.979	0.972	79.8	41.3	0.989	0.808	109	11.9	0.962	0.814
248	26.7	0.978	0.971	79.2	43.9	0.987	0.754	110	11.7	0.960	0.826
248	26.1	0.977	0.970	70.6	41.8	0.984	0.779	111	11.5	0.957	0.836
305	22.5	0.967	0.958	70.9	52.5	0.985	0.627	156	11.4	0.949	0.881
297	22.4	0.968	0.959	74.8	58.6	0.989	0.656	148	11.1	0.945	0.886

IX. SUMMARY

The heat exchanger Effectivenesses, AUs and NTUs have been evaluated for HX 3 through HX 9. The uncertainties associated with the present results are large. However since the temperature difference reached in each heat exchanger during the test is small, one can conclude that these heat exchangers are good. In this test, most AUs were found to be lower than the original ISABELLE design values primarily because the flow rates are smaller. The NTU values are reasonable. The Effectiveness are good. The heat exchnagers are therefore suitable for RHIC. No analysis is performed for the three parallel cores of heat exchangers HX 1 and HX 2 because one core is substantially colder than the other two cores. For the next refrigerator run, better flow distribution shall be provided in the three cores of HX 1 and HX 2 for evaluation.

ACKNOWLEDGMENT

The author would like to express his appreciation for the help provided by M. Iarocci and all personnel in the RHIC Cryogenic Section, and the valuable discussions and comments from A. Prodell.