TEST AND VERIFICATION RESULTS

EVLA Correlator Rack: Thermal Mock-up Tests

TVR Document: **A25031N0003**

Revision: 1.0

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Table of Contents

List of Tables

List of Figures

1 Revision History

Revision	Date	Changes/Notes	Author
Draft	Sept 13, 2004	Initial draft	Ralph Webber
Draft	Feb 7, 2005	More testing added [further testing]	Mark Halman
Draft	Feb 10, 2005	Edited document	Ralph Webber
Draft	April14.2005	More results added [Impeller testing]	Mark Halman
Draft	April 20, 2005	Edited document	Ralph Webber
Rev1	April 26, 2005	Executive summary added, tables changed, text added. Appendix added. Photographs added	Mark Halman

2 Introduction

This document describes the thermal cooling test results for the EVLA Thermal Cooling Test Description TVP Document: A25031N0000. The document presents the thermal test data for the purposes of evaluating airflow cooling. This document also details the performance of an aluminium heat sink and whether or not the expected thermal performance was achieved.

Airflow and heat sink temperatures were recorded at incremental power dissipations and with differing airflow schemes.

3 Executive Summary

3.1 Cooling Methods

Prior to testing, three methods of cooling were proposed.

3.1.1 Direct Liquid Cooling

Board mounted copper cold plate, external chiller and internal fans.

3.1.2 Closed Circuit Cooling

Monolithic heat sink, internal fans with an internal heat exchanger and external chiller.

3.1.3 Open Circuit Cooling

Monolithic heat sink, internal fans, high capacity HVAC ducted through the floor.

Closed circuit cooling and Direct liquid cooling were abandoned before testing began, as HVAC is the method favored by NRAO.

3.2 Open Circuit Cooling

Cooling the Correlator chips is achieved using a large monolithic heat sink mounted over the area of the board populated by the Correlator chips. To maintain the maximum die temperature of 45 ^{O}C, the heat sink must be 2-3 ^{O}C cooler. This allows for the thermal resistance between the die, case, and interface. Given those requirements a part was sources with a thermal resistance [rθ] of 0.06 ^{O}C/W . To achieve this performance the air velocity must exceed 3 m/s. Fan performance [airflow] is therefore critical.

3.2.1 Dual Inlet Scheme

Testing began with a Dual inlet scheme. It became clear from the airflow results [see Table 5-1] that there was <u>insufficient</u> flow by this method.
To confirm this result a series of thermal tests was performed [see Figure 3-1 and Table 5-2. and full results Table 9-4]. The temperature rise of the heat sinks [reported as dT] far exceeded the maximum required operating temp of ~ 45 ^{O}C [dT + ambient].

In Figure 3-1 the results from dual inlet are shown cross hatched . It can be see that at 10kW the temperature rise at some parts of the heat sink were over 50 ^{O}C . Correcting for altitude and adding 10 ^{o}C ambient air temp, the operating temp would be in the order of 70^{O}C+, clearly unacceptable.

Single air entry was proposed using high static pressure/flow Impellers that were originally sourced for the Closed circuit cooling method. *Single air entry* is detailed below.

3.2.2 Single Air Entry

This method exploits the fact that the change in air temp is quite low at flows greater than 5 m/s. If the supply temperature of the incoming air is low [10 to 15 ^{O}C], the exhaust air from the lower sub rack [ambient + 5 to 7 ^{O}C see section 10.3.4] can be used as Supply for the upper sub rack.

From Figure 3-1 , Figure 3-2 and full results sectionTable 9-6, it can be seen that there was a large improvement in performance both in airflow and temperature.

All the results are shown below in Figure 3-1 . Dual inlet are crosshatched, Single inlet are shown in solid, orange for blowing blue for sucking.

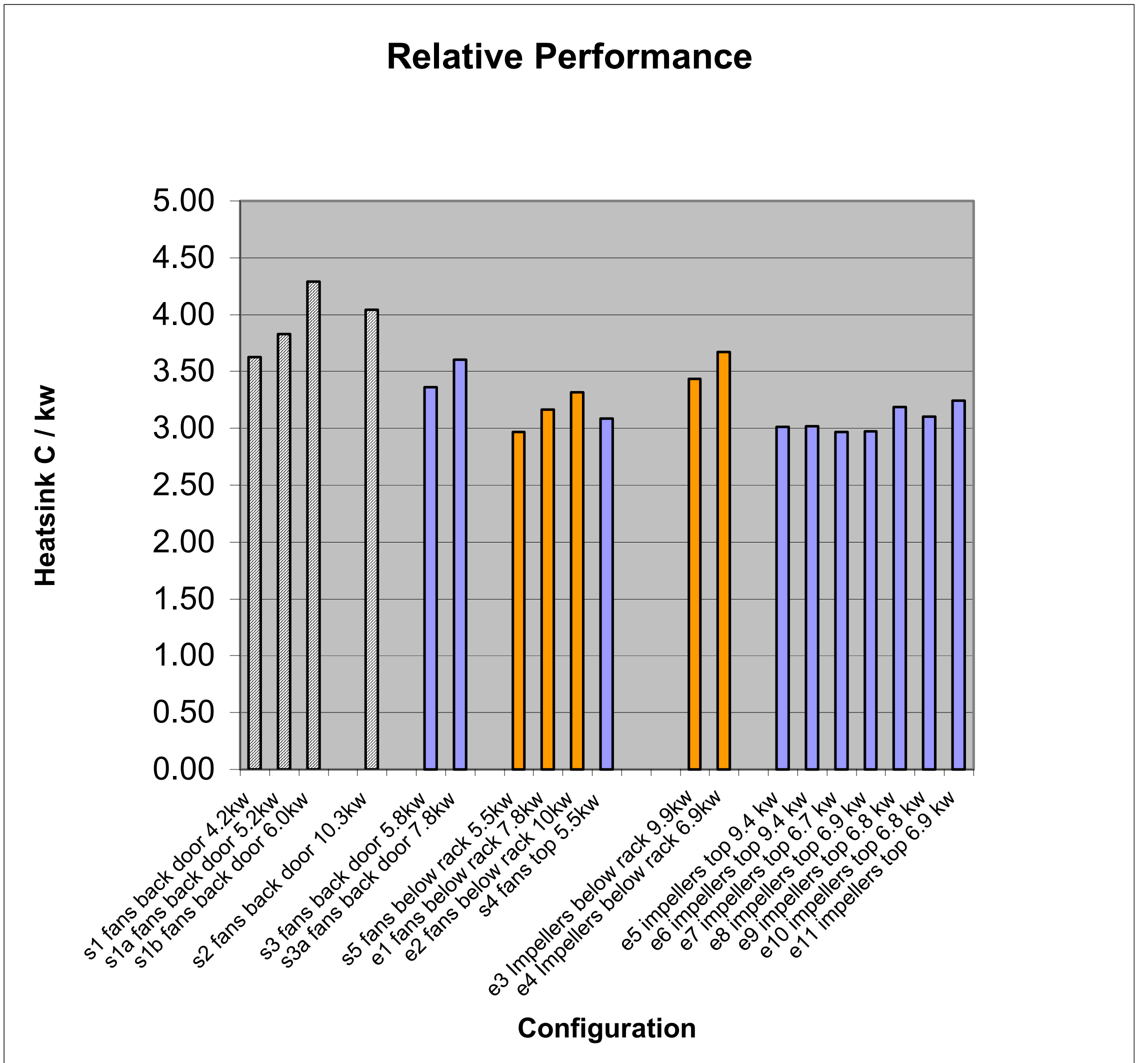

Figure 3-1 Relative Performance [all Tests]

3.2.3 AC Axial Fans

Axial fans were tested in both modes [blowing or sucking]. They were found to be slightly better when mounted at the bottom blowing. See 8.1 for a full summary of fan characteristics.

3.2.4 Motorized Impellers

Impellers were also tested in both modes. The flow was highest when mounted on the top of the enclosure. 4 impellers produced a higher flow than the 12 AC Axial fans. See 8.1 for a full summary of fan characteristics.

3.2.5 6kW Tests

Figure 3-2 shows all testing performed at ~6kW [corresponding to ~4 w/chip mounted on the heat sink] A 'figure of merit' dT/kW is used as the X axis, allowing all results performed under different conditions to be normalized and displayed on one axis.

This figure is more representative of the system performance than the calculated thermal resistance of the heat sink [$r\theta$] because it includes the heat load of other components *not* mounted on the heat sink. On the X axis are the two fan types and modes.

From these results the lowest value of dT/kW is 3.1 +/-0.15 using the motorized impellers. If the total Correlator enclosure load is 6 kW the heat sink will operate at a maximum temperature of 32 ^{O}C [corrected for altitude].

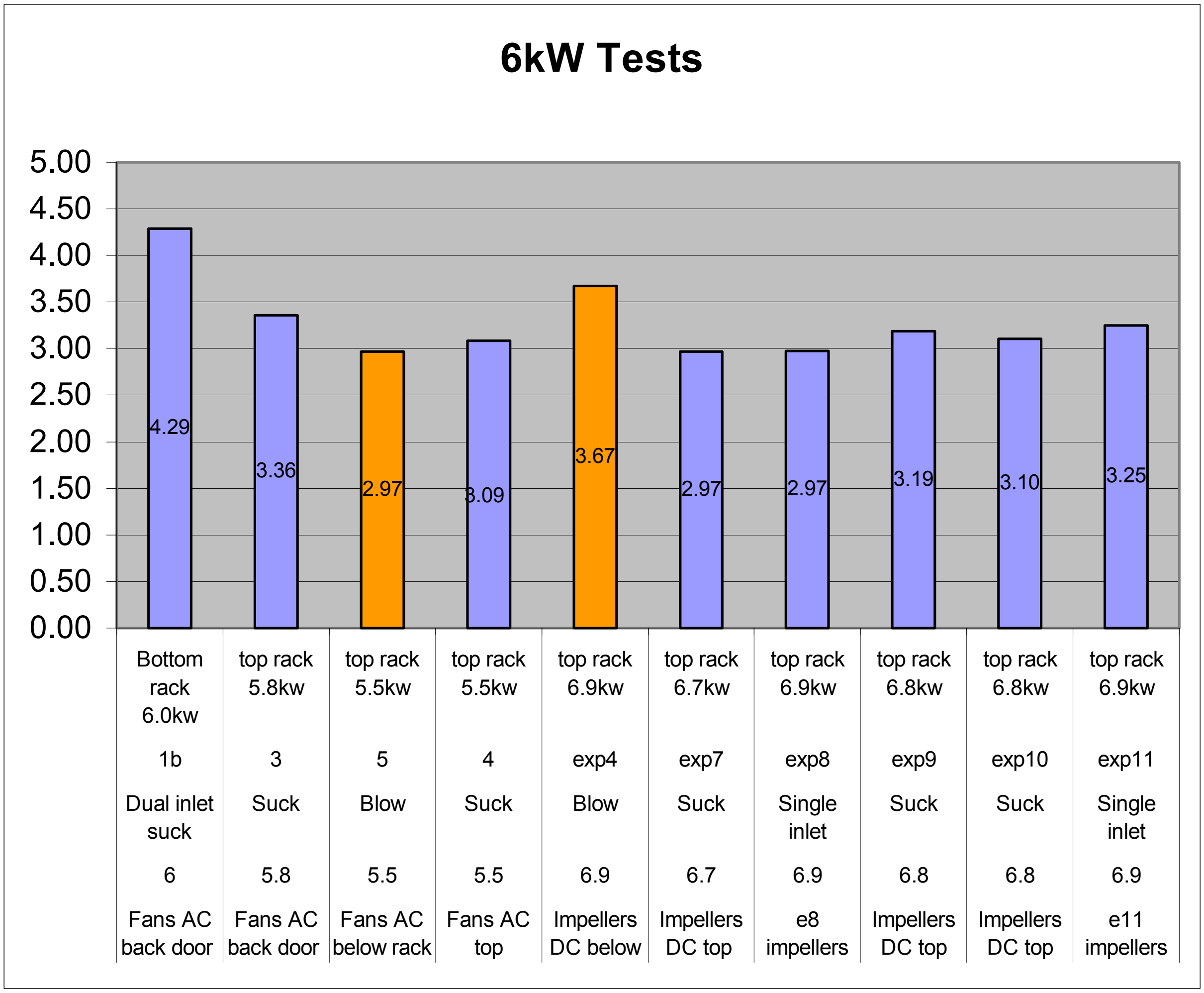

Figure 3-2 Relative Performance 6kW Tests

3.2.6 10kW Tests

Figure 3-3 shows testing performed at ~10kW [corresponding to ~6.7 w/chip mounted on the heat sink] As before a 'Figure of Merit' dT/kW is used as the X-axis and fan type/mode on the Y-axis. From these results dT/kW is 3.0 and within the error band of the 6kW tests. Only two tests were performed at 10 kW.

It is expected that other cooling mechanisms effect the overall performance, but it would seem airflow is by far the dominant factor. If the total Correlator enclosure load is 10 kW the heat sink will operate at a maximum temperature of 45.3 ^{O}C [corrected for altitude]. For detailed calculations see section 10 Appendix.

Note: It is expected that at 3.5 w/chip the heat sink will still operate at this point because other heat producing parts distributed within the enclosure will heat the common air supply.

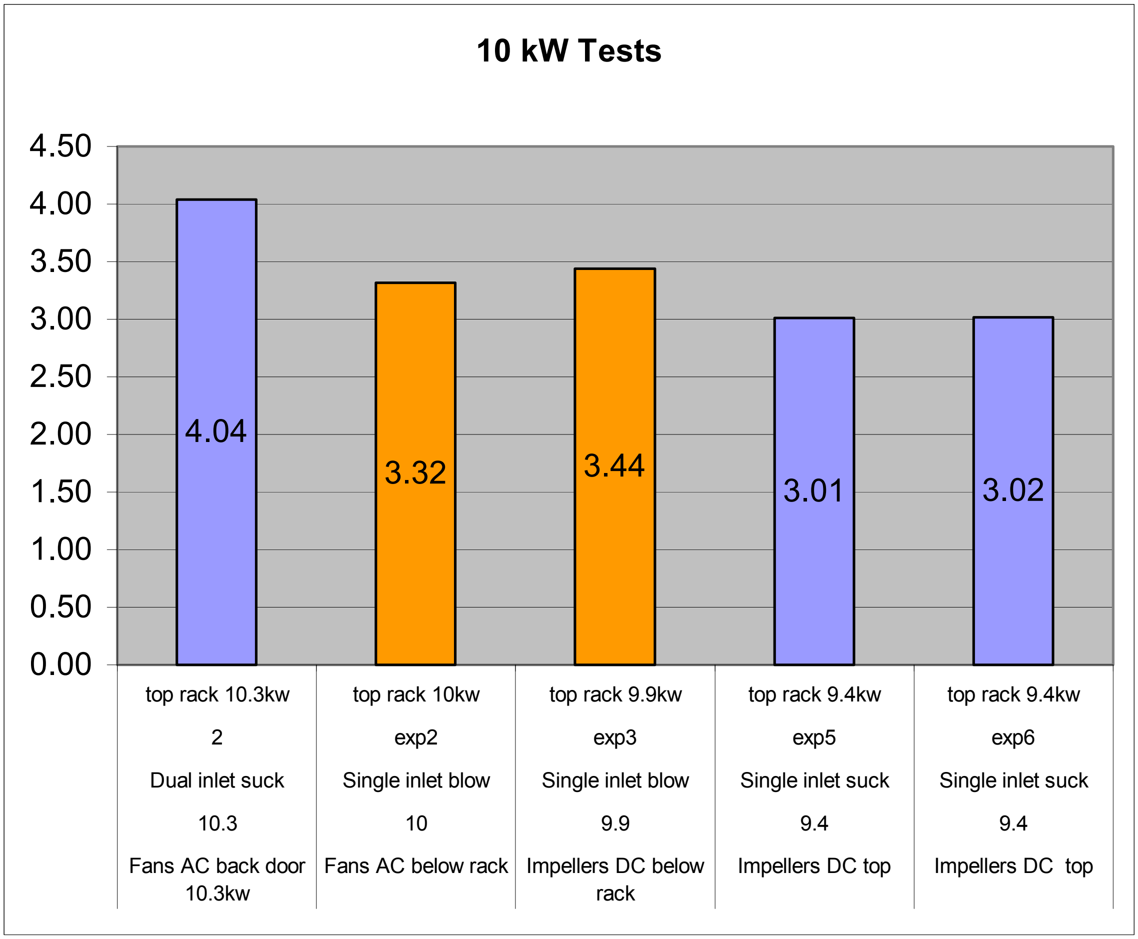

Figure 3-3 Relative Performance 10 kW Tests

3.2.7 Fan Failure - 6 kW

A single test was performed where the control wire to a single fan was disconnected [located over the board under test]. After approximately 50 minutes the heat sink in question reached thermal stability 8 ^{O}C higher than previously recorded with all four fans running.

3.3 Recommendations

From the test results it can be seen that the required maximum operating temperature of the Correlator chips can be achieved ~45^{O}C.

The method suggested relies on a large Monolithic heat sink and powerful fans.
4 DC Motorized Impellers combined with 10 ^{O}C supply air best suit the application, offering, low parts count, small form factor, highest MTBF and in the event of failure, hot swap replacement.

This method does require suitable air quality.

While every attempt has been made to accurately mimic the functional correlator, final operating temperature cannot be guaranteed until functional boards are tested in production enclosures.

4 Test Overview

4.1.1 Schedule of Equipment

Equipment Description: Thermal Test Enclosure

Equipment Status Level: Prototype

Equipment Serial Number: N/A

Equipment Configuration: Stock Hammond Enclosure, Schroff sub-racks reinforced.

Testing Dates: Nov 22, 2004 – April 25, 2005

4.2 Dual Inlet

4.2.1 Airflow

Airflow was measured at the top [exit] A,B,C and Bottom [entry] D,E,F of the heat sink in three of the possible nine slots in the sub rack. The sub racks were also placed in the upper position and all measurements repeated.

4.2.2 Temperature Measurement.

Similarly temperature was measured at the top A,B,C and Bottom D,E,F of the heat sink in three of the possible nine slots in the sub rack. The sub rack were also placed in the upper position and all measurements repeated.

4.3 Single Air Entry - Axial Fans

4.3.1 Airflow

Airflow was measured at the top [exit] A,B,C and bottom [entry] D,E,F of the heat sink in Slot 2 of the sub rack. The sub rack was placed in the upper position.

4.3.2 Temperature Measurement

Similarly temperature was measured at the top A,B,C and Bottom D,E,F of the heat sink Slot 2 of the upper sub rack. This [from previous testing] has proven to be to hottest point in the enclosure.

4.4 Single Air Entry – Motorized Impellers

4.4.1 Airflow

Airflow was measured at the top [exit] A,B,C only of the heat sink in Slot 2 in the upper sub rack. This is the lowest flow as can bee seen from the axial fan flow results. Because of this and the fact that the exact flow is heavily dependant on board layout further flow measurements were thought to be of little use.

4.4.2 Temperature Measurement

Temperature was measured at the top A,B,C and Bottom D,E,F of the heat sink slot 2 of the upper sub rack. This [from previous testing] has proven to be to hottest point in the enclosure.

5 Test Results

5.1 Dual Inlet

In this first test the 12 AC Axial fans were mounted on the rear door.

Anemometer probe depths for the following tests are as follows: A – 70mm, B – 190mm and C – 365mm. Rack location slots are identified from left to right, refer to drawing for positions.

5.1.1 Airflow Measurement

It can be see quite clearly that the airflow was inadequate [<3m/s highlighted in red] in almost all locations. It is thought that attempting to force air around a series of tight turns at quite high speed has led to dead spaces end eddies forming.

Position of subrack in enclosure	Position on heatsink		Position of heatsink in subrack		
	Top	Bottom	**Slot 2**	**Slot 5**	**Slot 9**
Upper subrack location					
	A		0.8	0.7	0.8
	B		0.7	1.7	1.8
	C		3.2	3.7	3.3
		D	0.3	0.3	0.4
		E	4.2	4.7	4.8
		F	0.6	0.7	3.4
Lower subrack location					
	A		0.8	0.7	0.8
	B		0.7	1.7	1.8
	C		3.2	3.5	3.3
		D	2.4	2.4	2.4
		E	2.7	3	3
		F	2	4.6	3.2

Table 5-1 AirFlow

5.1.2 Temperature Measurement

Here temperature and flow are recorded in a spreadsheet. Heat sink dT is calculated from the actual recorded temp, minus ambient temp. Total power is recorded and displayed as it is distributed on the boards.

A ‘figure if merit’ is calculated as dT [^oC]/kW by dividing the total power into the average of the tops of the heat sink temps A+B+C. This figure is used in the summary figures Figure 3-1 , Figure 3-2 and Figure 3-3, to allow direct comparison of all test data taken.

Exp Number s2					Ambient	Exit air						Date
Position	Temperatu	Flow	Flow	Flow	Temp	temp	Heatsink	HS Rt actu	HS Rt	Current	total power	
	slot 2	slot 2	slot 5	slot 9			dT	dT/ P[W]	data sheet	100		
A top	49.3	2.2	2.8	2.1	20.7	28.6	28.6	0.060			475	14.330
B	62.7	0.6	0.8	0.4	20.7		42	0.088			475	21.044
C	75.6	1	0.5	0.4	20.7		54.9	0.116			475	27.508
D	36.5	0.8	0.8	3.4	20.7		15.8	0.033			475	7.917
E	40.7	4.9	4.1	0.4	20.7		20	0.042			475	10.021
F	72.6	0.4	0.4	0.4	20.7		51.9	0.109			475	26.005
Average top		1.65	1.57	1.18	20.7		41.83	0.07	0.1		475	17.804
A bottom		3.2	3.7	3.3			0			56		
B		0.7	1.7	1.8			0					
C		0.8	0.7	0.8			0					
D		2	4.5	3.2			0					
E		3	3.3	3			0					
F		2.4	2.4	2.4			0					
Average	0.00	2.02	2.72	2.42			0.00	0.000	0.1		475	
Conditions												
Dual inlet												
12 Tarzan cooling fans back door mounted												
Top rack		V/device	1.62		Volts	Amps		Delta T [C] / Kw				
Xantrex				621.33	43	100	4300	4.04				
Fuji 39.2V x 93.5 A					39.2	93.5	3665.2					
3kw					56	42.6	2385.6					
Total power							10350.8					
watts/chip =			6.75									
Power in Bias circuit =			52.08									
Power in back components =			149.1		Check	10355						
Total board load =			687.18									
HS Rt data sheet =				0.06								

Table 5-2 12 Fans on Backdoor [6.7W/chip]

5.2 Single Air Entry Axial Fans

5.2.1 Airflow

The results from airflow testing have been combined with temperature in the following tables in section 5.2.2 Temperature Measurement, following. Flow was generally much higher >3.5m/s. Flow has been recorded location Slot2 as testing focused on worst case positions and highest temperature, this, determined from earlier testing

5.2.2 Temperature Measurement -Blowing

Exp Number	**2**		**Ambient**	**Exit air**		**HS Rt**			***12 Tarzan cooling fans below rack***			
Position	**Temp**	**Flow**	**Temp**	**Temp**	**Heatsink**	**actual**	**heatsink**	**sheet data**	***Single inlet***			
Slot 2	**C**	**m/s**	**C**	**C**	**dT**	**dT/ P[W]**	**load [W]**	**dT**	***Date***	04/04/2005		
A top	55.5	4.5	23.1	36.8	32.4	0.076	427.2	25.63				
B	57.5	3.3	23.1	36.8	34.4	0.081	427.2	25.63	***30% blockage at centre***			
C	56.2	3.6	23.1	36.8	33.1	0.077	427.2	25.63	**HS Rt data sheet =**		0.06	
D	43.1		23.1	36.8	20	0.047	427.2	25.63	***Exit air delta T***		**13.7**	
E	44.8		23.1	36.8	21.7	0.051	427.2	25.63				
F	42		23.1	36.8	18.9	0.044	427.2	25.63				
Average	49.85	3.80			**26.75**	0.06		25.63				
Av top					33.30							
									Delta T [C] / Kw		10.03	Kw
									3.32			
Power												
		Volts	Amps	Watts					**Axial Blowing**			
Xantrex		42.9	89	3818.1								
Fuji		43.3	89.6	3879.68								
3kw		48.1	36.1	1736.41								
Fans	1	115	5.21	599.15								
total cabinet watts				***10033.34***								
Watts per device =				5.93								
Power in Bias circuit =				50.06		Check	10033					
Power in back mounted components =				108.53								
Total insrumented board load =				585.79								

Table 5-3 *Fans Bottom [5.9W/chip]*

5.2.3 Temperature Measurement -Sucking

Exp Number s2					Ambient	Exit air						Date
Position	Temperatu	Flow	Flow	Flow	Temp	temp	Heatsink d	HS Rt actu	HS Rt data	Current	total power	
	slot 2	slot 2	slot 5	slot 9				dT/ P[W]		100		
A top	49.3	2.2	2.8	2.1	20.7	28.6	28.6	0.060			475	14.330
B	62.7	0.6	0.8	0.4	20.7		42	0.088			475	21.044
C	75.6	1	0.5	0.4	20.7		54.9	0.116			475	27.508
D	36.5	0.8	0.8	3.4	20.7		15.8	0.033			475	7.917
E	40.7	4.9	4.1	0.4	20.7		20	0.042			475	10.021
F	72.6	0.4	0.4	0.4	20.7		51.9	0.109			475	26.005
Average top		1.65	1.57	1.18	20.7		41.83	0.07	0.1		475	17.804
A bottom		3.2	3.7	3.3			0			56		
B		0.7	1.7	1.8			0					
C		0.8	0.7	0.8			0					
D		2	4.5	3.2			0					
E		3	3.3	3			0					
F		2.4	2.4	2.4			0					
Average	0.00	2.02	2.72	2.42			0.00	0.000	0.1		475	
Conditions												
Dual inlet												
12 Tarzan cooling fans back door mounted												
Top rack		V/device	1.62		Volts	Amps		Delta T [C] / Kw				
Xantrex				621.33	43	100	4300	4.04				
Fuji 39.2V x 93.5 A					39.2	93.5	3665.2					
3kw					56	42.6	2385.6					
Total power							10350.8					
watts/chip =			6.75									
Power in Bias circuit =			52.08									
Power in back components =			149.1		Check	10355						
Total board load =			687.18									
HS Rt data sheet =				0.06								

Table 5-4 12 Fans Back Door [6.7W/chip]

5.3 Single Air Entry DC Impeller

5.3.1 Airflow

The results from airflow testing have been combined with temperature in the following tables. Flow was much higher >3.5m/s. Flow has been recorded location Slot2 as testing focused on worst case positions and highest temperature, this, determined from earlier testing

5.3.2 Temperature Measurement Blowing

Exp Number	3		Ambient	Exit air		HS Rt			*4 EBM motorized Impellers fans below rack*			
Position	Temp	Flow	Temp	Temp	Heatsink	actual	heatsink	sheet data	*Single inlet*			
Slot 2	C	m/s	C	C	dT	dT/ P[W]	load [W]	dT	*Date*	05/04/2005		
A top	57	4.3	22.2	36.8	34.8	0.081	431.52	25.89				
B	57.2	3.8	22.2	36.8	35	0.081	431.52	25.89	*30% blockage at centre*			
C	55.1	3	22.2	36.8	32.9	0.076	431.52	25.89	HS Rt data sheet =		0.06	
D	44.5		22.2	36.8	22.3	0.052	431.52	25.89	*Exit air delta T*		**14.6**	
E	45		22.2	36.8	22.8	0.053	431.52	25.89				
F	41.3		22.2	36.8	19.1	0.044	431.52	25.89				
Average	50.02	3.70			**27.82**	0.06		25.89				
Av top					34.23							
									Delta T [C] / Kw		9.96	Kw
									3.44			
Power												
	include	Volts	Amps	Watts					Impeller Blowing			
Xantrex		42.8	89.9	3847.72								
Fuji		43.3	91.5	3961.95								
3kw		48.1	36	1731.6								
Fans	1	48.1	8.7	418.47								
total cabinet watts				***9959.74***								
Watts per device =				5.99								
Power in Bias circuit =				49.44		Check	9960					
Power in back mounted components =				108.23								
Total insrumented board load =				589.19								

Table 5-5 Impellers Blowing [9.9kW]

5.3.3 Temperature Measurement Sucking

Exp Number	**6**		**Ambient**	**Exit air**		**HS Rt**			***4 EBM motorized impellers above rack***			
Position	**Temp**	**Flow**	**Temp**	**Temp**	**Heatsink**	**actual**	**heatsink**	**sheet data**	***Single inlet***			
Slot 2	**C**	**m/s**	**C**	**C**	**dT**	**dT/ P[W]**	**load [W]**	**dT**	***Date***	06/04/2005		
A top	52.7	6	24.2	31.4	28.5	0.066	432	25.92				
B	53.3	6	24.2	31.4	29.1	0.067	432	25.92	***30% blockage at centre***			
C	52	6	24.2	31.4	27.8	0.064	432	25.92	**HS Rt data sheet =**		0.06	
D	41.2		24.2	31.4	17	0.039	432	25.92	***Exit air delta T***		**7.2**	
E	41.6		24.2	31.4	17.4	0.040	432	25.92				
F	39.5		24.2	31.4	15.3	0.035	432	25.92				
Average	46.72	6.00			**22.52**	0.05		25.92				
Av top					28.47							
									Delta T [C] / Kw		9.43	Kw
									3.02			
Power												
		Volts	Amps	Watts					**Impeller Sucking**			
Xantrex		42.99	90	3869.1								
Fuji		42.6	89.9	3829.74								
3kw		48.1	36	1731.6								
Fans	0	48.1	8.7	0								
total cabinet watts				***9430.44***								
Watts per device =				6.00								
Power in Bias circuit =				51.64		Check	9430					
Power in back mounted components =				108.23								
Total insrumented board load =				591.86								

Table 5-6 Impellers Sucking [9.4kW]

6 Conclusions

6.1 Air Flow - Dual Inlet

Initial airflow testing of the split flow dual air inlet design, [Table 5-1] indicated that there was insufficient flow of air to the edges of the heat sink. It is assumed that the inertia of the air combined with turbulence caused by attempting to force the cooling air around several 90 degree corners and obstructions, all in a confined space, has led to dead spaces and eddies forming.

Investigations into the airflow pattern would require the use of smoke generators and wind tunnel equipment etc. Flow however, was sufficient to allow thermal testing safely.

6.2 Thermal Testing - Dual Inlet

From the thermal testing results section Table 5-2, it is clear that the sections of heat sink with low flow heat up beyond the design operating temperature of 42 ^{o} C

From the data [Table 9-4], the thermal resistance is as high as 0.116 at the location of lowest flow. This would mean an operating temp of 54 ^{o} C at 4 W/chip with supply air at 15 ^{o} C corrected for 2100m altitudes.

Thermal testing has corroborated the flow test data. Areas with low flow have high temperatures and agree with the calculated performance taken from the heat sink manufacturers data sheets.

Dual Inlet in not suitable as a method of cooling the Correlator.

As the operating temp is much higher than the design goal, it was decided to try an alternate airflow scheme, referred to as **Single Air Entry.**

6.3 Air Flow - Single Air Entry

With air entering at the bottom of the enclosure and exiting at the top, cooling air does not need to turn through 90-degree corners. Flow is simply through the entire system in a straight line. Airflow is fairly consistent across the entire heat sink profile.

Air flow was measured across the heat sinks at the exit positions A, B and C. [Table 9-8] For a Blowing arrangement [12 AC fans at the bottom] Flow exceeded 5 m/s at all locations Velocity is fairly even with an approximate variation of only 5% from the average flow.

Airflow has been tested with the 12 AC Axial fans blowing from underneath and sucking from above at various power levels.

4 DC motorized impellers were also tested in both modes at various power levels. These fans have a higher static pressure capability and a flow three times that of the axial fans, but have a different form factor.

It was unclear how they would perform in the test rack in the blowing mode, as there is a restricted amount of room available for the discharge air to settle out from the very high speed and turbulent radial discharge.

The tests indicate that the total airflow in the blowing mode is slightly lower than expected. However in the sucking mode the flow is sufficient and will provide the necessary flow to cool the Correlator.

6.4 Thermal Testing - Single Air Entry

The heat sinks need an airflow of > 3 m/s to meet the required dT of 22 ^{o} C [at altitude] and hence the thermal resistance value of 0.06 ^{o} C/W, with the intended dissipated power of the load. Air velocity is fixed by that constraint and given that we know the cross sectional area of the sub rack, total volume is now known. Exit air temperature can now be calculated based on the known volume of air used. It was also measured and reported as exit air temperature.

Single air entry has only become possible because the overall temperature rise of the air [dT] is quite low. At a higher airflow, air exit temperature drops further. For an air flow of > 5 m/s, the heat sink performance changes little but exit air temp dT drops to 11 ^{o} C total or 5 ^{o} c per sub rack. The exit air from the lower sub rack can now be used for the entry air supply to the upper sub rack. With a design heat sink dot max of 22 ^{o} C and an initial supply air temp of 15 ^{o} C, we meet the maximum operating temp of 42 ^{o} C. on the upper sub rack heat sinks. Three tests were performed to confirm this.

6.4.1 12 Fans on Backdoor [6.7W/chip]

Results Table 9-6 compare with Table 9-4[dual inlet]. Clearly a massive improvement in airflow and much cooler heat sinks > 34 ^{o} C cooler at the hottest places rT drops from 0.11 ^{o} C/W to 0.07 ^{o} C/W.

6.4.2 12 Fans on Bottom [4W/chip] with Blockage at 30%

Results Table 9-8

Fans are expected to be more efficient mounted at the bottom and were moved to test this. A 30% blockage was added to simulate more closely the resistance posed by a bottom sub-rack complete with heat sinks. The data reflects this change and no other test can be compared directly due to this difference. The value of ^{o}C/kW can be used as a guide to overall performance.

However the results from this test indicates that a flow of > 5 m/s is possible within the rack at a total volume of > 1300 cfm.

Maximum heat-sink temperature in the test rack was 45 ^{o} C with entry air at 22 ^{o} C Heat sink performance meets or exceeds design goals, with a dT of less than 19 ^{o} C.

Correcting this for altitude, dT would rise to 22.4 $^{o.}$ With an air flow of > 5 m/s at 15 ^{o} C, the operating temperature would be 42.4 ^{o} C max, 29.4 ^{o} C min for the upper heat sinks and 37.4 ^{o} C max and 24.4 min ^{o} C for the lower heat sinks.

6.4.3 Motorized Impellers Blowing 9.9kW

Results Table 9-11 compare with Table 9-8 [value of ^{o}C/kW].
Mounted at the bottom of the rack flow appears slightly lower than the 12 axial fans.

Maximum heat-sink temperature in the test rack was 57 ^{o} C with entry air at 22.2 ^{o} C heat-sink, performance meets or exceeds design goals at 0.06, with a dT of 35 ^{o} C. With a supply air temp of 15 ^{o} C the operating temp [max] would be 50 ^{o} C.

Note: Since the start of this testing the total cabinet load estimate has gone up to around 10kW
.

6.4.4 Motorized Impellers Sucking 9.4kW

Results Table 9-13

Mounted at the top of the rack flow is now higher than the 12 axial fans. Maximum heat-sink temperature in the test rack was 53 ^{o} C with entry air at 24 ^{o} C Heat-sink performance meets or exceeds design goals at 0.05 ^{o} C/W, and a dT of less than 30 ^{o} C.

With a supply air temp of 15 ^{o} C the operating temp [max] would be 45 ^{o} C At altitude the supply air temperature will need to be reduced to 10 ^{o} C to meet the 45 ^{o} C max.

Note this is the maximum temperature of the hottest part of the heat sink. As the fans are now mounted after the heat load their power contribution [400W] can be neglected in calculations.

7 Summary Tables

7.1 Figure of Merit

Extensive testing has been performed over several months. As the testing progressed additional power supplies were added, total power changed and obstructions were places in the air flow path. None of the test can be compared directly because of these variables. In order to compare from test to test directly the results are normalized using a 'Figure of Merit'.

This value [in units of ^{o}C/kW] is the average of the maximum [(A+B+C)/3] Heatsink temperature change [dT], in Slot 2, Top subrack. This value is charted for both fan types and configurations.

Figure 3-1 Relative Performance [all Tests.
Shows all tests performed normalized to ^{0}C /kW. Dual inlet are shown crosshatched. Blowing in orange and sucking in blue.

It *appears* that there is some effect proportional to power, however it is thought this is a measurement error caused by dissipating large amounts of power into the screened room.

Small room temperature variations of as little as +/- 2 ^{0}C have an effect on the value of ^{0}C/kW of as much as +/- 8%. The room temperature is not regulated to less than 3 ^{0}C. All measurements were taken when thermal stability in the test rack was reached. [after 30 minutes minimum]

Figure 3-2 Relative Performance 6kW Tests.
Shows all tests performed at 6 to 7 kW normalized to ^{0}C/kw on the Y Axis. The last 5 measurements were made sequentially over a four-hour period.

Figure 3-3 Relative Performance 10 kW Tests
Shows all tests performed at 10 KW normalized to ^{0}C/kw on the Y Axis.

8 Further Improvements

8.1 Fan Selection

8.1.1 Axial Fans

1. The AC fans tested performed adequately, however there are 12 per enclosure, leading to a low MTBF.
2. The Fan assembly covers the entire top [or bottom] of the enclosure, leaving no room for cabling.
3. An internal AC supply is not planned for the production racks.
4. At 50 Hz [eMerlin] the AC fan performance degrades to 26% and are not suitable. See Figure 10-6
5. The DC version of the fan has only 60% of the capacity of the AC fan and are also not suitable.

8.1.2 Motorized Impellers

1. The motorized impellers performed adequately with better performance when drawing air through from the top [sucking]
2. Positioned at the exit, the heat from the motors [400W] does not contribute to the system operating temperature.
3. 4 Motorized impellers can replace 12 axial fans and will have the static pressure to overcome higher system resistance without loss of flow. [System resistance is expected to increase with functional boards, mezzanine cards and power supplies mounted on the boards.]
4. A slightly higher capacity Impeller is available [+10%] with a lower operating speed. This should further reduce the MTBF.
5. Motorized impellers use 48VDC, are programmable and have a tachometer output for speed monitoring and failure detection.

8.2 Sub Racks

Sub racks with a more robust construction and less restriction to airflow are planned.

9 Full Results

All results tabulated.

xp Number s1					Ambient	Exit air				
Position	emperature	Flow	Flow	Flow	Temp	temp	Heatsink dT	HS Rt actua	Rt data sh	eat sink loa
	slot 2	slot 2	slot 5	slot 9				dT/ P[W]		W
A top		2.2	2.8	2.1		24.4				
B		0.6	0.8	0.4						
C		1	0.5	0.4						
D		0.8	0.8	3.4						
E		4.9	4.1	0.4						
F		0.4	0.4	0.4						
A bottom	38.1	3.2	3.7	3.3	20.8	24.4	17.3	0.073		238
B	36.4	0.7	1.7	1.8	20.8		15.6	0.066		238
C	33.3	0.8	0.7	0.8	20.8		12.5	0.053		238
D	29.1	2	4.5	3.2	20.8		8.3	0.035		238
E	27	3	3.3	3	20.8		6.2	0.026		238
F	26.9	2.4	2.4	2.4	20.8		6.1	0.026		238
Average	31.80	2.02	2.72	2.42				0.000	0.1	238
Av top							15.13			
Conditions								Delta T [C] / Kw		
Date								3.63		
Two inlet					Volts	Amps				
12 Tarzan cooling fans back door mounted										
Bottom rack										
Xantrex 41.5 x 56					41.5	56	2324			
9 Boards	V/device		1.62							
3kw 56v x 33 A					56	33	1848			
Total power W							4172			
Watts per device =			3.36							
Power in Bias circuit =			12.91							
Power in back components =			115.5							
Total board load =			370.33			Check	4171.67			
HS Rt data sheet =			0.06							

Table 9-1 12 Fans on Back Door [3.4W/chip]

Exp Number	s1a				Ambient	Exit air	Heatsink	HS Rt	HS Rt	heat sink	
Position	Temp	Flow	Flow	Flow	Temp	temp	dT	actual	data sheet	load	
	slot 2	slot 2	slot 5	slot 9				dT/ P[W]		W	
A top		2.2	2.8	2.1		25.2					
B		0.6	0.8	0.4							
C		1	0.5	0.4							
D		0.8	0.8	3.4							
E		4.9	4.1	0.4							
F		0.4	0.4	0.4							
A bottom	43.6	3.2	3.7	3.3	20.5	25.2	23.1	0.068		338	
B	41.4	0.7	1.7	1.8	20.5		20.9	0.062		338	
C	36.6	0.8	0.7	0.8	20.5		16.1	0.048		338	
D	32.3	2	4.5	3.2	20.5		11.8	0.035		338	
E	29.6	3	3.3	3	20.5		9.1	0.027		338	
F	29.2	2.4	2.4	2.4	20.5		8.7	0.026		338	
Average	35.45	2.02	2.72	2.42				0.084	0.1	238	
Av top							20.03				
Conditions											
Date											
Two inlet											
12 Tarzan cooling fans back door mounted											
Bottom rack					Volts	Amps					
Xantrex 42.3 x 80					42.3	80	3384			Delta T [C] / Kw	
9 Boards	V/device		1.62							3.83	
3kw 56v x 33 A					56	33	1848				
Total Watts							5232				
Watts per device =				4.80							
Power in Bias circuit =				26.34							
Power in back components =				115.5		Check	5238.64				
Total board load =				487.44							
HS Rt data sheet =				0.06							

Table 9-2 12 Fans on Back Door [4.8W/chip]

Exp Numbe	s1b				Ambient	Exit air					Date
Position	emperatur	Flow	Flow	Flow	Temp	temp	Heatsink dT	HS Rt actua	Rt data sh	eat sink load	
	slot 2	slot 2	slot 5	slot 9				dT/ P[W]		W	
A top		2.2	2.8	2.1		26					
B		0.6	0.8	0.4							
C		1	0.5	0.4							
D		0.8	0.8	3.4							
E		4.9	4.1	0.4							
F		0.4	0.4	0.4							
A bottom	50	3.2	3.7	3.3	20.8	26	29.2	0.069		426	
B	47.1	0.7	1.7	1.8	20.8		26.3	0.062		426	
C	42.5	0.8	0.7	0.8	20.8		21.7	0.051		426	
D	34.8	2	4.5	3.2	20.8		14	0.033		426	
E	32.2	3	3.3	3	20.8		11.4	0.027		426	
F	37.7	2.4	2.4	2.4	20.8		16.9	0.040		426	
Average	40.72	2.02	2.72	2.42			19.92	0.05	0.1	426	
Av top							25.73				
Conditions											
Date											
Two inlet		**9 boards**									
12 Tarzan cooling fans back door mounted											
Bottom rack		V/device	1.62		Volts	Amps					
Xantrex					41.5	100	4150			Delta T [C] / Kw	
3kw					56	33	1848			4.29	
watts/chip =				6.00			5998	Sum			
Power in Bias circuit =				41.15							
Power in back components =				115.5		Check	5956				
Total board load =				588.65							
HS Rt data sheet =				0.06							

Table 9-3 12 Fans on Back Door [6.0W/chip]

Exp Number s2					Ambient	Exit air						Date
Position	Temperatu	Flow	Flow	Flow	Temp	temp	Heatsink d	HS Rt actu	HS Rt data	Current	total power	
	slot 2	slot 2	slot 5	slot 9				dT/ P[W]		100		
A top	49.3	2.2	2.8	2.1	20.7	28.6	28.6	0.060			475	14.330
B	62.7	0.6	0.8	0.4	20.7		42	0.088			475	21.044
C	75.6	1	0.5	0.4	20.7		54.9	0.116			475	27.508
D	36.5	0.8	0.8	3.4	20.7		15.8	0.033			475	7.917
E	40.7	4.9	4.1	0.4	20.7		20	0.042			475	10.021
F	72.6	0.4	0.4	0.4	20.7		51.9	0.109			475	26.005
Average top		1.65	1.57	1.18	20.7		41.83	0.07	0.1		475	17.804
A bottom		3.2	3.7	3.3			0			56		
B		0.7	1.7	1.8			0					
C		0.8	0.7	0.8			0					
D		2	4.5	3.2			0					
E		3	3.3	3			0					
F		2.4	2.4	2.4			0					
Average	0.00	2.02	2.72	2.42			0.00	0.000	0.1		475	
Conditions												
Dual inlet												
12 Tarzan cooling fans back door mounted												
Top rack		V/device	1.62		Volts	Amps		Delta T [C] / Kw				
Xantrex				621.33	43	100	4300	4.04				
Fuji 39.2V x 93.5 A					39.2	93.5	3665.2					
3kw					56	42.6	2385.6					
Total power							10350.8					
watts/chip =			6.75									
Power in Bias circuit =			52.08									
Power in back components =			149.1		Check	10355						
Total board load =			687.18									
HS Rt data sheet =				0.06								

Table 9-4 12 Fans on Backdoor [6.7W/chip]

Exp Number s3					Ambient	Exit air						Date
Position	Temperatu	Flow	Flow	Flow	Temp	temp	Heatsink d	HS Rt actu	HS Rt data	Current	total power	
	slot 2	slot 2	slot 5	slot 9				dT/ P[W]				
A top	40.9				21.4	30.5	19.5	0.062			316	14.687
B	41.7				21.4		20.3	0.064			316	15.289
C	40.2				21.4		18.8	0.059			316	14.159
D	31.2				21.4		9.8	0.031			316	7.381
E	31.5				21.4		10.1	0.032			316	7.607
F	31.9				21.4		10.5	0.033			316	7.908
	36.23	0.00	0.00	0.00	21.4		14.83	0.05	0.1			11.172
Av top							19.53					
	Conditions											
	12 Tarzan cooling fans back door mounted											
	top rack		cal fact	Volts	Amps				Delta T [C] / Kw			
	Xantrex 43v x 100A			41.9	66.8	2798.92			3.36			
Recall'd	**Fuji 39.2V x 93.5 A**		4	38.4	65.4	627.84						
	3kw 56v x 42.6 A			56	42.6	2385.6						
						5812.36						
	Single inlet											
	watts/chip =			4.51								
	Power in Bias circuit =			23.24						mv wire	371	600.00
	Power in back components =			149.1		Check	5797			amps	60	97.04
	Total board load =			496.99						a/mv wire	0.161725	
	HS Rt data sheet =				0.06					fuji monitor point		3.93
										A/V mon		24.69

Table 9-5 12 Fans on Backdoor [4.5W/chip]

Exp Number s3a					Ambient	Exit air						
Position	Temperatu	Flow	Flow	Flow	Temp	temp	Heatsink d	HS Rt actu	HS Rt data	Current	total power	
	slot 2	slot 2	slot 5	slot 9				dT/ P[W]				
A top	49.7				21.4	30.5	28.3	0.090			316	21.315
B	50.5				21.4		29.1	0.092			316	21.917
C	48.7				21.4		27.3	0.086			316	20.561
D	36				21.4		14.6	0.046			316	10.996
E	36.6				21.4		15.2	0.048			316	11.448
F	36.8				21.4		15.4	0.049			316	11.599
	43.05	0.00	0.00	0.00	21.4		21.65	0.07	0.1			16.306
Av top							28.23					
Average	0.00	0.00	0.00	0.00			0.00	0.000	0.1		475	
	Conditions											
	12 Tarzan cooling fans back door mounted											
	top rack		cal fact	Volts	Amps				Delta T [C] / Kw			
	Xantrex 43v x 100A			43.8	101.7	4454.46			3.60			
Recall'd	Fuji 39.2V x 93.5 A		4	39.6	102.2	1011.78						
	3kw 56v x 42.6 A			56	42.4	2374.4						
						7840.64						
	Single inlet											
	watts/chip =			6.86								
	Power in Bias circuit =			53.87								
	Power in back components =			148.4		Check	7771					
	Total board load =			696.53								
	HS Rt data sheet =				0.06							

Table 9-6 12 Fans on Back Door [6.8W/chip]

Exp Number s4					Ambient	Exit air						Date
Position	Temperatu	Flow	Flow	Flow	Temp	temp	Heatsink d	HS Rt actu	HS Rt data	Current	total power	
	slot 2	slot 2	slot 5	slot 9				dT/ P[W]				
A top	40.2				23	30.5	17.2	0.054			316	12.954
B	40.6				23		17.6	0.056			316	13.256
C	39				23		16	0.051			316	12.051
D	32.6				23		9.6	0.030			316	7.230
E	32.6				23		9.6	0.030			316	7.230
F	32.4				23		9.4	0.030			316	7.080
	36.23	0.00	0.00	0.00	23		13.23	0.04	0.1			9.967
Av top							16.93					
Conditions												
12 Tarzan cooling fans mounted on top [sucking]												
top rack			cal fact	Volts	Amps				Delta T [C] / Kw			
Xantrex 41.5 x 59.8				41.5	59.8	2481.7			3.09			
Fuji 41.5 x 59.8			4	41.5	59.8	620.425						
3kw 56v x 42.6 A				56	42.6	2385.6						
						5487.725						
Single inlet												
watts/chip =			4.04									
Power in Bias circuit =			18.63									
Power in back components =			149.1		Check	5480						
Total board load =			458.35									
HS Rt data sheet =				0.06								

Table 9-7 12 Fans on Top [4.0W/chip]

Exp Number		**s5**	**Ambient**	**Exit air**		**HS Rt**			**Conditions**		
Position	**Temp**	**Flow**	**Temp**	**Temp**	**Heatsink**	**actual**	**heatsink**	**sheet data**	***Date***	########	
Slot 2	**C**	**m/s**	**C**	**C**	**dT**	**dT/ P[W]**	**load [W]**	**dT**	***Single inlet***		
A top	46.3	5.6	22.1	33	24.2	0.084	288	0.00	***12 Tarzan cooling fans below ra***		
B	46.3	6	22.1	33	24.2	0.084	288	0.00			
C	44.5	5.4	22.1	33	22.4	0.078	288	0.00			
D	36.1		22.1	33	14	0.049	288	0.00			
E	35.1		22.1	33	13	0.045	288	0.00			
F	36.1		22.1	33	14	0.049	288	0.00			
Average	40.73	5.67	22.1		18.63	0.06		0.00			
Av top					23.60						
top rack			cal fact	Volts	Amps						
Xantrex 41.5 x 59.8				41.5	59.8	2481.7			Delta T [C] / Kw		
Fuji 41.5 x 59.8			1	41.5	59.8	2481.7			2.97		
Fans						600					
3kw 56v x 42.6 A				56	42.6	2385.6					
Total power W						7949					
Single inlet											
30% blockage at centre											
watts/chip =			4.04								
Power in Bias circuit =			18.63								
Power in back components =			149.1		Check	7941					
Total board load =			458.35								
HS Rt data sheet =				0.06							

Table 9-8 12 Fans on Bottom [4W/chip] with Blockage at 30%

Exp Numb	1		Ambient	Exit air		HS Rt			*12 Tarzan cooling fans below rack*			
Position	Temp	Flow	Temp	Temp	Heatsink	actual	heatsink	sheet data	*Single inlet*			
Slot 2	C	m/s	C	C	dT	dT/ P[W]	load [W]	dT	*Date*	04/04/2005		
A top	47.6	4.5	23.7	36.4	23.9	0.076	316.32	18.98				
B	49.2	3.3	23.7	36.4	25.5	0.081	316.32	18.98	*30% blockage at centre*			
C	47.9	3.6	23.7	36.4	24.2	0.077	316.32	18.98	HS Rt data sheet =		0.06	
D	38.6		23.7	36.4	14.9	0.047	316.32	18.98	*Exit air delta T*		12.7	
E	39.7		23.7	36.4	16	0.051	316.32	18.98				
F	37.6		23.7	36.4	13.9	0.044	316.32	18.98				
Average	43.43	3.80			19.73	0.06		18.98				
Av top					24.53							
									Delta T [C] / Kw		7.76	Kw
									3.16			
Power												
	include	Volts	Amps	Watts					**Axial Blowing**			
Xantrex		41.5	65.9	2734.85								
Fuji		41.5	64.7	2685.05								
3kw		48.1	36.1	1736.41								
Fans	1	115	5.21	599.15								
total cabinet watts				7755.46								
Watts per device =				4.39								
Power in Bias circuit =				25.54		Check	7755					
Power in back mounted components =				108.53								
Total insrumented board load =				450.38								

Table 9-9 12 Fans on Bottom [4.4W/chip]

Exp Numb	**2**		**Ambient**	**Exit air**		**HS Rt**			***12 Tarzan cooling fans below rack***			
Position	**Temp**	**Flow**	**Temp**	**Temp**	**Heatsink**	**actual**	**heatsink**	**sheet data**	***Single inlet***			
Slot 2	**C**	**m/s**	**C**	**C**	**dT**	**dT/ P[W]**	**load [W]**	**dT**	***Date***	04/04/2005		
A top	55.5	4.5	23.1	36.8	32.4	0.076	427.2	25.63				
B	57.5	3.3	23.1	36.8	34.4	0.081	427.2	25.63	***30% blockage at centre***			
C	56.2	3.6	23.1	36.8	33.1	0.077	427.2	25.63	**HS Rt data sheet =**		0.06	
D	43.1		23.1	36.8	20	0.047	427.2	25.63	***Exit air delta T***		**13.7**	
E	44.8		23.1	36.8	21.7	0.051	427.2	25.63				
F	42		23.1	36.8	18.9	0.044	427.2	25.63				
Average	49.85	3.80			**26.75**	0.06		25.63				
Av top					33.30							
									Delta T [C] / Kw		10.03	Kw
									3.32			
Power												
		Volts	Amps	Watts					**Axial Blowing**			
Xantrex		42.9	89	3818.1								
Fuji		43.3	89.6	3879.68								
3kw		48.1	36.1	1736.41								
Fans	1	115	5.21	599.15								
total cabinet watts				***10033.34***								
Watts per device =				5.93								
Power in Bias circuit =				50.06		Check	10033					
Power in back mounted components =				108.53								
Total insrumented board load =				585.79								

Table 9-10 12 Fans on Bottom [5.9W/chip]

Exp Numb	**3**		**Ambient**	**Exit air**		**HS Rt**			***4 EBM motorized Impellers fans below rac***			
Position	**Temp**	**Flow**	**Temp**	**Temp**	**Heatsink**	**actual**	**heatsink**	**sheet data**	***Single inlet***			
Slot 2	**C**	**m/s**	**C**	**C**	**dT**	**dT/ P[W]**	**load [W]**	**dT**	***Date***	05/04/2005		
A top	57	4.3	22.2	36.8	34.8	0.081	431.52	25.89				
B	57.2	3.8	22.2	36.8	35	0.081	431.52	25.89	***30% blockage at centre***			
C	55.1	3	22.2	36.8	32.9	0.076	431.52	25.89	**HS Rt data sheet =**		0.06	
D	44.5		22.2	36.8	22.3	0.052	431.52	25.89	***Exit air delta T***		**14.6**	
E	45		22.2	36.8	22.8	0.053	431.52	25.89				
F	41.3		22.2	36.8	19.1	0.044	431.52	25.89				
Average	50.02	3.70			**27.82**	0.06		25.89				
Av top					34.23							
									Delta T [C] / Kw		9.96	Kw
									3.44			
Power												
	include	Volts	Amps	Watts					**Impeller Blowing**			
Xantrex		42.8	89.9	3847.72								
Fuji		43.3	91.5	3961.95								
3kw		48.1	36	1731.6								
Fans	1	48.1	8.7	418.47								
total cabinet watts				***9959.74***								
Watts per device =				5.99								
Power in Bias circuit =				49.44		Check	9960					
Power in back mounted components =				108.23								
Total insrumented board load =				589.19								

Table 9-11 Motorized Impellers Blowing 9.9kW

Exp Numb	**4**		**Ambient**	**Exit air**		**HS Rt**			***4 EBM motorized impellers below rack***			
Position	**Temp**	**Flow**	**Temp**	**Temp**	**Heatsink**	**actual**	**heatsink**	**sheet data**	***Single inlet***			
Slot 2	**C**	**m/s**	**C**	**C**	**dT**	**dT/ P[W]**	**load [W]**	**dT**	***Date***	05/04/2005		
A top	49.2	6	21.7	32.6	27.5	0.087	316.32	18.98				
B	49.5	6	21.7	32.6	27.8	0.088	316.32	18.98	***30% blockage at centre***			
C	47.6	6	21.7	32.6	25.9	0.082	316.32	18.98	**HS Rt data sheet =**		0.06	
D	38.6		21.7	32.6	16.9	0.053	316.32	18.98	***Exit air delta T***		**10.9**	
E	39.1		21.7	32.6	17.4	0.055	316.32	18.98				
F	36.5		21.7	32.6	14.8	0.047	316.32	18.98				
Average	43.42	6.00			**21.72**	0.07		18.98				
Av top					27.07							
									Delta T [C] / Kw		7.37	Kw
									3.67			
Power												
		Volts	Amps	Watts					**Impeller Blowing**			
Xantrex		41.5	65.9	2734.85								
Fuji		41.5	60	2490								
3kw		48.1	36	1731.6								
Fans	1	48.1	8.7	418.47								
total cabinet watts				***7374.92***								
Watts per device =				4.39								
Power in Bias circuit =				25.54		Check	7375					
Power in back mounted components =				108.23								
Total insrumented board load =				450.08								

Table 9-12 Motorized Impellers Blowing 7.3kW

Exp Numb	**5**		**Ambient**	**Exit air**		**HS Rt**			***4 EBM motorized impellers above rack***			
Position	**Temp**	**Flow**	**Temp**	**Temp**	**Heatsink**	**actual**	**heatsink**	**sheet data**	***Single inlet***			
Slot 2	**C**	**m/s**	**C**	**C**	**dT**	**dT/ P[W]**	**load [W]**	**dT**	***Date***	06/04/2005		
A top	52.6	6	24.1	31.4	28.5	0.066	432.96	25.98				
B	53.6	6	24.1	31.4	29.5	0.068	432.96	25.98	***30% blockage at centre***			
C	51.9	6	24.1	31.4	27.8	0.064	432.96	25.98	**HS Rt data sheet =**		0.06	
D	41.4		24.1	31.4	17.3	0.040	432.96	25.98	***Exit air delta T***		**7.3**	
E	41.8		24.1	31.4	17.7	0.041	432.96	25.98				
F	39.7		24.1	31.4	15.6	0.036	432.96	25.98				
Average	46.83	6.00			**22.73**	0.05		25.98				
Av top					28.60							
									Delta T [C] / Kw		9.49	Kw
									3.01			
Power												
	include	Volts	Amps	Watts					**Impeller Sucking**			
Xantrex		43	90.2	3878.6								
Fuji		42.7	90.9	3881.43								
3kw		48.1	36	1731.6								
Fans	0	48.1	8.7	0								
total cabinet watts				***9491.63***								
Watts per device =				6.01								
Power in Bias circuit =				51.87		Check	9492					
Power in back mounted components =				108.23								
Total insrumented board load =				593.05								

Table 9-13 Motorized Impellers Sucking 9.4kW

Exp Numb	**6**		**Ambient**	**Exit air**		**HS Rt**			***4 EBM motorized impellers above rack***			
Position	**Temp**	**Flow**	**Temp**	**Temp**	**Heatsink**	**actual**	**heatsink**	**sheet data**	***Single inlet***			
Slot 2	**C**	**m/s**	**C**	**C**	**dT**	**dT/ P[W]**	**load [W]**	**dT**	***Date***	06/04/2005		
A top	52.7	6	24.2	31.4	28.5	0.066	432	25.92				
B	53.3	6	24.2	31.4	29.1	0.067	432	25.92	***30% blockage at centre***			
C	52	6	24.2	31.4	27.8	0.064	432	25.92	**HS Rt data sheet =**		0.06	
D	41.2		24.2	31.4	17	0.039	432	25.92	***Exit air delta T***		**7.2**	
E	41.6		24.2	31.4	17.4	0.040	432	25.92				
F	39.5		24.2	31.4	15.3	0.035	432	25.92				
Average	46.72	6.00			**22.52**	0.05		25.92				
Av top					28.47							
									Delta T [C] / Kw		9.43	Kw
									3.02			
Power												
		Volts	Amps	Watts					**Impeller Sucking**			
Xantrex		42.99	90	3869.1								
Fuji		42.6	89.9	3829.74								
3kw		48.1	36	1731.6								
Fans	0	48.1	8.7	0								
total cabinet watts				***9430.44***								
Watts per device =				6.00								
Power in Bias circuit =				51.64		Check	9430					
Power in back mounted components =				108.23								
Total insrumented board load =				591.86								

Table 9-14 Motorized Impellers Sucking 9.4kW

Exp Numb	**7**		**Ambient**	**Exit air**		**HS Rt**			***4 EBM motorized impellers above rack***			
Position	**Temp**	**Flow**	**Temp**	**Temp**	**Heatsink**	**actual**	**heatsink**	**sheet data**	***Single inlet***			
Slot 2	**C**	**m/s**	**C**	**C**	**dT**	**dT/ P[W]**	**load [W]**	**dT**	***Date***	06/04/2005		
A top	43.6	6	23.1	28.1	20.5	0.071	288	17.28				
B	43.1	6	23.1	28.1	20	0.069	288	17.28	***30% blockage at centre***			
C	42.4	6	23.1	28.1	19.3	0.067	288	17.28	**HS Rt data sheet =**		0.06	
D	35		23.1	28.1	11.9	0.041	288	17.28	***Exit air delta T***		**5**	
E	35.2		23.1	28.1	12.1	0.042	288	17.28				
F	33.7		23.1	28.1	10.6	0.037	288	17.28				
Average	38.83	6.00			**15.73**	0.05		17.28				
Av top					19.93							
									Delta T [C] / Kw		6.71	Kw
									2.97			
Power												
		Volts	Amps	Watts					**Impeller Sucking**			
Xantrex		41.5	60	2490								
Fuji		41.5	60	2490								
3kw		48.1	36	1731.6								
Fans	0	48.1	8.7	0								
total cabinet watts				***6711.6***								
Watts per device =				4.00								
Power in Bias circuit =				23.25		Check	6712					
Power in back mounted components =				108.23								
Total insrumented board load =				419.48								

Table 9-15 Motorized Impellers Sucking 6.7kW

Exp Numb	**8**		**Ambient**	**Exit air**		**HS Rt**			***4 EBM motorized impellers above rack***			
Position	**Temp**	**Flow**	**Temp**	**Temp**	**Heatsink**	**actual**	**heatsink**	**sheet data**	***Single inlet***			
Slot 2	**C**	**m/s**	**C**	**C**	**dT**	**dT/ P[W]**	**load [W]**	**dT**	***Date***	07/04/2005		
A top	45.9		25.2	30.5	20.7	0.067	308.16	18.49				
B	46.5		25.2	30.5	21.3	0.069	308.16	18.49	***30% blockage at centre***			
C	45.2		25.2	30.5	20	0.065	308.16	18.49	**HS Rt data sheet =**		0.06	
D	37.5		25.2	30.5	12.3	0.040	308.16	18.49	***Exit air delta T***		**5.3**	
E	37.8		25.2	30.5	12.6	0.041	308.16	18.49				
F	36.2		25.2	30.5	11	0.036	308.16	18.49				
Average	41.52	0.00			**16.32**	0.05		18.49				
Av top					20.67							
									Delta T [C] / Kw		6.95	Kw
									2.97			
Power												
		Volts	Amps	Watts					**Impeller Sucking**			
Xantrex		41.5	64.2	2664.3					**Drift test**		[repeat of 7]	
Fuji		41.1	62.3	2560.53								
3kw		48	36	1728								
Fans	0	48	8.7	0								
total cabinet watts				***6952.83***								
Watts per device =				4.28								
Power in Bias circuit =				24.88		Check	6953					
Power in back mounted components =				108.00								
Total insrumented board load =				441.04								
time				13:35								

Table 9-16 Motorized Impellers Sucking 6.9kW Drift Test

Exp Numb	**9**		**Ambient**	**Exit air**		**HS Rt**			***4 EBM motorized impellers above rack***			
Position	**Temp**	**Flow**	**Temp**	**Temp**	**Heatsink**	**actual**	**heatsink**	**sheet data**	***Single inlet***			
Slot 2	**C**	**m/s**	**C**	**C**	**dT**	**dT/ P[W]**	**load [W]**	**dT**	***Date***	07/04/2005		
A top	43.3		21.8	27.1	21.5	0.072	298.56	17.91				
B	44.1		21.8	27.1	22.3	0.075	298.56	17.91	***30% blockage at centre***			
C	42.8		21.8	27.1	21	0.070	298.56	17.91	**HS Rt data sheet =**		0.06	
D	34.4		22	27.1	12.4	0.042	298.56	17.91	***Exit air delta T***		**5.3**	
E	34.7		22	27.1	12.7	0.043	298.56	17.91				
F	33.2		22	27.1	11.2	0.038	298.56	17.91				
Average	38.75	0.00			**16.85**	0.06		17.91				
Av top					21.60							
									Delta T [C] / Kw		6.78	Kw
									3.19			
Power												
		Volts	Amps	Watts					**Impeller Sucking**			
Xantrex		41.5	62.2	2581.3					**Drift test**		[repeat of 7]	
Fuji		41.1	60	2466								
3kw		48	36	1728								
Fans	0	48	8.7	0								
total cabinet watts				***6775.3***								
Watts per device =				4.15								
Power in Bias circuit =				24.10		Check	6775					
Power in back mounted components =				108.00								
Total insrumented board load =				430.66								
Time				14:05								

Table 9-17 Motorized Impellers Sucking 6.7kW Drift Test

Exp Numb	**10**		**Ambient**	**Exit air**		**HS Rt**			***4 EBM motorized impellers above rack***			
Position	**Temp**	**Flow**	**Temp**	**Temp**	**Heatsink**	**actual**	**heatsink**	**sheet data**	***Single inlet***			
Slot 2	**C**	**m/s**	**C**	**C**	**dT**	**dT/ P[W]**	**load [W]**	**dT**	***Date***	07/04/2005		
A top	44.7		23.4	28.7	21.3	0.070	302.4	18.14				
B	45.3		23.4	28.7	21.9	0.072	302.4	18.14	***30% blockage at centre***			
C	44		23.4	28.7	20.6	0.068	302.4	18.14	**HS Rt data sheet =**		0.06	
D	36		23.4	28.7	12.6	0.042	302.4	18.14	***Exit air delta T***		**5.3**	
E	36		23.4	28.7	12.6	0.042	302.4	18.14				
F	34.4		23.4	28.6	11	0.036	302.4	18.14				
Average	40.07	0.00		exp10	**16.67**	0.06		18.14				
Av top					21.27							
									Delta T [C] / Kw		6.85	Kw
									3.10			
Power												
		Volts	Amps	Watts					**Impeller Sucking**			
Xantrex		41.5	63	2614.5					**Drift test**		[repeat of 7]	
Fuji		41.1	61.1	2511.21								
3kw		48	36	1728								
Fans	0	48	8.7	0								
total cabinet watts				***6853.71***								
Watts per device =				4.20								
Power in Bias circuit =				24.41								
Power in back mounted components =				108.00								
Total insrumented board load =				434.81								
Time				14:50								

Table 9-18 Motorized Impellers Sucking 6.9kW Drift Test

Exp Numb	**11**		**Ambient**	**Exit air**		**HS Rt**			***4 EBM motorized impellers above rack***			
Position	**Temp**	**Flow**	**Temp**	**Temp**	**Heatsink**	**actual**	**heatsink**	**sheet data**	***Single inlet***			
Slot 2	**C**	**m/s**	**C**	**C**	**dT**	**dT/ P[W]**	**load [W]**	**dT**	***Date***	07/04/2005		
A top	46.2		24.3	30.1	21.9	0.071	307.68	18.46				
B	48.8		24.3	30.1	24.5	0.080	307.68	18.46	***30% blockage at centre***			
C	45.6		24.3	30.1	21.3	0.069	307.68	18.46	**HS Rt data sheet =**		0.06	
D	37.7		23.9	29.6	13.8	0.045	307.68	18.46	***Exit air delta T***		**5.8**	
E	37.4		23.9	29.6	13.5	0.044	307.68	18.46				
F	35.8		23.9	29.6	11.9	0.039	307.68	18.46				
Average	41.92	0.00		exp10	**17.82**	0.06		18.46				
Av top					22.57							
									Delta T [C] / Kw		6.95	Kw
									3.25			
Power												
		Volts	Amps	Watts					**Impeller Sucking**			
Xantrex		41.5	64.1	2660.15					**Drift test**		[repeat of 7]	
Fuji		41.1	62.4	2564.64								
3kw		48	36	1728								
Fans	0	48	8.7	0								
total cabinet watts				***6952.79***								
Watts per device =				4.27								
Power in Bias circuit =				24.84								
Power in back mounted components =				108.00								
Total insrumented board load =				440.52								
Time												

Table 9-19 Motorized Impellers Sucking 6.9kW Drift Test

10 Appendix

10.1 Board Design Schematic and Component Selection

Bridge rectifiers have been chosen to mimic the thermal performance of all major power dissipating devices, the Correlator, FPGA's, ASICS and RAM. These parts are mounted on the topside of the board, under an aluminum-finned heat sink. Each bridge contains four diodes and can be driven, by varying the current to a power level close to the device it is intended to represent.

Rectifiers were chosen because the device form factor is quite close to all components, measuring 18mm x 22mm x 4mm and can be mounted to the heat sink with an interface material similar to that intended for the real boards.

Diodes also have the advantage over power resistors in that; power dissipated is proportional to applied current in a near linear relationship, whereas power dissipation in power resistors follows the square of the applied voltage [or I as I = V/R]. The control of the power is therefore more easily regulated in rectifiers.

Additionally most power semiconductor devices dissipating more than a few watts are designed to be heat sink mounted, as operating at high temperature can damage them. Power resistors are unlikely to be damaged by operating at high temp and are not normally mounted to heat sinks. This may also explain why rectifiers are approximately 1/5 the cost of mountable power resistors. 1152 devices have been used.

The top of the boards are divided into three circuits of 24 bridges each arranged in series mounted on the heat sink. [Figure 10-1 Thermal Baseline Board]. Three Bias resistors are used to set the current through each circuit, thereby enabling various power levels to be set and controlled by varying one common power supply [voltage]. The bias resistors also serve to represent other power dissipating devices not mounted on the heat sink. These are local low voltage DC/DC power supplies and the PC104.

On the other side of the board are 25 560-ohm thick film power resistors representing all back mounted components. Total power is 130 watts at a supply voltage of 50 volts. By arranging the boards in this way, it is possible to adjust the output power of all boards simultaneously. It is intended to connect all heat sink mounted components to a common power supply and all back mounted resistors to a second common power supply.

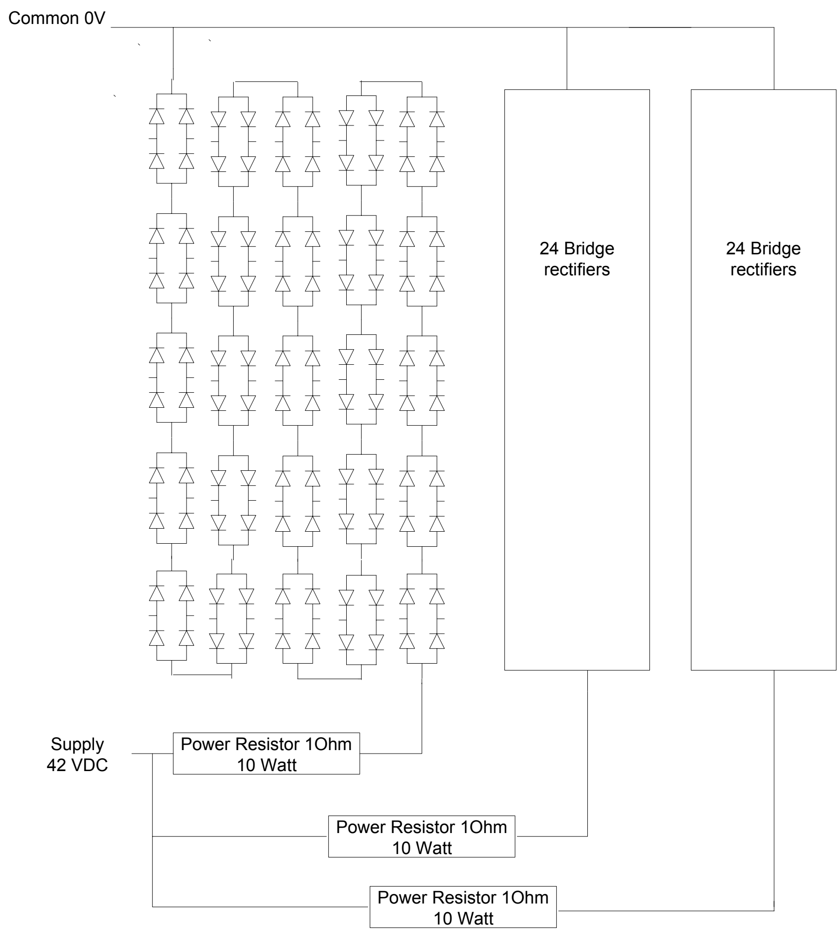

Figure 10-1 Thermal Baseline Board Schematic

Cross sectional view of thermal mock-up baseline board showing position of components and heat sink.

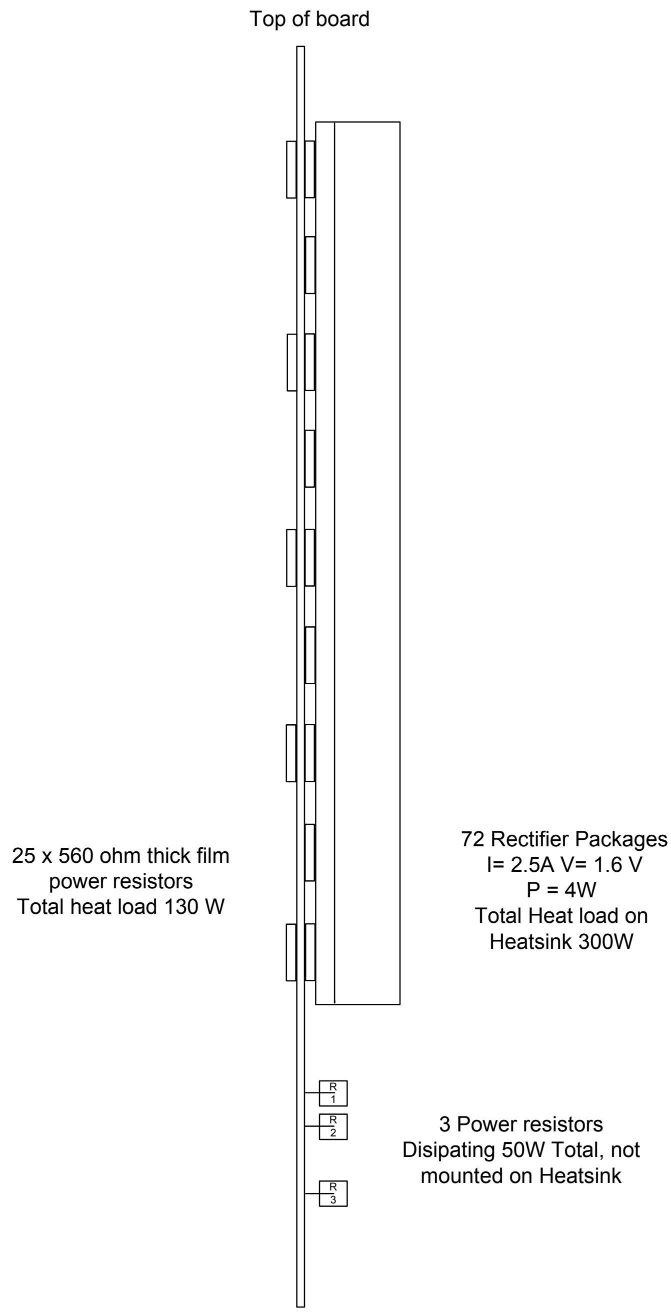

Figure 10-2 Thermal Baseline Board (Cross-Sectional View)

Front side of board with heat sink [Aavid 63340] and component positions shown.

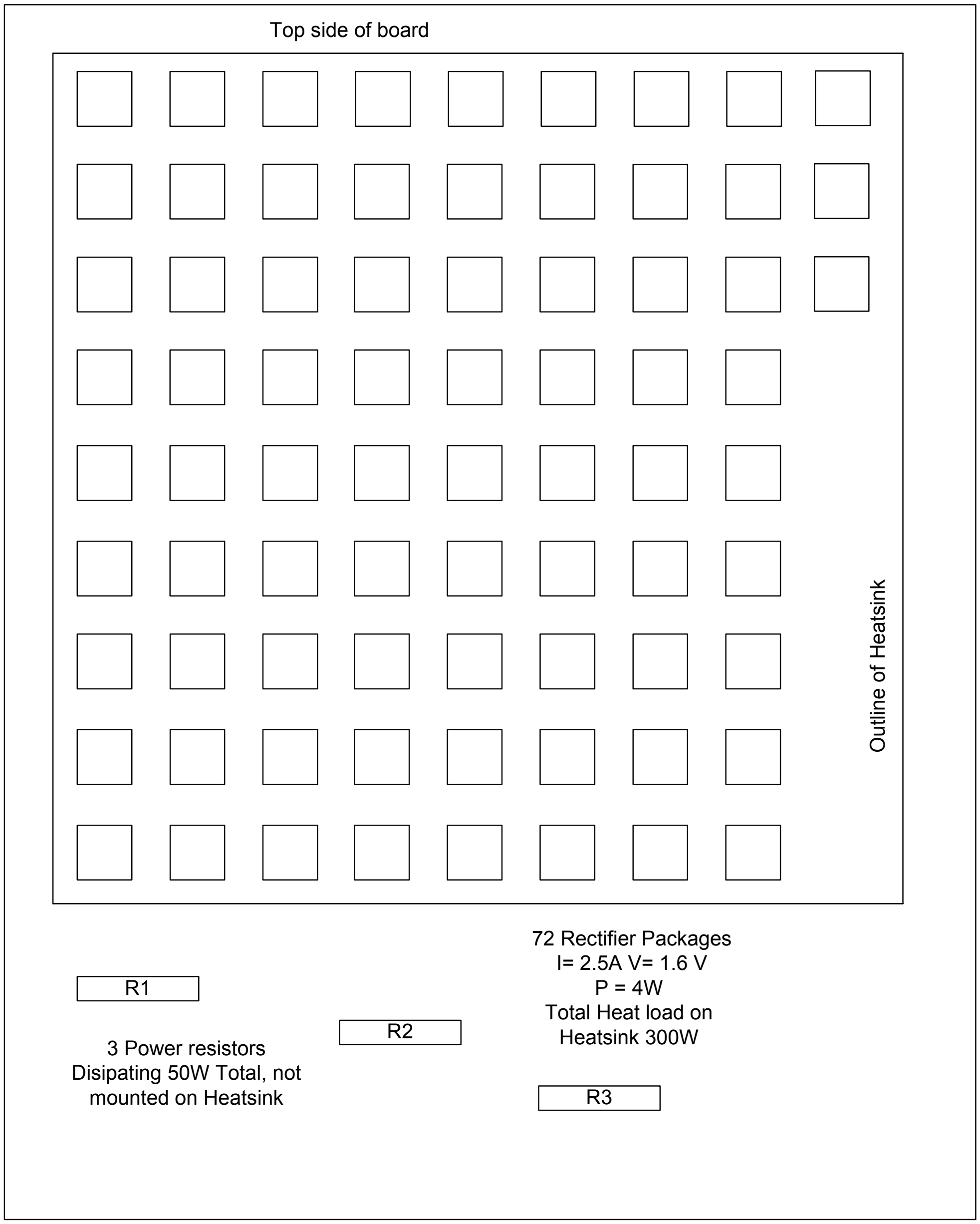

Figure 10-3 Thermal Baseline Board (Front View)

Back side of board showing thick film power resistors.

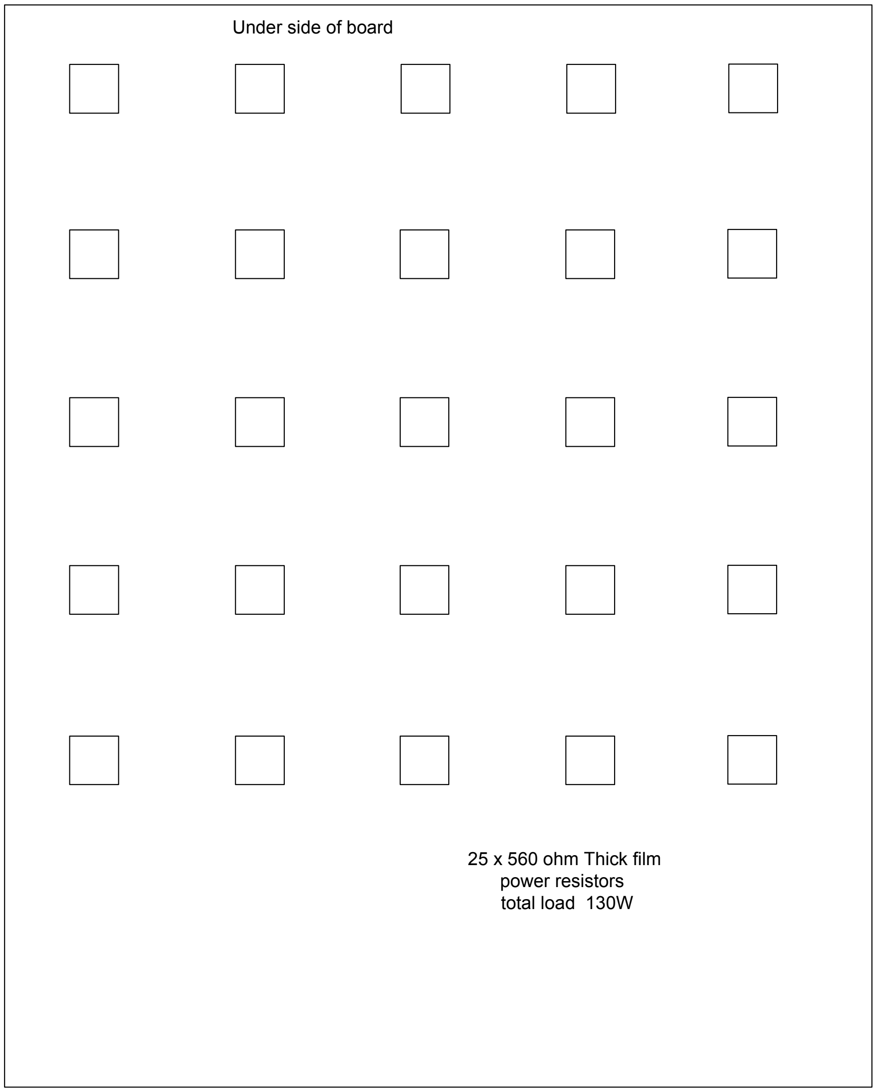

Figure 10-4 Thermal Baseline Board (Back View)

10.2 <u>Thermal Component Selection</u>

10.2.1 Heat sink

Given space limitations [requirements], board size, component density, component power dissipation and placement, a heat sink size of 350mm x 350mm x 33mm was selected and used for thermal calculations. Note, other considerations taken into account were:

- *Availability*: Some heat sink profiles are not stocked, so for prototype testing purposes are unavailable.
- *Cost*: Minimum production runs of some heat sink extrusions are in the order of 150 ft at US $220 /ft and incur tooling charges.
- *Weight*: Has an impact on enclosure and sub rack design and therefore the availability of these and other components.

10.2.2 Fan Selection

Finned Heat sink performance is largely dependant upon airflow. As with heat sink selection, fan selection has also to be made based on similar considerations, space, fit, availability etc. Therefore heat sink performance has to be traded against desired/possible airflow.

In the Dual Circuit Cooling airflow design, axial fans have been chosen to give an estimated flow of 2000cfm, with flow through the sub racks between 1200cfm and 900cfm. Cross section area is estimated at 1 sq ft. Thus flows are expected to be up to 1200 lfm [6.1] m/s and 900 lfm [4.6m/s] respectively.

The proposed arrangement is a pull or push design. Pressure drops have been measured at 0.5 inches of water. Two types of fans are to be tested, axial and motorized impellers.

In the single entry design the airflow is expected to be less than the max cfm of the unloaded fan performance. [12 axial fans at 320 cfm or 4 impellers at 500cfm] A flow of greater than 1400 cfm will be adequate.

Actual flows will need to be determined experimentally. Average values of 2m/s to 5m/s are used for further calculation.

10.3 Thermal Component, Calculations

10.3.1 Calculation of the Thermal Resistance for Heat Sink

Given the previously mentioned restrictions on heat sink and fan parameters the optimum profile [for testing purposes] has been chosen as a stock item, part number 63340 manufactured by Aavid Thermalloy .

The heat sink is cut down to 350mm x350mm from the standard Aavid profile [431mm x 350mm]. Aavid have a standard performance calculation tool available on their web site for this material[i]. However because we intend to use a non standard part, it is not possible to use the thermal resistance calculation tool directly, instead to calculate thermal resistance from the Aavid 63340 data sheet an equivalent fin area has to be specified. It is assumed that this will lead to a small error. The figure below represents the performance of a 431mm x 280mm section [1224 cm^2].

10.3.2 Temperature Rise of Heat Sink

From the Aavid data sheet at airflow of 1000 lfm [5m/s], thermal resistance is estimated to be:

$\theta = 0.063$ °C/W

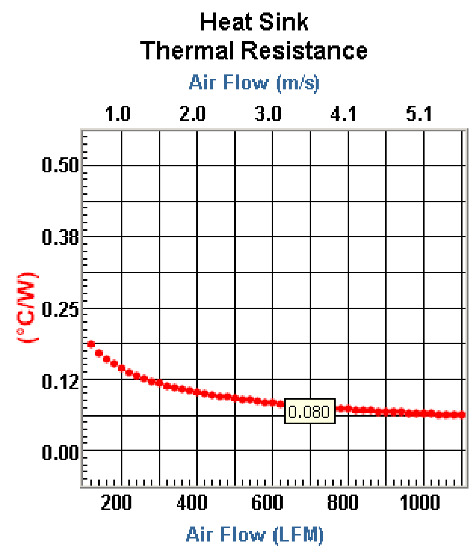

Figure 10-5 Heat Sink Thermal Resistance

Note: this is the maximum best-case airflow using all the fans at 100% capacity. It may be possible to reduce the airflow and thereby extend the fan life, after the results of the thermal testing have been evaluated.

For a lower flow of 2 m/s, $\theta = 0.101$ °C/W

Dissipating a load of 300 watts [64 correlator chips @ 4W + 16 recirculation controllers @ 2.7W] the temperature rise ΔT would be:

300W x 0.063°C/W °= 19° C @5m/s

300W x 0.101°C/W °= 30.3° C @2m/s

However as it is expected that the ambient air pressure under operating conditions is lower due to operating at 7000ft above sea level. A derating factor of 0.85[ii] has to be applied to the ΔT, for a corrected ΔT of:

300W x 0.063°C/W °C / 0.85 = 22.3°C @5m/s
300W x 0.101°C/W °C / 0.85 = 35.6°C @2m/s

Assuming an ambient temperature of 21°C the heat sink operating temperature would be:

21°C + 22.3°C = 43.3°C @5m/s
21°C + 35.6°C = 56.6°C s @2m/s

For a 10C ambient the heat sink temp would be:

10°C + 23.3°C = 33.3°C @5m/s
10°C + 35.6°C = 45.6°C @2m/s

10.3.3 Junction/Die Temperature

Estimated[iii] thermal resistance for Junction to case of the correlator chip is θj°C = 0.5 °C/W, therefore there will be an additional 2°C rise in junction to case temperature on a 4W correlator chip.

Note: Thermal resistance of the interface material is neglected as it is estimated to be less than 1°C, when using materials such as A-Pli [Aavid] with a θ of 0.1°C/in²/W.

10.3.4 Volumetric Flow of Air to Cool an Electronic Device[1]

Overall enclosure power dissipation and the enclosure temperature rise can be used to calculate the volume of air required for cooling using the relationship:

$V = K * P_v / \Delta T$

Where:
V = Volumetric flow rate m^3/h [measured volume in unit time]
P_v = Power dissipation in Watts [1 watt = 1 joule/second]
ΔT = Temperature change °C
K = Constant, from 1/Cp φ [3.7 at 2100m]
Where Cp equals isobaric specific heat capacity of air 0.27 Wh / kg * K or [1KJ / Kg * k]
Where φ equals air density 1.2 Kg/m^3 at 20°C and 1 Atm [1Kg / m^3 at 2100 m]

Thus for an air flow rate V = 2028 m^3 /h [1200cfm]

---

[1] Elma Catalogue and others

Temperature change of the air $\Delta T = K * P_v / V$

$\Delta T = 3.7 \times 8000W / 2028m^3$

$= 14.6^oC$

10.4 Enclosure Pressure Losses and System Resistance

10.4.1 Calculation of the System Resistance

Once exit air temperature and system power levels are measured it is possible to determine system resistance. Volume is calculated using the volumetric heating value see [10.3.4]. Flow is calculated using the estimated cross section. This value of *actual flow* is then compared to the fan performance graph [supplied by the fan manufacturer]. System resistance is read from the graph where *actual flow*, our operating point, intersects the fan performance curve. [Red line]

By this method, the frictional losses are calculated to give a pressure drop of approximately 0.52 inches of water.

System pressure was measured with a water manometer at 0.5 inches of water, and was found to be in good agreement with calculated value.

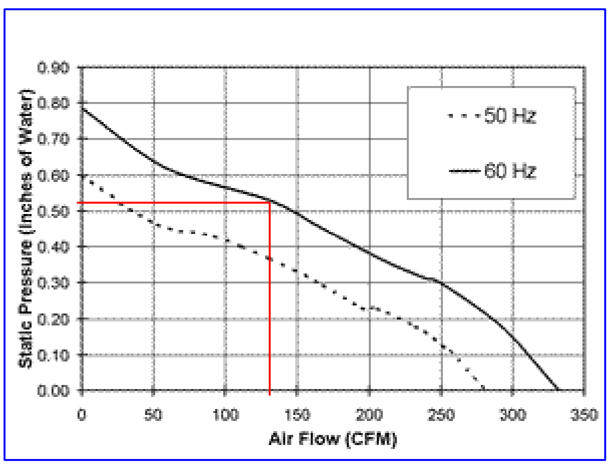

Figure 10-6 Axial Fan Performance (Comair –Rotron)

10.4.2 Estimated temperature -Dual Circuit Cooling

A combination of 10C ambient air @ 2 m/s would give a Die temp of [300W x 0.101°C/W °C / 0.85] + [4W x 0.5°C/W] +10° C = **47.6°C**.

A combination of 21C ambient air @ 5 m/s would give a Die temp of [300W x

0.063°C/W °C / 0.85] + [4W x 0.5°C/W] +21° C = **45.3°C.**

10.4.3 Estimated temperature -Single Circuit Cooling

At an operating point of 6.5kW

A combination of 15C ambient air @ 5 m/s would give a Die temp of ;

Lower sub rack heat sinks

[300W x 0.063°C/W °C / 0.85] + [4W x 0.5°C/W] +15° C = **39.3°C**.

Upper sub rack heat sinks

[300W x 0.063°C/W °C / 0.85] + [4W x 0.5°C/W] +20° C = **44.3°C.**

10.4.4 Fan MTBF

The intention of reducing operational temperature is to extend system life and increase reliability. Some consideration will need to be given to fan failure.

Typical fan life is 80,000 hrs MTBF. In an Axial fan arrangement, the complete correlator would contain upwards of 400 fans. On average a fan would need replacing every 8 days. A minimum number of fans and the lowest flow rate for a given temperature should increase overall MTBF.

In a single air entry arrangement using DC motorized impellers fan numbers are reduced to less than 130.

10.4.5 Measurement Errors

On the back of the board are 25 thick film power resistors dissipating in the order of 130 watts. The effect of this on the adjacent board, or of transmission through the board has not been taken into account in the calculations shown here.

Software simulations of board performance **do** take into account this extra heat load, and some small discrepancy is therefore expected.

11 Photographs of the Test Rack

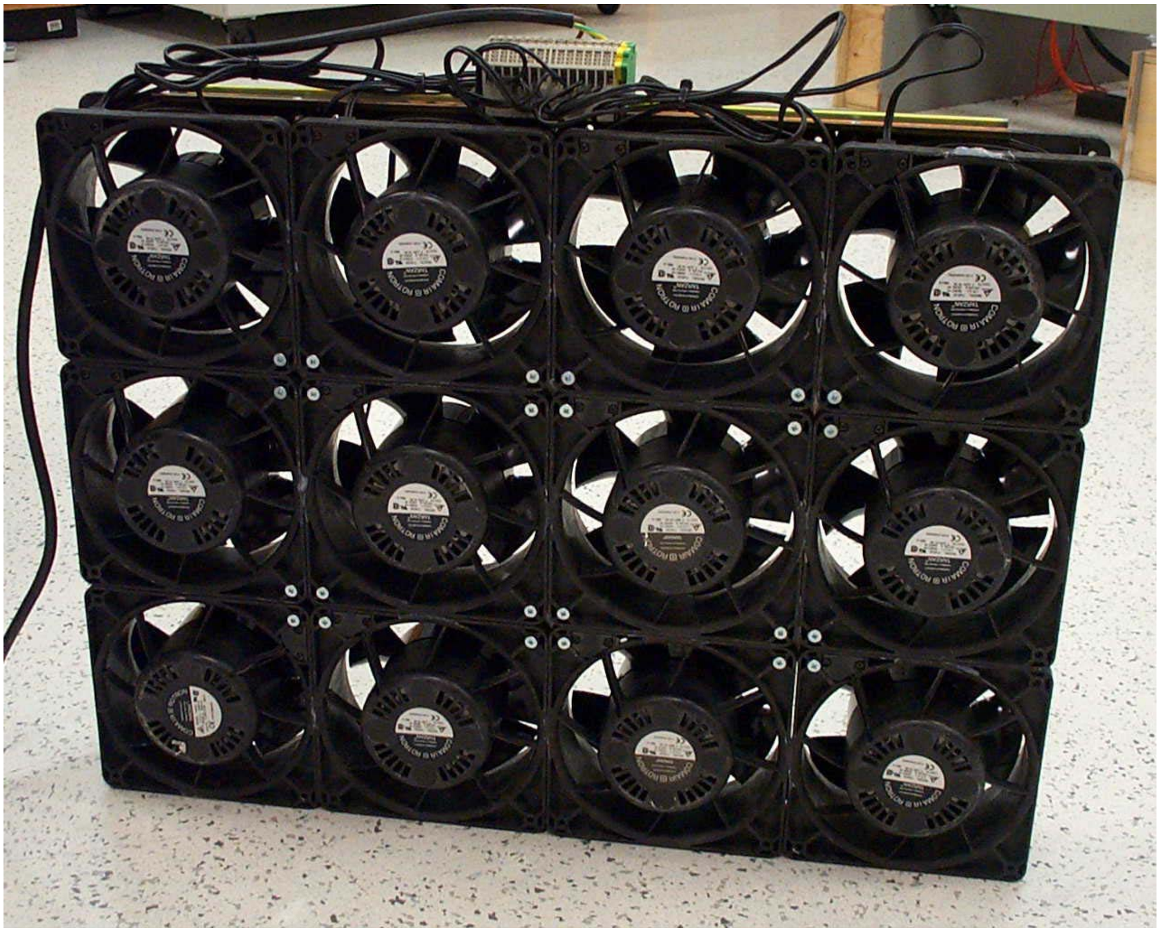

Figure 11-1AC Axial fan assembly

Figure 11-2 Impellers above Upper Subrack

Figure 11-3 Impeller Discharge

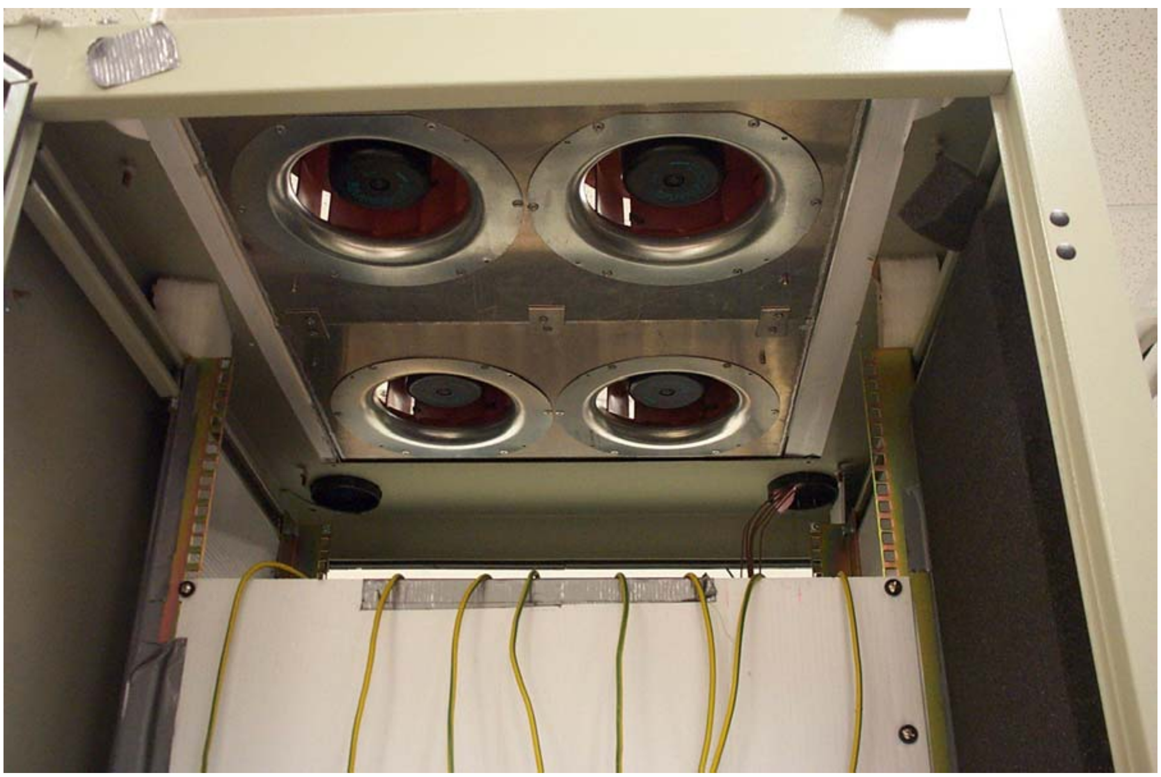

Figure 11-4 Impellers Viewed from Rear

Figure 11-5 Thermal Test Rack (covers removed)

[i] http://www.aavidthermalloy.com/products/bondfin/thermal.shtml

[ii] How to Select a Heat Sink, Seri lee, Advanced thermal engineering http://www.aavidthermalloy.com/technical/papers/pdfs/select.pdf

[iii] Simulation data for BGA FF896. Device packaging and thermal characteristics Xilinx.com