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THERMACORE, INC.

LEOLA, PENNSYLVANIA

COST-EFFECTIVE SOLAR COLLECTORS USING HEAT PIPES

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FOREWARD

This report is submitted to the United States Department of Energy, Office of Conservation and Solar Application, Research and Development Branch for Heating and Cooling, Dr. Frederick H. Morse, Chief, and covers the work conducted by Thermacore, Inc. under Contract DE-AC04-77CS04099. The work was performed under the direction of Dr. Charles Bankston, Acting Program Manager from the DOE R&D Branch, Heating and Cooling Office, who also serves as the contract technical monitor from the Los Alamos Scientific Laboratories.

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Systems Implications, Design and Integration was done under a subcontract with GE, Ronald C. Hodge, Program Manager.

Heat Pipe fluid investigation has been doen by Dr. Alan G. MacDiarmin, Consultant, Inorganic Chemistry.

TABLE OF CONTENTS

	Page
Foreward	i
Acknowledgements	ii
Table of Contents	iii
List of Figures	iv
List of Tables	v
Abstract	vi
1. Introduction	1
2. Design Verification Tests	6
3. Continued Initial Test Data	31
4. Conclusion and Recommendations	35

LIST OF FIGURES

<u>Figure No.</u>	<u>Figure Title</u>	<u>Page</u>
1.1	Program Schedule	2
1.2	Task Flow Diagram	3
2.1	Heat Pipe-Fin Assembly	7
2.2	Test Loop and Instrumentation	9
2.3	TC-100 and Heat Pipe Collectors	10
2.4	Heat Pipe Collector	11
2.5	Instantaneous vs Inlet Temperature	15
2.6	Heat Pipe Collector and TC 100-8 Shroud Collector All Day Efficiency	16
2.7	Heat Pipe Collector & TC 100-8 Shroud Collector All Day Efficiency	17
2.8	Heat Pipe Collector & TC 100-8 Shroud Collector All Day Efficiency	18
2.9	Heat Pipe Collector & TC 100-8 Shroud Collector All Day Efficiency	19
2.10	Heat Pipe Collector & TC 100-8 Shroud Collector All Day Efficiency	20
2.11	ΔT vs Time of Day Heat Pipe Collector & TC 100-8 Shroud Collector	22
3.1	Life Test Data	32

LIST OF TABLES

<u>Table No.</u>	<u>Table Title</u>	<u>Page</u>
2.1	Operating Conditions	14
2.2	Summary of Test Data	28
2.3	Instantaneous Efficiency Optimum Tilt	29
2.4	All-Day Efficiencies-Optimum Tilt	29
2.5	Instantaneous Efficiency 60° Tilt	29
2.6	All-Day Efficiencies 60° Tilt	29
2.7	Stagnation Temperatures	30
2.8	Average ΔT History	30

ABSTRACT

The objective of the program is the demonstration of high performance, cost effective, non-concentrating solar collectors using heat pipes. The end product will be directly applicable for efficient use with absorption and Rankine cycle chillers. Evacuated tubular solar collectors were selected as the only economical non-concentrating approach capable of efficient operation of chillers. The General Electric TC family of collectors was chosen because of their high level of performance and compatibility with heat pipe integration.

Heat pipe fluid-vessel combinations continued to be life tested at design and stagnation conditions for time periods exceeding 14000 hours. Additional testing was carried out at the lower end of the environment temperature range by freeze-thaw testing of several water heat pipes. Additional fluids search work resulted in developing a procedure to purify trimethylborate.

Eight trimethylborate heat pipes were fabricated and installed in a modified GE TC-100 solar panel. Solar performance tests were performed on the heat pipe collector and a standard TC-100 collector. Heat pipe collector performance exceeded 90% of the TC-100.

A source of water compatible steel, NP454, was identified as was an experimental tubing manufacturer. The current availability of NP454 and the successful demonstration of antifreeze mechanisms lays the ground work for testing a heat pipe collector using water heat pipes.

1. INTRODUCTION

This interim report documents the work performed by Thermacore, Inc., its subcontractor and consultants under Contract DE-AC04-77CS04099. The object of the program is to investigate the cost effectiveness of heat pipe solar collectors.

During the reporting period, work concentrated on the design verification testing of the heat pipe collector using trimethylborate heat pipes. Trimethylborate-1010 steel heat pipes were used as they were the best fluid-vessel combination available at the time. However, water is a generally superior heat transfer fluid if its shortcomings of freeze expansion and incompatibility with most steels can be overcome. A water compatible steel alloy, NP454, was identified, and proven by extensive life testing. Freeze resistance was demonstrated with copper-water and 347SS-water heat pipes using a technique applicable to NP 454. When coupled with the recent availability of NP454 coil stock and success in finding a manufacturer willing to fabricate NP454 tubing, the impetus is provided to repeat the design verification testing with water heat pipes.

The Program Schedule and Task Flow Diagram are seen in Figures 1.1 and 1.2.

Significant life test heat pipes will continue to be tested. Freeze-thaw testing will continue. It is anticipated that the recommendation for additional testing of the trimethylborate heat pipe collector and the standard TC-100 along with repeating the design verification tests with NP454 water heat pipes will be carried out.

Figure 1.1

PROGRAM SCHEDULE

Figure 1.2

TASK FLOW DIAGRAM

1.1 Background

Prior work analyzed pertinent collector systems and established heat pipe design goals for optimum system performance. From this analysis, separate components were designed and fabricated. The search for an improved heat pipe fluid was initiated. The component design was subjected to careful scrutiny from the system integration and producibility viewpoints. Heat pipes, collector-to-heat pipe and heat pipe-to-pumped-fluid loop interfaces were tested in the laboratory and in an outdoor collector facility. Initial cost estimates were done for several heat pipe fluid-vessel combinations.

Based on the initial design and test results, the collector system was re-evaluated with emphasis on the advantages of the heat pipe. This analysis showed that the heat pipe collector should provide a 9-13% reduction in cost per unit energy delivered as compared to the standard TC-100. Additional cost savings at the system level could be realized by elimination of intermediate heat exchanger by the use of potable water in a draindown system which may be possible with the heat pipe collector placed in an east-west orientation.

A production processing equipment concept was formulated from which a laboratory prototype processor was designed. This processor reduces the critical steps in processing a heat pipe from 30 minutes to 15 seconds. Based on the production processor, a cost analysis showed that the heat pipe could be manufactured for \$1.50 (1978 dollars) which was the base line goal (1977 dollars).

A test plan was written from which the design of the heat pipe collector can be verified. The search for fluids and on-going tests narrowed the fluid-vessel combination to four: trimethylborate-1010

steel, ethanol-1010 steel, water-NP454, and water-copper. However, the water systems were without an adequate freeze resistant mechanism also capable of withstanding stagnation conditions.

1.2 Summary

Life testing and evaluation of heat pipe fluid-vessel combinations continued. An additional 19 heat pipes were fabricated and tested. The total number of heat pipes tested now stands at 94. An additional 56,500 hours of electrical testing were accumulated, bringing the total to 123,500 hours. Individual pipes exceed 14,000 hours.

Testing at the environmental extremes continued. Two trimethylborate-1010 steel heat pipes and one ethanol-1010 steel heat pipe were stagnation tested in the solar panel for 300 days each. A copper-water heat pipe with a fiber glass wick has survived 335 freeze-thaw cycles. Two copper-water-copper-wick heat pipes have survived 160 cycles each.

Eight trimethylborate-1010 steel heat pipes were fabricated and placed in an modified TC-100 collector which was connected in series with a standard TC-100 collector.⁶ Comparative testing over a two month period provided 10 days of performance tests. From the test results, while not fully understood at this time, it was concluded that the present trimethylborate heat pipe collector is approximately 10% less efficient than the standard TC-100 collector. However, additional testing should be carried out to clarify the results.

2. DESIGN VERIFICATION TESTING

The culmination of the work to date was the design verification testing which was performed during April and May 1979. The heat pipe selected for testing was trimethylborate-1010 steel which was the best fluid-vessel combination available at the time when hardware was committed. It would have been desirable to use the water-NP454 combination, however, this was not possible as NP454 coil stock was not available, nor had a manufacturer been identified which would convert the sheet into tubing.

2.1 Heat Pipe Fabrication

A single collector panel requires eight heat pipes. Accordingly, 10 heat pipes were fabricated from which eight were chosen for the verification test. The heat pipe design is seen in Figure 2.1.

The 1010 steel vessels were degreased, vacuum fired, bent to shape and stored in an inert atmosphere to prevent oxidization of the clean steel. Individually the pipes were fitted with end caps, evacuation tube and leak checked. The copper fins were attached by vacuum brazing with silver-copper eutectic braze material. Following the brazing operation the vacuum system was backfilled with dry argon, which prevented air or moisture from entering the heat pipes.

The argon filled heat pipe was immediately transferred to the processing station, where it was connected and evacuated. This station was designed for vacuum out-gassing of the heat pipe at 200°C and the glass ampoule of specially purified trimethylborate at 100°C. The objective of vacuum out gassing was to remove any traces of absorbed gases on the inner surface of the heat pipe and to assure that no water was present. Water reacts with trimethylborate to form methanol and boric acid thus

Figure 2.1

HEAT PIPE-FIN ASSEMBLY

rendering the heat pipe unusable.

Following vacuum-out gasing, the heat pipe was cooled and the glass ampoule broken, with the subsequent vacuum distillation of the trimethylborate into the heat pipe. Upon completion of the distillation, the heat pipe was temporarily valved off from the vacuum system. The heat pipe was then heated to the desired temperature and allowed to stabilize. After stabilization, thermal measurements were taken quarter-hourly to detect any performance changes. If any changes were detected, the valve to the vacuum systems was opened and any collection of non-condensable gases and a small amount of trimethylborate were pumped out.

This process was repeated until the heat pipe operated for a minimum of four hours with no indication of performance change, at which time the heat pipe was sealed off from the vacuum system by welding the evacuation tube. The heat pipe was then tested overnight to assure that the performance was stable.

All of the heat pipes were tested at 70°C (158°F) transferring in excess of the required maximum 108 watts with less than a 10°C measured ΔT . Following fabrication of the heat pipes, they were delivered to GE for insertion into the test manifold.

2.2 Test Setup

The standard TC-100 and heat pipe collector were set-up as seen in Figure 2.2. Figure 2.3 shows the two collectors side-by-side. The heat pipe collector is on the right. Figure 2.4 is a close-up of the heat pipe collector.

The engineering prototype manifold is shown at the top of the heat pipe collector. This prototype manifold was built to simulate a die-stamped production manifold in terms of resultant pressure drop. The

Figure 2:2 Test Loop and Instrumentation

predicted production manifold pressure drop was 0.65 psi at a 0.75 gpm flow rate.¹ The measured ΔP across the engineering prototype manifold was 0.65 psi at 0.75 gpm flow rate.

2.3 Test Plans

The test plan as developed and presented in the second interim report¹ had the following objectives:

1. Compare the performance of the heat pipe collector to the TC-100 collector.
2. Validate the analytical predictions.
3. Obtain operational experience with the heat pipe collector.

The performance of the heat pipe collector relative to the TC-100 collector was to be assessed by evaluating and comparing the instantaneous and all-day efficiencies of the two collectors at 100, 200 and 300°F inlet temperatures for flow rates of 0.25, 0.5, and 0.75 gpm. The TC-100's design flow rate is 0.25 gpm, and the heat pipe collector's designed flow rate is 0.75 gpm.

Following these tests, the collectors were to be stagnated for three days with subsequent testing at optimum flow rates with a 100°F inlet temperature. Additionally, the test loop was to be set up so that each collector received identical solar insolation and had essentially equivalent inlet fluid temperature.

The test procedure was to measure and record the flow rates, insolation and temperatures from which the instantaneous and all-day collection efficiencies were calculated. These efficiencies were then used to compare the performance of the heat pipe collector to that of the standard TC-100 collector.

In the test set-up shown in Figure 2.2, T_1 , T_2 , T_3 , T_4 , T_{17} and T_{18} were RTD probes used to measure critical fluid temperatures. T_5 , T_6 , T_7 , T_8 , T_9 , T_{10} , T_{11} , T_{12} , T_{13} , T_{14} , T_{15} , T_{16} were thermocouples used primarily during stagnation testing and were attached directly to the fin, serpentine loop or heat pipe. P_1 , P_2 , P_3 , P_4 measured the pressure drop across each collector. In addition, the flow rates, direct insolation, diffuse insolation, and collector tilt angle were also recorded.

An error analysis was performed to determine test instrumentation and hardware accuracies. Cumulative test instrumentation errors resulted in a $\pm 1.8\%$ measurement accuracy. In order to minimize the impact of shroud-to-shroud variations, twenty-four (24) shrouds were individually tested. By analyzing the individual shroud performance data, two (2) equivalent eight shroud sets were identified, coded and installed into the test collectors.

Test data was printed out every five minutes except one hour before and one hour after solar noon. During this time, the data was recorded every minute.

2.4 Test Data, Results & Analysis

The two collectors were tested according to the test plan with modifications as dictated by initial results. The operating conditions for each test performed is seen in Table 2.1.

Table 2.1

Operating Conditions

STRIP CHART NO.	FLOW RATE IN GPM		DESCRIPTION	INLET TEMP. IN ° F		TILT ANGLE	COMMENTS
	TC100	HEAT PIPE					
125	.250	.750	Performance	100		Optimum	
127	.250	.750	Performance	200		Optimum	
128	.250	.750	Performance	300		Optimum	
129	.250	1.000 .500	Performance	200		Optimum	Heat pipe flow was changed at Solar Noon
130	.250	.750	Performance	100		60°	TC100 was shut off at Solar Noon
132	.250	.750	Performance	100		60°	
133	.250	.750	Performance	200		60°	
134	.250	.750	Performance	300		60°	
134-A	-	-	Stagnation	-		Optimum	
135	.250	.750	Post Stagna- tion Performance	120		Optimum	

A summary of the test data and instantaneous efficiencies at solar noon for all of the strip charts except #135 is seen in Table 2.2. Figure 2.5 shows the instantaneous efficiencies of the two collectors as a function of inlet temperature, tilt and flow rate. The useful energy collected and all-day efficiencies are shown for the two collectors in Figures 2.6 through 2.10. Tables 2.2 through 2.6 compare the instantaneous and all-day efficiencies of the two collectors at optimum and a 60° tilt

Figure 2.5

INSTANTANEOUS VS INLET TEMPERATURE

Figure 2.6

HEAT PIPE COLLECTOR & TC 100-8 SHROUD COLLECTOR ALL DAY EFFICIENCY

Figure 2.7

HEAT PIPE COLLECTOR & TC 100-8 SHROUD COLLECTOR ALL DAY EFFICIENCY

Figure 2.8

HEAT PIPE COLLECTOR & TC 100-8 SHROUD COLLECTOR ALL DAY EFFICIENCY

Figure 2.9

HEAT PIPE COLLECTOR & TC100-8 SHROUD COLLECTOR ALL DAY EFFICIENCY

Figure 2.10

HEAT PIPE COLLECTOR & TC 100-8 SHROUD COLLECTOR ALL DAY EFFICIENCY

for 100, 200, and 300°F inlet temperature and optimum flow for each collector.

As mentioned in the summary, and as can be seen by a cursory look at the test data the trimethylborate heat pipe collector's performance was less than the standard TC-100. However, the results are not fully understood as will be obvious in the following description of the tests.

2.4.1 Chart 125

This was the first set of data taken. The inlet temperature was 100°F. The solar noon instantaneous efficiencies were 50.8% for the heat pipe and 50.4% for the TC-100. The all day efficiencies were 37.8% for the heat pipe and 39.1% for the TC-100. The optimum tilt angle was 33°.

These results were very encouraging in that it was expected that the heat pipe collector would be slightly less efficient at a 100°F inlet temperature and would get increasingly better as inlet temperature rose.

2.4.2 Chart 127

The second day of testing was done at an inlet temperature of 200°F. The optimum angle was 29°. The heat pipe collector had efficiencies of 34.1% at solar noon and 23.9% all day, while the TC-100 showed 37.2% at solar noon and 30.8% all day. As can be seen, the heat pipe collector did not improve as expected, and in fact, there was a marked reduction in efficiency. Accordingly, it was decided to analyze the data in greater depth to see if an explanation could be found for the lower heat pipe performance, and at the same time obtain test data at 300°F.

Figure 2.11

ΔT VS TIME OF DAY HEAT PIPE COLLECTOR & TC 100-8 SHROUD COLLECTOR

2.4.3 Chart 128

This test was done with an inlet temperature of 300°F and the optimum tilt angle of 29°. The heat pipe collector efficiencies were 29% at solar noon and 19.0% all day. The TC-100 had efficiencies of 31.9% and 21%. Again the heat pipe collector operated at a reduced efficiency, however, its relative performance to the TC-100 was better than for the 200°F inlet temperature.

2.4.4 Data Analysis-Chart 125, 127, and 128

Analysis of the test data revealed a variation in the ΔT in the heat pipe manifold while the flow rate remained constant and the solar insolation was on a constant up-ramp. During the same time, the TC-100 showed a uniformly increasing ΔT in the manifold flow. This is seen graphically in Figure 2.11 for test chart #125. The solar insolation was unimpeded until 13:00.

The most significant data lies between 9 and 10:30 where the TC-100 has a continuously increasing ΔT and the heat pipe has numerous peaks and valleys. The flow rate was checked and found to be constant to within 1.5%. However, the heat pipe collector's ΔT varied by 40% at 10:15. The absolute difference in magnitude of the ΔT 's results from the heat pipe collector having three times the flow rate of the TC-100.

The data chart numbers 127, and 128 also showed the ΔT variation but to a lesser degree at each higher temperature. Accordingly, it was hypothesized that the heat pipes were encountering liquid entrainment which heretofore had not been observed in the laboratory testing of these trimethylborate heat pipes or other test heat pipes on the program.

When liquid entrainment occurs there is a buildup of liquid in the condenser section of the heat pipe. This, in essence, shuts off the heat pipe from the pumped loop by creating a large ΔT through the liquid slug in the condenser. Thus, the efficiency goes down and the absorber temperature goes up. When the liquid in the condenser empties, there is an instantaneous increase in the efficiency due to the removal of the stored heat in the absorber. The condenser empties when the gravitational head of the liquid exceeds the supporting pressure which includes the dynamic forces of the vapor and surface tension.

The combined effect is an undulation in the instantaneous efficiency of the heat pipe collector, which upon integrating over the day produces a reduced efficiency. This reduction occurs when the absorber temperature rises as the heat pipe condenser fills up with trimethylborate.

The heat pipe temperatures and absorber fin temperatures were reviewed and observed to follow to a lesser degree the undulation that the manifold ΔT and efficiency³ did. However, this was somewhat obscured by the thermal inertia of the system.

Based on the belief that liquid entrainment was causing the problem, it was decided to test the collectors at an off-optimum steep tilt angle to see if the performance would improve.

2.4.5 Chart 129

Prior to off-optimum testing it was decided to retest the collectors at 200°F inlet at optimum tilt with a flow rate of 1.0 and 0.5 gpm through the heat pipe manifold while maintaining 0.25 gpm through the TC-100. Although data was taken, the results were very obscure as the day was very high in diffuse radiation due to clouds. Accordingly, the instantaneous efficiencies can not be compared directly since the heat pipe collector has

a different thermal inertia than the TC-100.

2.4.6 Chart 130

This was the first test at a 60° tilt. The inlet temperature was 100°F . The heat pipe collector had a 47.4% efficiency at solar noon. The TC-100 measured 46.5%. The test was terminated shortly after solar noon due to equipment problems.

2.4.7 Chart 132

This was also a 100°F inlet test with a 60° tilt. The heat pipe collector had efficiencies of 47.5% instantaneous and 36.4% all day. The TC-100 measured 52.6% instantaneous and 44.9% all day. Examination of individual data points showed that the TC-100's efficiency tracked the insolation rate by its known thermal inertia. However, the heat pipe collector's efficiency seemed to be out of synchronization with the TC-100 and insolation rate, indicating that some liquid entrainment may have been taking place.

2.4.8 Chart 133

This test was performed at 200° inlet temperature and a 60° tilt. The heat pipe collector had efficiencies of 34.3% at solar noon and 24.3% all day. The TC-100 was 36.4% at solar noon and 28.7% all day.

The heat pipe collector still did not operate as efficiently as the TC-100. However, by comparing the 200°F inlet data in Tables 2.3 through 2.6 it is seen that the heat pipe collector's performance relative to the TC-100 is better at the 60° tilt angle than at the optimum angle.

Since the 200°F inlet tests were the only ones in which the insolation

rate was not varying, one concludes that the trimethylborate heat pipes did experience some degree of liquid entrainment.

2.4.9 Chart 134

This test was done at 300°F inlet at a 60° tilt. The heat pipe collector had a 27.2% solar noon efficiency as compared to 27.8% for the TC-100. The all day efficiency was not obtained due to cloud cover in the afternoon.

2.4.10 Stagnation Tests - Chart 134-A

The two collectors were subjected to three days of stagnation conditions. The collectors were at an optimum tilt of 29°. Representative stagnation temperatures are seen in Table 2.7. It is interesting to note that the heat pipe collector has a lower stagnation temperature than the TC-100, which is attributed to partial heat pipe operation and/or natural gas convection within the heat pipes transporting some of the energy from the absorber to the manifold.

2.4.11 Chart 135 - Post Stagnation

Following stagnation the two collectors were tested at a 100°F inlet and optimum tilt of 22°. The test data was inconclusive since the insolation rate was varying. However, there did appear to be a larger difference in the efficiency of the two collectors.

The heat pipe collector would operate at reduced efficiency if the trimethylborate fluid decomposed at stagnation. This could be observed by comparing the ΔT between the absorber temperature and fluid outlet temperature. If the heat pipe fluid decomposed, the ΔT would increase.

Table 2.8 shows this ΔT for tapes number 125 and 135, before and after stagnation at an inlet temperature of 100°F. From this, it appears that at least one of the two heat pipes instrumented did experience a performance degradation which may have been from fluid decomposition.

These results are in direct contrast to previously tested trimethylborate heat pipes which did not degrade after extensive stagnation testing.

Table 2.2 Summary of Test Data

TEST NUMBER	125		127		128		129			130		132		133		134	
	HP	YC100	HP	YC100	HP	YC100	HP	YC100	HP	HP	YC100	HP	YC100	HP	YC100	HP	YC100
DATE (1979)	4/11		4/19		4/20		4/23			4/30		5/7		5/8		5/9	
TIME (LOCAL)	1200		1200		1200		1200		1215	1300		1300		1300		1304	
TUBE LOT	812154		812154		812154		812154			812154		812154		812154		812154	
	.874		.874		.874		.874			.874		.874		.874		.874	
	.041		.041		.041		.041			.041		.041		.041		.041	
INLET (°F)	115.0	107.8	231.5	226.3	317.6	313.7	206.2	203.2	208.6	112.1	106.5	117.8	111.9	206.1	202.0	298.9	295.1
AMBIENT (°F)	58.89		55.67		57.91		73.12	73.19	73.32	66.59		75.65		80.29		85.01	
INSOLATION (BTU/HR-FT ²)																	
TOTAL	331.29		350.97		341.44		241.77	241.77	231.62	282.38		251.00		263.31		258.99	
DIRECT	265.56		290.20		276.51		86.04	86.04	104.42	*		202.59		205.72		217.84	
% DIFFUSE	19.8		17.3		19.0		64.4	64.4	54.9	24.2		32.0		34.4		30.5	
FLOW RATE (GPM)	.746	.244	.756	.251	.755	.249	1.007	.251	.508	.744	.251	.762	.255	.754	.257	.752	.247
TILT ANGLE	33°		29°		29°		29°	29°	29°	60°		60°		60°		60°	
WIND SPEED	.11		13.87		4.99			3.79		4.48		5.83		6.29		6.36	
	50.82	50.44	34.11	39.18	28.97	31.92	39.42	42.58	38.06	47.44	46.51	47.54	52.60	34.31	36.40	27.21	27.82
Cp (BTU/GAL-°F)	.890	.890	.938	.938	.970	.970	.927	.927	.927	.887	.887	.890	.890	.925	.925	.962	.962
S. G.	1.035	1.037	.992	.992	.945	.947	1.000	1.000	1.000	1.036	1.038	1.034	1.036	1.0017	1.0038	.987	.990

COMMENTS

Very High Diffuse
Heat: Pipe Flow
Rate Halved at
Solar Noon.

*Pyreheliometer
Was Broken.
r Measured @ 1334
TG100 Flow Stopped
@ Noon

Table 2.3 Instantaneous Efficiency Optimum Tilt

T_{IN} IN OF	η_{HP}	η_{TC100}	$\frac{\eta_{TC100}-\eta_{HP}}{\eta_{TC100}}$
100	50.8%	50.4%	-1%
200	34.1%	39.2%	13%
300	29.0%	31.9%	9%

Table 2.4 All-Day Efficiencies-Optimum Tilt

T_{IN} IN OF	η_{HP}	η_{TC100}	$\frac{\eta_{TC100}-\eta_{HP}}{\eta_{TC100}}$
100	37.8%	39.1%	3%
200	23.9%	30.8%	22%
300	19.0%	21.0%	10%

Table 2.5 Instantaneous Efficiency 60° Tilt

T_{IN} IN OF	η_{HP}	η_{TC100}	$\frac{\eta_{TC100}-\eta_{HP}}{\eta_{TC100}}$
100	47.5%	52.6%	10%
200	34.3%	36.4%	6%
300	27.2%	27.8%	2%

Table 2.6 All-Day Efficiencies 60° Tilt

T_{IN} IN OF	η_{HP}	η_{TC100}	$\frac{\eta_{TC100}-\eta_{HP}}{\eta_{TC100}}$
100	36.4%	44.9%	19%
200	24.3%	28.7%	15%

Table 2.7 Stagnation Temperatures

Tape 134-A - 5/11/79 - Optimum Tilt

Time of Day	HEAT PIPE COLLECTOR		TC-100 Tube 6
	Heat Pipe #3	Heat Pipe #6	
12:30	580	654	651
12:45	592	574	657
1:00	600	580	659
1:15	598	582	660
1:30	601	583	660
1:45	586	566	637

Table 2.8 Average ΔT History

Tape # Outlet Fluid Temp. Date	#125 $T_f \approx 130^\circ\text{F}$ 4/11/79	#135 $T_f \approx 130^\circ\text{F}$ 5/17/79
Heat Pipe		
Pipe #3 ΔT	64.1 $^\circ\text{F}$	110.6 $^\circ\text{F}$
Pipe #6 ΔT	77.3 $^\circ\text{F}$	82.0 $^\circ\text{F}$
Flow Rate	0.741gpm	0.755gpm
Std. TC-100		
Position 6 ΔT	20.2 $^\circ\text{F}$	17.0 $^\circ\text{F}$
Flow Rate	0.25gpm	0.252gpm

3. CONTINUED INITIAL TEST DATA

During the reporting period, an additional 19 heat pipes were fabricated and tested. The total number of heat pipes tested in the program now stands at 94. An additional 56,500 hours of electrical testing were accumulated, bringing the total to 123,000 hours. The significant life test data as of June 30, 1979 is seen in Table 3.1.

3.1 Stagnation Tests

At the beginning of the reporting period one ethanol-1010 steel and two trimethylborate - 1010 steel heat pipes were put on stagnation tests. The ethanol heat pipe survived less than one full day. The two trimethylborate heat pipes were left on stagnation for 10 days, removed, retested and showed no change. They were replaced on stagnation test for 30 days, removed, retested and again showed no sign of degradation.

These two heat pipes have continued on stagnation testing for the past 300 days with no apparent large amount of thermal decomposition. The pipes are currently in the process of being retested to determine if degradation has taken place.

These results appear to be in direct opposition to those obtained in the verification tests. However, since trimethylborate does not appear to perform sufficiently well enough to merit its use, the difference in the two stagnation tests is only academic.

3.2 Life Tests

As seen in Table 3.1, only three vessel systems are still being life tested. Heat pipe S-25 which was the best trimethylborate heat

LIFE TEST DATA

PIPE	MATERIAL	FLUID	TEMP-°C	HOURS	ΔT - °C			
					0-10	10-20	20-30	>30
S-3	1010 ST	H ₂ O	175-225	13,750	TEST	TERMINATED		X
Cu-1	CDA-101	H ₂ O	150	13,750	X			
NP-454-1	NP-454	H ₂ O	175-200	11,450	X			
NP-454-3	NP-454	H ₂ O	150	9,050	X			
18SR-2	18SR	H ₂ O	200-225	7,900	TEST	TERMINATED		X
18SR-3	18SR	H ₂ O	175	8,400	TEST	TERMINATED		X
18SR-4	18SR	H ₂ O	225	7,900	TEST	TERMINATED		X
ATS-13	1010 ST	(CH ₃ O) ₃ B	75	10,200	TEST	TERMINATED		
S-24	1010 ST	(CH ₃ O) ₃ B	175 25-300	300 300 days	X X	REMOVED FROM STAGNATION FOR RETESTING		
S-25	1010 ST	(CH ₃ O) ₃ B	175	7,450	X			

Figure 3.1

pipe is being continued strictly for academic reasons, as is Cu-1, the copper-water heat pipe. As discussed in the second interim report, the use of copper as a heat pipe vessel is ruled out because of cost and the necessity to limit stagnation temperature.

The long term success of NP454-water heat pipes is very encouraging. This coupled with the current availability of the material, a manufacturer to make it into tubing and the freeze resistant success as described in section 3.3, provides the incentive to repeat the design verification tests with the higher performance NP454-water system.

3.3 Freeze-Thaw Cycle Tests

At the close of the second interim report a copper-water heat pipe with fiberglass wicking has survived 144 cycles. However, the use of fiberglass is limited to the operational limit of 165°C, as above this the fiberglass is dissolved. To date, this heat pipe has survived 335 cycles. Likewise, several copper-water heat pipes with copper wicks had been tested with unacceptable results.

During the reporting period, two copper water heat pipes with shaped copper wicks were constructed. These two heat pipes have survived 160 freeze-thaw cycles each. The success of these tests is associated with the fact that the copper wick does not conform to the shape of the inside diameter of the heat pipe. Accordingly, the wick does not reinforce the ice as it forms.

Thermacore on its own funds has extended the testing of the freeze resistant heat pipes to include stainless steel-water heat pipes with a stainless steel wick. To date this heat pipe has survived 335 freeze-thaw cycles.

The success of these metal wicked heat pipes is quite encouraging for the potential use of NP454-water heat pipes. However, NP454 wire mesh is not available. Accordingly, an alternate will be required. Thermacore has on another program, tested 347-SS screen for water compatibility and found it to be unacceptable.

To date only preliminary tests have been carried out on Thermacore's IR & D funds, but these tests indicate that a perforated thin metal foil maybe useable as the freeze resistant wick. Additional tests are currently being carried out, and a small quantity of NP454 metal foil has been made from left over strip and will be used to verify the anti-freeze capability and water compatibility of perforated NP454 foil.

4. CONCLUSIONS AND RECOMMENDATIONS

The summary of the design verification test results and continued initial testing is as follows:

1. The heat pipe collector using trimethylborate working fluid is less efficient than the control collector, an unmodified General Electric TC-100. The average efficiency reduction is roughly 10%
2. The trimethylborate heat pipe collector showed wide variations in instantaneous efficiency (up to 25%) while the flow rate was held constant to within a few percent, and the insolation rate was on a uniform up ramp.
3. The variations in measured efficiency are greatest at low operating temperature and low tilt angle.
4. The heat pipe collector had a lower stagnation temperature than the standard TC-100 (600F versus 660F).
5. Test data after stagnation has a spread greater than apparent differences. However, some heat pipe temperatures did indicate a lower performance.
6. Low cost steel alloy NP454 and water as a heat pipe vessel/fluid system show no degradation after 13,000 hours operating life at simulated collector conditions.
7. NP454 is available and can be made into tubing.
8. Specially formed metal wicks accommodated the freeze expansion of water for several hundred cycles without failures.

4.1 Conclusions

The conclusions of the design verification testing of the trimethylborate heat pipe collector are as follows:

1. Lower efficiency results from wide variations in instantaneous

measurements. These variations most probably result from a combination of the following.

- a. Trimethylborate as a heat pipe fluid is inadequate especially at low temperature and low tilt angles. The inadequacy of the fluid causes liquid entrainment which is probably enhanced by the offset in the heat pipe.
 - b. The higher coolant flow rate through the heat pipe collector makes test results more sensitive to variations in temperature measurements.
 - c. The thermal inertia of the heat pipe collector is different than the TC-100. Accordingly, the time constants are different, which must be reflected in comparing the data, especially for varying insolation rates.
 - d. The collection fins on the heat pipes were fully annealed, permitting some distortion during insertion into the evacuated glass shrouds. This may have reduced surface contact and increased temperature losses within the collector.
 - e. Possible instrumentation errors.
2. Based on off-optimum tilt performance, where the heat pipes experienced less entrainment, the heat pipe collector's performance relative to the TC-100 did improve with increasing temperature as the thermal analysis had shown.

4.2 Recommendations

Based on the above conclusions the following recommendations are made.

1. Carry out basic diagnostic tests of the trimethylborate heat pipe collector to determine the exact cause of the wide variations in

instantaneous efficiency.

2. Make comparison tests in the solar collector of trimethylborate heat pipes with and without the offset. (Three purified trimethylborate capsules are available).
3. Based on the findings of 1 and 2 design, fabricate and test an advanced water-NP454, heat pipe collector, complete with freeze resistant heat pipes.

References

1. Cost Effective Solar Collectors Using Heat Pipes - Interim Progress
Report #2 April 1978 - September 1978.